ISSN : 0974 - 7451 Volume 10 Issue 11

Environmental Science

An Indian Journal

Current Research Paper

ESAIJ, 10(11), 2015 [395-404]

Modelling and optimization of reverse osmosis technique process papramеters to treat chicken industry wastewater

K.Thirugnanasambandham, V.Sivakumar*

Department of Food Technology, Kongu Engineering College, Perundurai, Erode-638052, TN, (INDIA)

E-mail: drvsivakumar@yahoo.com

ABSTRACT

Water demand and wastewater production in chicken industries of India are steeply increasing, and the gap between water supply and demand is getting wider. Furthermore, the constraints for water resources development are also raising due to high investment costs. Treatment of chicken industry wastewater by reverse osmosis (RO) system might be technically and economically viable to cope with water scarcity and overcome the water deficit in chicken industry. Therefore in this present study techno-economical feasibility of chicken industry wastewater treatment by RO was investigated.. From the results initial pH of 7, feed flow rate of 70 LPH and operating pressure of 6 bars were determined as optimal conditions with a maximum permeate flux of 44 LPH and TDS removal of 99 %. Finally, three factors at three levels Box-Behnken response surface design (BBD) were used to develop a mathematical model.

KEYWORDS

Pretreated chicken effluent;
Reverse osmosis;
BBD design;
Model development;
Optimization.

INTRODUCTION

Last few decades environmental degradation mainly due to the discharge of untreated industrial wastewater to the ecological system is a crucial problem in India[1]. Among various kinds of industries, in a chicken processing industry, the effluent mainly comes from various units such as parboiling, soaking, steaming and milling which was usually discharged directly into soil or natural water resources. Moreover, this industry generates a huge amount of wastewater, which is harmful to the living organisms and aquatic life[2]. Hence, there is a critical need to develop a technically and economically viable treatment technique to treat chicken industry wastewater. Conventionally, wastewaters are treated by various treatment technologies such as adsorption[3], electrocoagulation[4], electro-oxidation[5], biosorption[6] and biological process[7]. But, these treatment methods shows drawbacks such as long retention time, lower removal efficiency of toxic matters and makes the treated wastewater for non reusable due to the presence of considerable amount of toxic matters in the treated wastewater[8]. But, nowadays membrane separation using reverse osmosis (RO) gives excellent results when applied sensibly to recover the reusable water from industrial wastewaters[9]. Mean while, RO has been applied to treat a wide variety of industrial effluents, however sometimes RO membrane gets fouling due to the presence of more suspended solids and high TDS, which reduce the life of the membrane[10]. Therefore, treatment of industrial wastewaters by RO membrane requires the pre-treatment technique to decrease the fouling and enhance the RO treatment efficiency for recover the reusable wastewater[11]. Moreover, the process parameters of RO treatment method such as initial pH, feed flow rate and operating pressure are more complex and its optimization will pave the way for effective water recovery and removal efficiency of dissolved solid matters. Optimization and simulation studies of such RO treatment process variables are absolutely essential for industrial scale-up.

In conventional optimization technique, a single factor is varied while all other factors are kept constant for a particular set of experiments. Similarly, other variables would be individually optimized through the single dimensional searches which show the long treatment time and incapable of reaching the true optimum without consideration of interaction among the process variables[12]. The technique of defining and investigating all possible conditions in a complex nature experiment involving multiple process variables is known as response surface methodology (RSM). RSM is a technique for designing experiment, which helps the researchers to build models, evaluate the effects of several factors and achieve the optimum conditions for desirable responses in addition to reducing the number of experiments[13].

However, to our best knowledge, there is no study was conducted to treat chicken mill industry wastewater using RO membrane for the recovery of reusable water. Hence, in this present study a pilot scale RO membrane unit was fabricated and it was used to investigate and optimize the process variables such as initial pH, feed flow rate and operating pressure on performance of RO treatment method for pre-treated chicken industry wastewater to recover the reusable wastewater. In our previous studies we reported that the treatment of chicken industry wastewater using electrocoagulation treatment process[14]. Even though, this treatment method removes considerable amount of toxic matters, dissolved matters removal was very low and hence it was non-reusable. So, this pre-treated chicken industry wastewater was used in this present study for RO treatment method. Treatment efficiency of proposed RO treatment method was investigated by determining the permeate flux and total dissolved solids (TDS) removal. Finally, RSM coupled with Box-Behnken response surface design (BBD) was used to study the individual and interactive effect of process variables and optimize the RO treatment process by developing mathematical models with high coefficient of determination values.

MATERIALS AND METHODS

Raw wastewater and chemicals

The wastewater used in this study was collected from chicken industry near Erode, TamilNadu, India and were stored at 4 °C prior to the experiments. The characteristics of wastewater were determined using method described by American Public Health Association (APHA). All the chemicals (HCl and NaOH) used in this study were analytical grade and purchased from local suppliers from Erode, TamilNadu. The TDS rejection and permeate flux was calculated by using the method described in elsewhere[15].

Experimental setup of reverse osmosis system

The picture of the reverse osmosis system was shown in Figure 1. Experiments were carried out with spiral-wound cross flow membrane module, which was provided by New Venus industries, Chennai, TamilNadu. Characteristics of RO membrane used in this study was shown in TABLE 1. Wastewater to be treated was stored in plastic tank and its pH was adjusted by 1 N HCl or 1N NaOH. The peristaltic pump was used to adjust the desired feed flow rate of the wastewater and it was monitored by manometer, where as operating pressure was measured and tuned by using pressure gauge. Permeate water was used to analysis the TDS concentration.

BBD response surface design

In this present study, response surface method-

Figure 1 : Picture of reverse osmosis (RO) unit

TABLE 1 : Membrane characteristics

Membrane specifications	
Material	Polyamide
Surface area	2 m^2
Structure	Asