For Domestic Wastewater Treatment, Finding Optimum Conditions by Particle Swarm Optimization and Experimental Design

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Abstract**—** *Performing jar test method is used for finding out optimum conditions (coagulant type, coagulant dose, pH etc.)for treatment of domestic wastewater before physicochemical process, or coagulation process. In this study, Response Surface Method (RSM) is applied to determine optimum combinations of coagulant dose and pH value in jar test. Alum,* $FeCl_3$ *and* $FeSO_4$ *are used as coagulant and compared with highest removal efficiency of their two responses which turbidity and chemical oxygen demand (COD).Finding equations from RSM are also evaluated with Particle Swarm Optimization (PSO) method by using Matlab Program. Alum and Ferric Chloridedose500 mg/lat pH7 found as optimum conditions for domestic wastewater treatment. COD removal for Alum and Ferric Chloride are 90% and 70%,respectively.In addition, Because of becoming low COD removal (maximum 50%) and ineffectively color removal, Ferric Sulfate coagulant found as inconvenient for treating domestic wastewater.*

Keywords—* *Optimization, Domestic Wastewater Treatment, pH, COD, Turbidity, PSO, RSM.

I. INTRODUCTION

Development of industry and rising of population in urban areas increase the amount of domestic wastewater day by day. Releasing of untreated waste water pollute fresh water sources. Therefore, treatment of wastewater is important to meet the growing freshwater demand.

Inappropriate usage of water can only be decreased with developing water techniques (JSackson et al., 2001; Bixio et al., 2006; Karr et al., 1991; Saurer et al., 2008; Shiva et al., 2002, S.Sarıoglu 2005). One of the water controlling policies is separating into gray water and black water. In addition, gray water is treated easier instead of fixed wastewater (Mülleger et al., 2003; Scheumann et al., 2007 S.Sarıoglu 2005).

Gray water comes from bathing, wash basins or sinks, washing machines, dish washing, kitchen etc. Gray water doesn't include urine and faces, so it contains less organic matter and nutrients than black water (Sarıoglu 2005; Schafer et al., 2006; Ramon et al., Eriksson et al., 2002; Jefferson et al., 2004; March et al., 2004).

Gray water can be separated into low-load and high-load. High-load wastewater has more concentration of detergent than the other one. Kitchen, washing machine and dishwashing machine waters are high-load type. On the other hand, low-load wastewater which comes from bathing, wash basins or sinks wastewater has low concentration of detergent.

Gray water has less polluted, so treatment of it is more easy and economic than black one (Sarıoglu, 2011; Ramon et al., 2004; Nolde, 1999; Eriksson ve ark., 2002; Sandec, 2006). Treated gray water can be reused for toilet flushing, irrigation of lawns, parks, washing of vehicles, fire protection and concrete production water etc(Anderson et al., 2003; Angelakis et. al.2001; Friedler et al., 2001, Sarıoglu, 2011).

Mixing of black and gray wastewater can be treated with difficulty and not a good way of urban wastewater usage. Figure 1.gives conventional and alternative methods for urban water usage and treatment. In conventional one, black wastewater and gray wastewater are mixed. But, in alternative method, gray waste water is treated easy and then reused (March et al., 2004).

In this study, gray wastewater coming from washing machines was treated with coagulation method by using Alum, $FeCl_3$ and $FeSO_4$ coagulant and found proper concentration of them for treatment with statistical optimization approach.

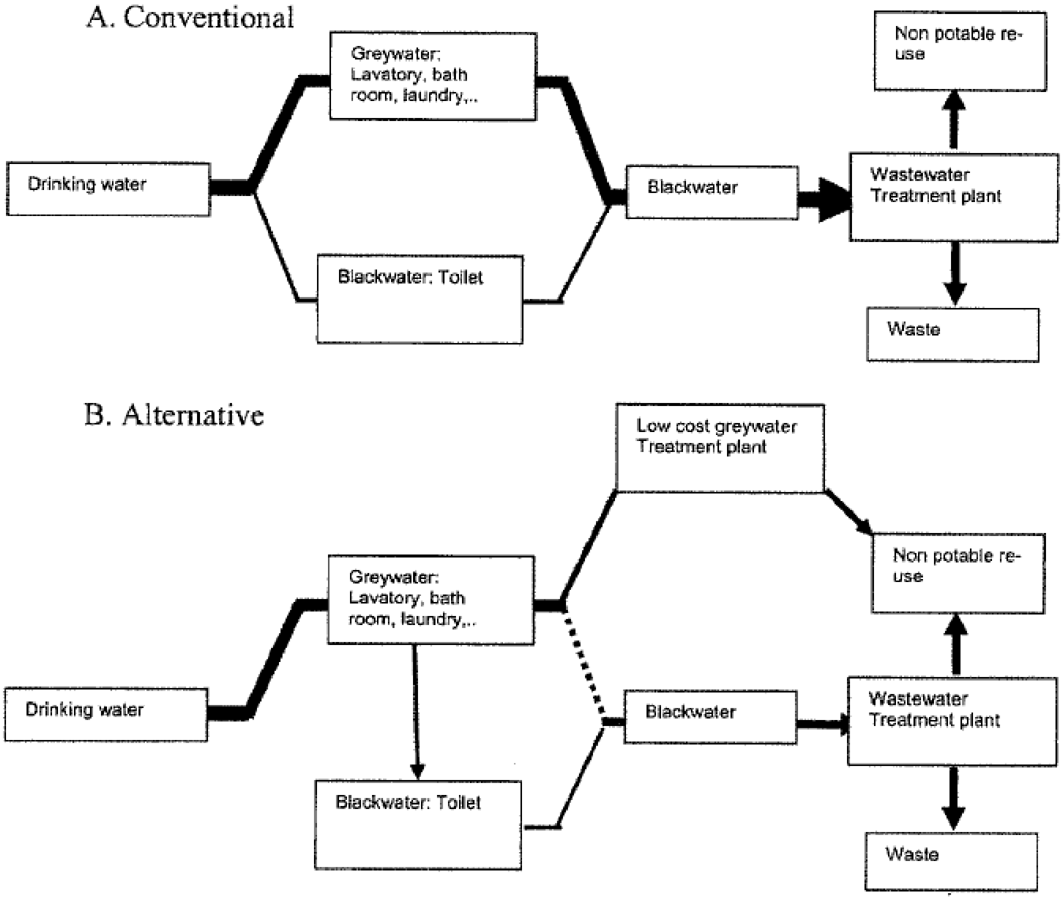


FIGURE 1: CONVENTIONAL AND ALTERNATIVE SCHEMES FOR URBAN WATER USE AND TREATMENT (MARCH ET AL., 2004)

II. MATERIAL AND METHOD

2.1. Characteristic of Wastewater

In this study, waste water samples are taken from washing machine. The measured characteristics of wastewater are given in Table 1.

TABLE 1
THE MEASURED CHARACTERISTICS OF THE DOMESTIC WASTEWATER

Pollutant Parameters	Quantity
Turbidity (FTU)	295
COD (mg/L)	1680
PH	7.6

2.2. Jar Test

Three different coagulants were used in the jar test: aluminum sulfate [$Al_2(SO_4)_3.18H_2O$] (or Alum), Ferric Chloride [$FeCl_3$], ferric sulfate [$Fe(SO_4)_3$]purchased from Merck. The coagulation pH was adjusted according to pH levels in Table 2. These pH levels achieved by adding %20 HCl solution or %20 NaOH solution just before dosing of the coagulant. The coagulation process using the jar test was carried out using 250 ml jars. pH of the solution were measured using pH meter (Mettler Toledo). The pH adjustments were also done respectively by adding HCl and NaOH. All experiments were carried out at room temperature.

The turbidity and chemical oxygen demand (COD) of wastewater was measured using a water analysis system (Orbeco-Hellige, Model 975-MP).The chemicals of Bioscience Inc. are used for COD analysis also. The experimental conditions for each run are given in the design matrix in Table 2.

TABLE 2
THE LEVELS OF THE FACTORS IN THE DESIGN MATRIX

Actual Variable, Unit			LEVELS				
		Symbols	Lowest -α (-1,414)	Low -1	Center 0	High +1	Highest +α (+1,414)
Aluminum Sulfate	Dose (mg/L)	X1	292	500	1000	1500	1700
	pH	X2	6.17	7	9	11	11.8
Ferrous Sulfate	Dose (mg/L)	X1	292	500	1000	1500	1700
	pH	X2	6.17	7	9	11	11.8
Ferric Sulfate	Dose (mg/L)	X1	292	500	1000	1500	1700
	pH	X2	6.17	7	9	11	11.8

2.3. Response Surface Method (RSM)

Experimental design involves what is known as a universe of prediction, because it deals with combinatorial relationship between independent variables. Then, the functional relationships between parameters are treated with regression methods. The mass fraction of coagulant (X_1), pH values (X2) are considered to be the main variables affecting the turbidity in domestic wastewater treatment. The pH of wastewater is 7-11 and experiment is performed under room temperatures. The experimental design adopted had two factors (coagulant concentration and pH value). The coded values of the independent variables (-1 = lowest level, 0 = medium level, 1 = highest level) were calculated. The dependence of the turbidity on these parameters was determined with first and second-degree polynomials. Linear model and non-linear models are given below.

Linear model (Raymond, 1971):

$$Y = f(x) = bo + \sum_{i=1}^{2} biXi + \sum_{\substack{i=1 \\ i<j}}^{2} bijXjXi \tag{1}$$

Non-linear Model:

$$Y = f(x) = bo + \sum_{i=1}^{2} biXi + \sum_{\substack{i=1 \\ i<j}}^{2} bijXjXi + \sum_{i=1}^{2} biiXi^2 \tag{2}$$

Where b_0, b_i, b_{ii} and b_{ij} linear, interaction and quadratic term, respectively are constant and regression coefficients of the model, and X_i are the independent variables in coded values.

In the experimental design method, model parameters are estimated by forming and optimal plan matrix. Generally, the coded values of the parameters are used in the plan matrix.

$$Xi = \frac{Ui - Uio}{\Delta Uio} \tag{3}$$

Here, Xi is the coded value of the variables; i the real values of the variables, U_{io} the average values of the variables, and ΔU_i the step interval of the variables.

The plan matrices are formed in the following sequential order. Firstly, the area to be searched and a central plan are selected. The initial coordinate is applied to central plan. Next, the step interval of the change for each parameter is determined. The selection of the center of the plan and of the step interval is due to the definition of the model, 2n experiments must be carried out. The number of experiments for a nonlinear model is $2^n + 2n + 1$. Here, '2' indicates two levels, the highest and lowest, of the selected operating parameters X_i and n is the number of parameters (Zeybek et al., 2007).

The optimization was done using numerical approach. The goal of the optimization was set to finding the operating conditions that would give the maximum COD and turbidity removal efficiency in order to determine relationships between the factors and responses.

The experimental design, the statistical analysis and optimization were accomplished with the Response Surface Method in Design-Expert 9.0 programme, which wasshowed the result of 3D surface and 2D contour plots.

2.4. Particle Swarm Optimization (PSO)

In many optimization problems, the size of the search space rapidly increases with number of variables and domain of the values they can take. Finding an optimization in these search space quickly becomes an interactable problem, due to find sufficiently good solution in polynomial time (Babuska and Schutter, 2008).

Particle Swarm Optimization (or PSO) (Kenedy and Eberhart, 1995) has been developed to solve nonlinear multidimensional optimization problems. The best position everwas succeed in achieving by each individual, also called its experience, is retained in memory. Then, the information of this experience is transfer onto part or the whole population. In anology to flocks of birds, PSO casts the optimization problem in a parameter space, through which a set of particles flies.

The basic flow for the PSO algorithm is shown in figure 2. A population of random vectors and velocities are created as the swarm of particles. These particles are randomly placed, and each move in random directions, but as the algorithm is performed, swarming behavior emerges as the particles probe the multi-dimensional surface.

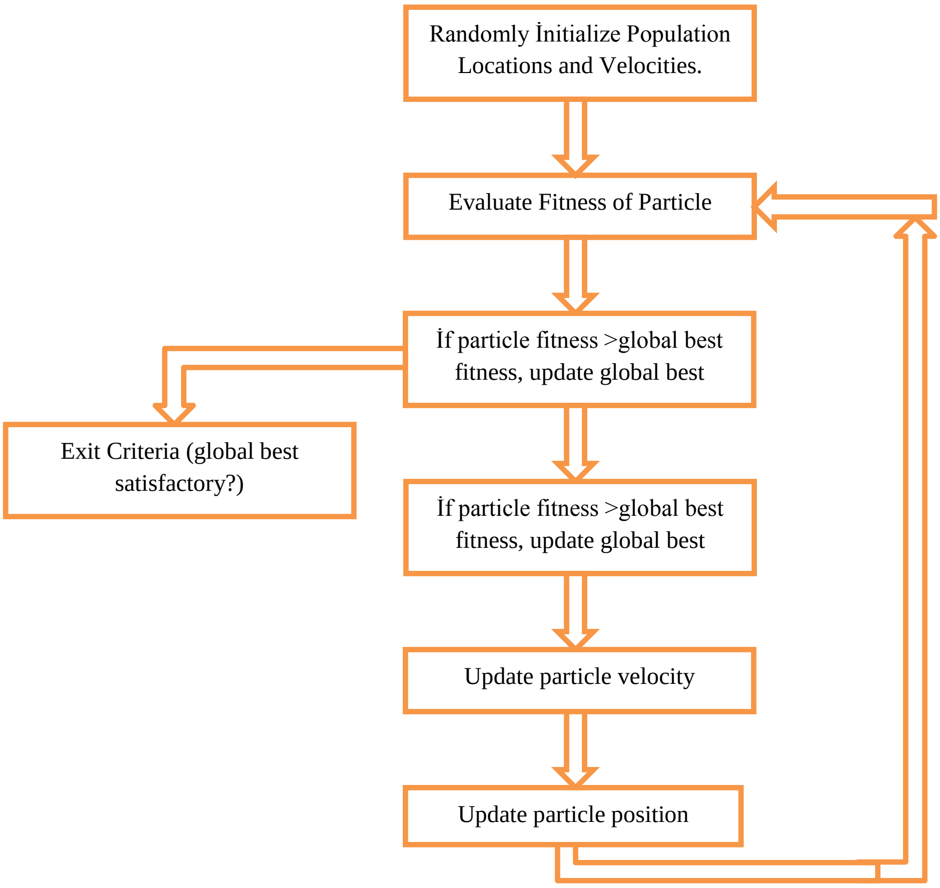


FIGURE 2: BASIC PSO ALGORITHM.

In PSO, the particles update their state in each iteration of the algorithm is given with the following Equations (4)-(5);

$$v_i(t+1) = w(t)v_i(t) + c_1r_1(t)\,[x_{i,pbest}(t) - x_i(t)] + c_2r_2(t)\,[x_{i,gbest}(t) - x_i(t)] \tag{4}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{5}$$

Where t is the current time step, x_i (t), the position of a particle, v_i (t) its velocity, $X_{i,pbest}(t)$ the personal best position, $x_{i,gbest}(t)$ the global best position at time t. In addition, w(t) is the inertia weight, $r_{1,2}(t)$, random variables, and $c_{1,2}$ acceleration constants.

In each iteration, a fitness function F : X → R is evaluated for the values of $x_i(t)$ and compared to the personal best values $x_{i,\,pbest}(t)$. If a better value, corresponding to a higher fitness, has been found for a particle i, its personal best value is replaced by $x_i(t)$. If the maximum of x_i (t) over all i in some neighborhood is higher than the current $X_{i,gbest}(t)$, the latter value is replaced by that value. Sometimes, the neighborhood is considered to cover the complete swarm. Therefore, the local best is called the global best position of a particle. Each particle in the swarm is attracted towards its personal best solution and its global best solution. In this way, it learns to find the optimum of the fitness function, not only by its own experience, but from other members of the swarm as well. The values of the inertia weight w(t) and the range of the random variables $r_{1,2}(t)$ influence the convergence of the particle swarm. The positive acceleration constants $c_{1,2}$ trade off exploration and exploitation.

III. RESULTS AND DISCUSSION

3.1. Response Surface Methodology

The turbidity and COD removal efficiency were investigated to the minimum amounts of coagulants and optimum the value of pH. The main features of response surface methods lend themselves well to study of multiple response situations. Diagrams showing the fitted surface in the form of contours of constant response often indicate more than one region where the predicted response is at a level which is considered to be satisfactory. The researcher can then use this information, in addition to similar contours for a second response, to arrive at a setting (X_1, X_2,…X_t) that represents approximately the "best" operating conditions. The turbidity and COD removal of the treated wastewater was chosen as the dependent variable to be studied.

In these experiments, two independent variables investigated were coagulant concentration (X_1) and pH value (X_2). Initially, a simple 2^2 factorial experiments was planned in order that yield studied. The levels of the factors are given in Table 2. The following equations show coded variables.

$$X1 = \frac{C(Coagulant) - \overline{C(Coagulant)}}{\Delta C\ (Coagulant)} \quad , \qquad X2 = \frac{PH - \overline{PH}}{\Delta PH} \tag{6}$$

The results apply to the Central Composite Design (CCD) of RSM to observe the effects of the concentration of coagulant and the value of pH. Therefore, these program supplies to us compare of the single, the linear and the interactive effects of coagulant dose and pH value.

The CCD application of results of alum, ferric chloride and ferric sulfate coagulants are given Equations (7)-(12). Y_1 and Y_2 show us the COD and turbidity removal efficiency for all coagulants. For the COD removal, the terms of this model were found to be X_1, X_2, X_1X_2, X_1^2 and X_2^2.

COD removal Y_1 (%) :

$$Y_1\ (Alum) = +86.79 - 8.13{*}X_1 - 16.82{*}X_2 - 8.25{*}X_1X_2 - 3.66{*}X_1^2 - 10.86{*}X_2^2 \tag{7}$$

$$Y_1\ (FeCl_3) = 75.10 - 3.06{*}X_1 - 10.48{*}X_2 - 10.75{*}X_1X_2 - 10.42{*}X_1^2 - 14.67{*}\ X_2^2 \tag{8}$$

$$Y_1\ (FeSO_4) = 74.50 - 2.60{*}X_1 + 10.55{*}X_2 - 8.00{*}X_1X_2 - 4.75{*}X_1^2 - 20.75{*}\ X_2^2 \tag{9}$$

Turbidity removal Y_2 (%) :

$$Y_2\ (\text{Alum}) = +91.40-0.10*X_1-4.57*X_2-0.50*X_1X_2+1.86*X_1^{2}+0.12*X_2^{2} \qquad (10)$$

$$Y_2\ (\text{FeCl}_3) = +81.11-3.26*X_1+2.1*X_2+3.25*X_1X_2-1.12*X_1^{2}-4.62*X_2^{2} \qquad (11)$$

$$Y_2\ (\text{FeSO}_4) = +74.50-10.23*X_1+21.70*X_2-18.91*X_1X_2-9.73*X_1^{2}-24.73*X_2^{2} \qquad (12)$$

From the Analysis of Variance (ANOVA),p-values of regression, lack of fit R-square values are tested. According to analysis variance Table (3)-(4), the values of lack of fit are smaller than 0.05 and R-square values are obtained range from 0.89 to 0.98. In addition, normal probability plot can be seen in figure (3)-(5). Therefore the model residuals' distribution is normal and also this model fits the Response Surface Methodology.

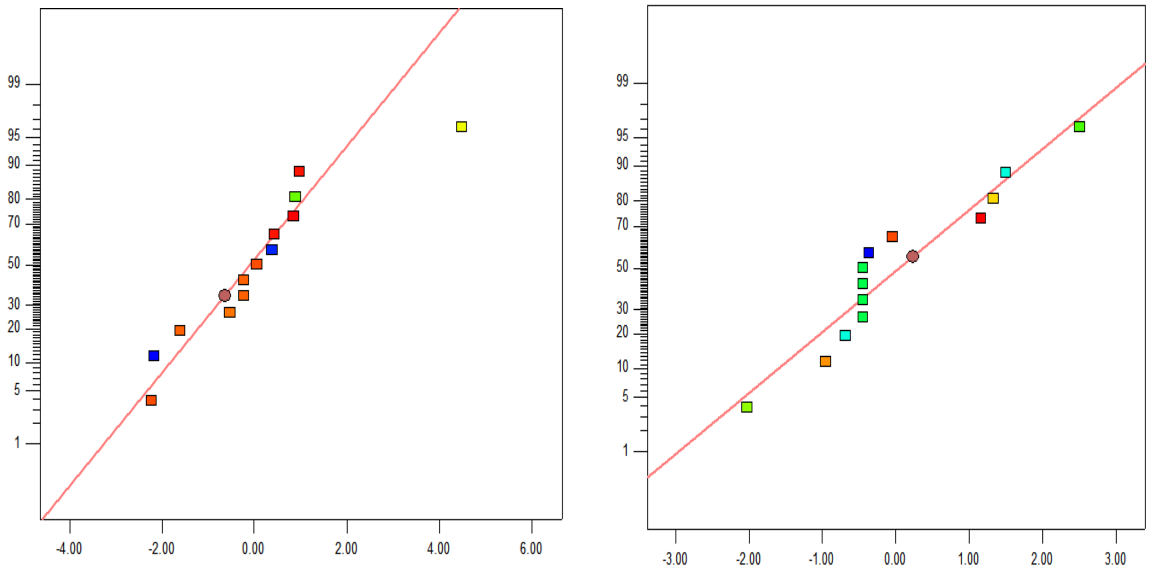


FIGURE 3: NORMAL PROBABILITY PLOTS OF RESIDUALS USING ALUM FOR (A) TURBIDITY (B) COD REMOVAL.

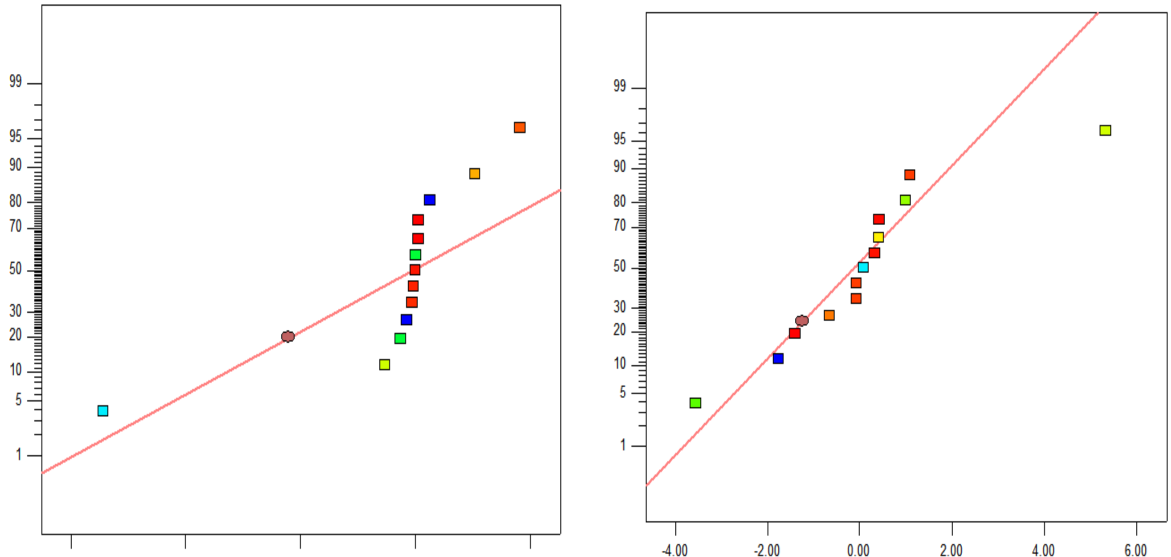


FIGURE 4: NORMAL PROBABILITY PLOTS OF RESIDUALS USING $FeCl_3$ FOR (A) TURBIDITY (B) COD REMOVAL

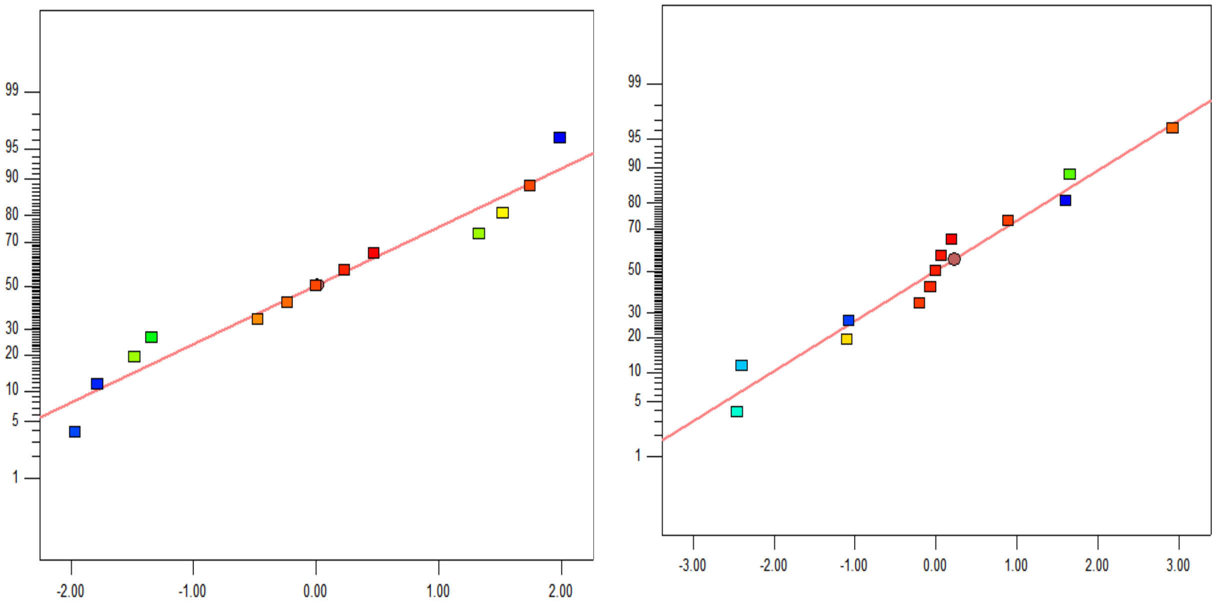


FIGURE 5: NORMAL PROBABILITY PLOTS OF RESIDUALS USING $FeSO_4$ FOR (A) TURBIDITY (B) COD REMOVAL

3.2. The COD removal efficiency

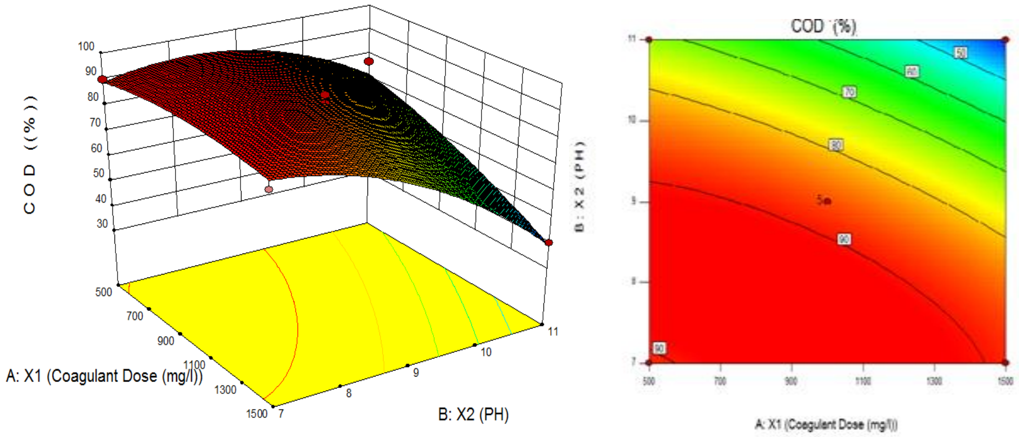
The significance of the parameters is decided to using Fisher's 'F'test which gives the linear, quadratic and interaction effects of the factors. If p-value is less than 0.05, the effect of the factors is significant. In addition, the smaller p-value indicates the more significant effect (Trinh T. Vd 2011).Moreover, the high R-square values of the models confirm their agreements with the experimental data.

The linear (dose, pH), interaction (dose×pH) and quadratic effects (dose×dose, pH×pH) are given in Table 3. The results of Alum and $FeCl_3$coagulants are significant with all p-values<0.05. The linear and the interaction of the pH factor are more significant than the dose factor. So pH factor could be defined as the major determining condition for all of the coagulants.

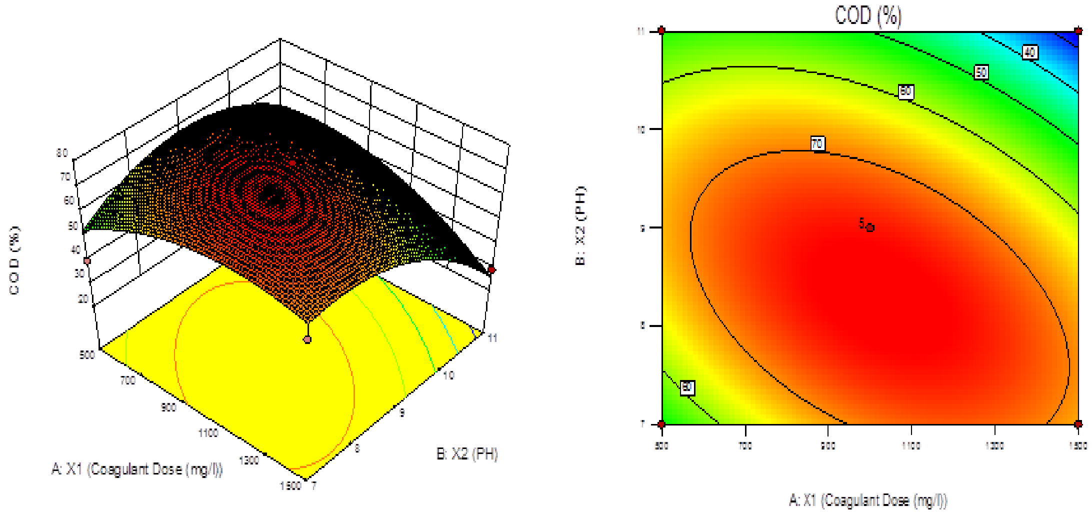
TABLE 3
RESULTS OF ANALYSIS OF VARIANCE (ANOVA) FOR COD REMOVAL MODEL

ALUM					$FeCl_3$				$FeSO_4$			
Source	**Degree of Freedom**	**Mean Square**	**F-Value**	**P-Value**	**Degree of Freedom**	**Mean Square**	**F-Value**	**P-Value**	**Degree of Freedom**	**Mean Square**	**F-Value**	**P-Value**
Model	5	775.17	58.31	<0.0001 significant	5	763.42	11.74	0.0036 significant	3	775.54	4.01	0.0022
Dose	1	528.8	39.78	0.0004	1	797.42	12.26	0.03166	1	234.01	1.21	0.3348
PH	1	2240.18	168.51	<0.0001	1	1801.37	27.72	0.0077	1	5.95	0.031	0.0028
Dose×PH	1	272.25	20.48	0.0027	1	382.79	5.89	0.0315	1	2086.66	10.80	0.6675
Dose × Dose	1	93.14	7.01	0.0331	1	186.13	2.86	0.0110				0.0962
PH×PH	1	796.7	59.93	0.0001	1	551.94	8.49	0.0019				0.0004
Residual	7	13.29			7	65.01			9	193.22		
Lack of fit	3	26.09	7.05	0.0448	3	148.35	58.98	<0.0001	5	345.79	137.66	0.0094
Pure error	4	3.7			4	2.52			4	2.51		
R^2 =0.98 $R_{djusted}{}^2$ =0.96					R^2 =0.89 $R_{djusted}{}^2$ =0.80				R^2 =0.90 $R_{djusted}{}^2$ =0.83			

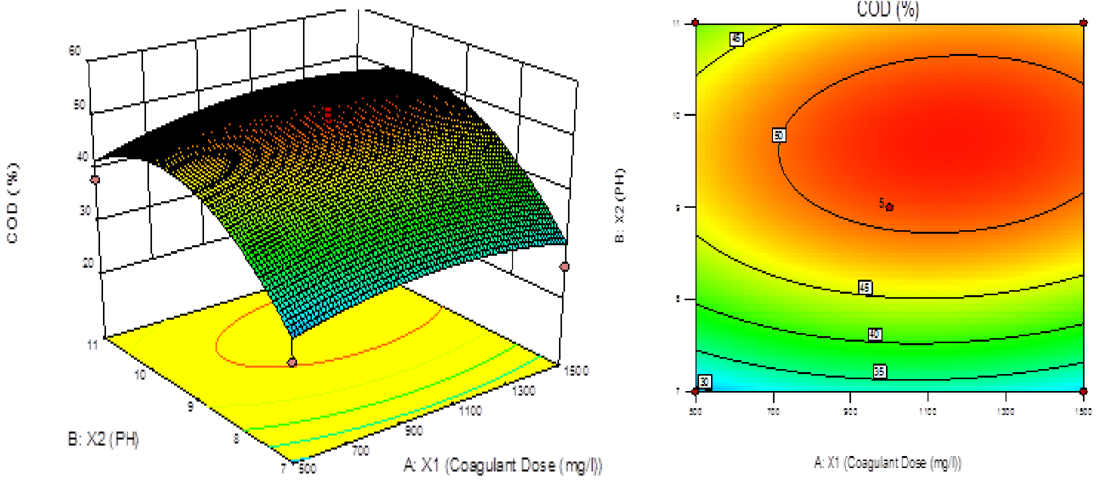
Figure 6 shows COD removal of the 3D surface plots of response and 2D contour plots for Alum $FeCl_3$ and $FeSO_4$. Simultaneous decrease in the doses of coagulant and pH values for Alum and $FeCl_3$led to increase in COD removal. For the combination of the pH range from 7 to 9 and Alum dose range from 500 to 1000 mg/l, more than 90% COD were removed. In addition, the maximum COD removal appeared at the pH range from 8 to 10 and $FeCl_3$ dose range from 700 to 1300 mg/l. Finally, the maximum COD removal obtained at the pH range from 9 to 10 and $FeSO_4$ range from 900 to 1300 mg/l.



A. **ALUM**



B. **$FeCl_3$**



C. **$FeSO_4$**

FIGURE 6: THE 3D SURFACE AND 2D CONTOUR PLOTS OF THE COD REMOVAL FOR A) ALUM, B) $FeCl_3$ AND C) $FeSO_4$.

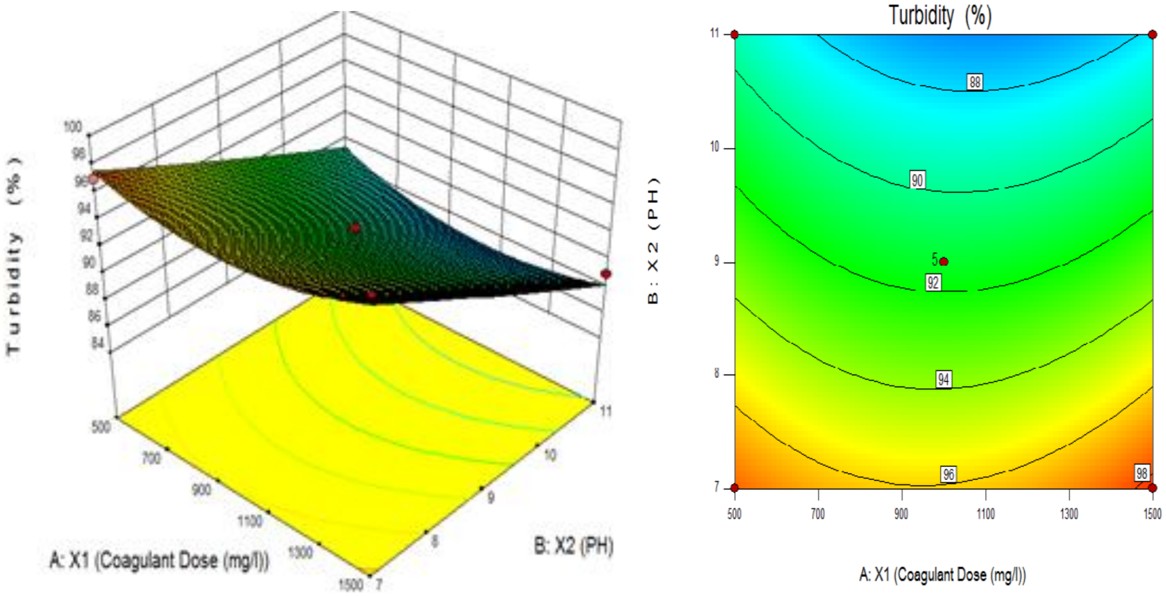
3.3. The turbidity removal efficiency

Table 4 revealed that the results of the analysis of variance (ANOVA) for Alum and $FeCl_3$ coagulant were very significant, because of smaller p-value <0.05. The high R-square values ($R^2 = 0.9681$) of the models confirm their agreements. The linear of the pH factor was more significant. Therefore, pH factor could be defined as the major determination condition of the turbidity of removal efficiency for Alum coagulant. The result of the turbidity for $FeCl_3$coagulant was not significant, because of the p-value >0.05.

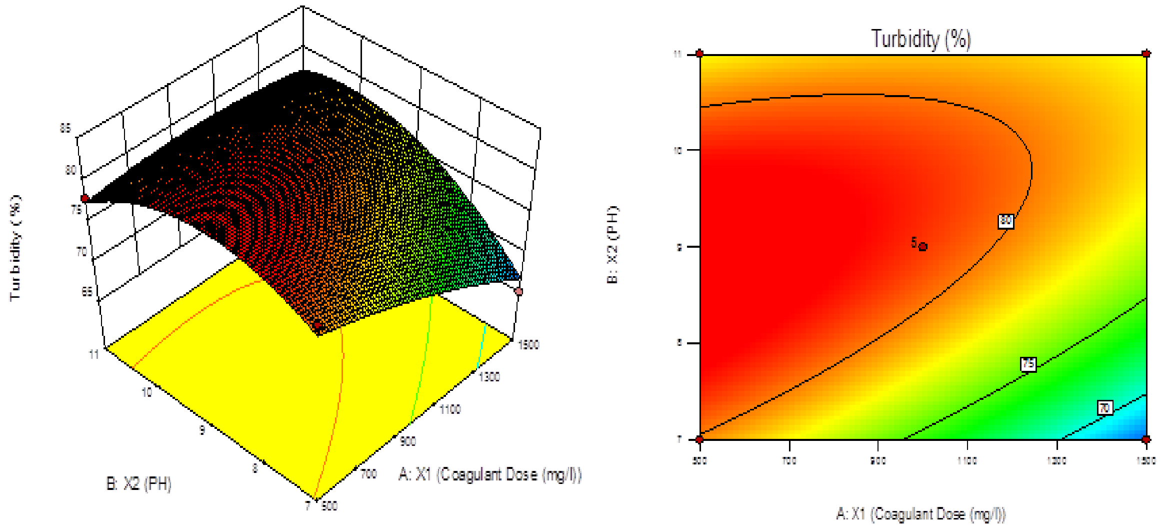
TABLE 4
RESULTS OF ANALYSIS OF VARIANCE (ANOVA) FOR TURBIDITY REMOVAL MODEL

	ALUM				$FeCl_3$				$FeSO_4$			
Source	**Degree of Freedom**	**Mean Square**	**F-Value**	**P-Value**	**Degree of Freedom**	**Mean Square**	**F-Value**	**P-Value**	**Degree of Freedom**	**Mean Square**	**F-Value**	**P-Value**
Model	5	38.16	42.55	<0.0001 significant	3	671.77	2.05	0.0007 significant	5	3440.83	5.38	0.0016 significant
Dose	1	0.086	0.096	0.7661	1	110.90	3.39	0.0016	1	1253.38	1.96	0.3765
PH	1	165.46	184.51	<0.0001	1	91.86	0.28	0.0147	1	6036.73	9.44	0.0065
Dose×PH	1	1.00	1.12	0.3260	1	812.54	12.25	0.0100	1	2229.26	3.49	0.0794
$Dose^2$	1	24.15	26.93	0.0013				0.1560	1	1709.67	2.67	0.1522
PH^2	1	0.090	0.10	0.7602				0.0003	1	6729.23	10.53	0.0002
Residual	7	0.90			9	327.49			7	639.16		
Lack of fit	3	1.03	1.28	0.3943	5	588.16	355.97	0.0148	3	1491.21	12805.56	0.0003
Pure error	4	0.80			4	1.65			4	0.12		
$R^2 = 0.97$ $R_{adjusted}^2 = 0.95$					$R^2 = 0.93$ $R_{adjusted}^2 = 0.88$				$R^2 = 0.91$ $R_{adjusted}^2 = 0.84$			

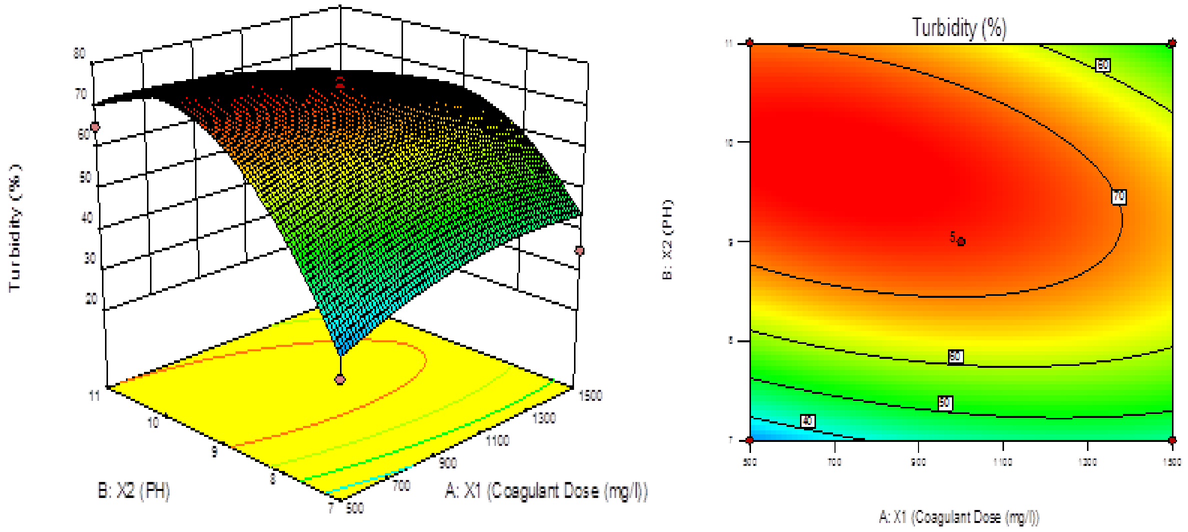
Table 4 shows that the linear (dose, pH), interaction (dose×pH) and quadratic effects (dose×dose, pH×pH) of model terms. For Alum coagulant, the linear pH factor was more significant than others, which are smaller p-value <0.05. Therefore, the linear pH factor could be defined as the major determining condition of turbidity removal for Alum coagulant. In addition, quadratic pH factor (pH × pH) is the major determining condition of turbidity removal for $FeCl_3$ and $FeSO_4$ coagulants.



A. Alum



B. FeCl$_3$



C. FeSO$_4$

FIGURE 7: THE 3D SURFACE AND 2D CONTOUR PLOTS OF THE TURBIDITY REMOVAL FOR A) ALUM, B) FeCl$_3$ AND C) FeSO$_4$.

Figure 7 shows the 3D surface plots of response and 2D contour plots of the quadratic models with respect to turbidity removal for Alum, FeCl$_3$ a FeSO$_4$, respectively. Simultaneous decrease in the doses of coagulant for all of the coagulants led to increase in turbidity removal. The maximum turbidity is removed at the combination of the pH range from 7 to 9 and Alum dose range from 500 to 800 mg/l. Moreover, the maximum turbidity removal was observed at the combination of the pH range from 7 to 9 and FeCl$_3$ dose range from 500 to 900 mg/l. Finally, the combination of the pH range from 9 to 11 and FeSO$_4$ dose range from 500 to 1000 mg/l, the maximum turbidity removal was observed.

For FeSO$_4$ coagulant, obtained maximum turbidity removal is % 70 at the pH range from 9 to 11 and FeSO$_4$ dose range from 500 to 1000 mg/l. But, because of Cl$^-$ions of detergent, effectively color removal is not obtained from Ferric Sulfate coagulant. Therefore, Ferric Sulfate coagulant is not convenient for treating domestic wastewater.

3.4. PSO Application

The values c$_1$ and c$_2$ are 1,494. Equation (4)-(5) can be rewritten as following equations.

$$v_i(t+1) = w(t)v_i(t) + 1{,}494\times r_1(t)\,[x_{i,pbest}(t) - x_i(t)] + 1{,}494\times r_2(t)\,[x_{i,gbest}(t) - x_i(t)] \quad (13)$$

$$x_i(t+1)= x_i(t)+ v_i(t+1) \tag{14}$$

Number of iteration and particles are 500 and 50, respectively. In addition, number of dimension is two and also, inertial weight is chosen randomly between 0, 4 to 0, 9 by PSO Matlab programme.

PSO is applied to Equations (7)-(12) and results of efficient COD and turbidity removal values are given Table 5. Although, Response Surface Methodology only gives the range value of pH and coagulants dose for all the coagulants, results are moved closer to a particular value as expected for PSO method.

TABLE 5
PSO RESULTS OF EFFICIENT COD AND TURBIDITY REMOVAL

	COD		**Turbidity**	
	pH	Dose (mg/l)	pH	Dose (mg/l)
Alum	7.25	500.46	7.16	1499.8
Ferric Chloride	7.11	500.14	9.09	511.22
Ferric Sulfate	8.52	500.15	7.40	500.36

IV. CONCLUSION

The physicochemical process or coagulation process is common in water treatment. In this work, the Central Composite Design of Response Surface Methodology has been successfully applied to this process for the treatment of domestic wastewater. Simultaneous removals of COD and turbidity are investigated to evaluate effects of coagulant dose and pH and then determined the optimum conditions. The results of the ANOVA carries out that the COD and turbidity removal are significant with smaller p-values <0.05. Moreover, good correlation coefficients of %97.66 and %96.81 are obtained respectively for COD and turbidity removal. This study reveals that alum is more efficient than $FeCl_3$ and $FeSO_4$ for removal COD and turbidity. Absolute value of pH and coagulant dosage was found by PSO algorithm. Alum is recommended for the coagulation of best treatment domestic waste water.

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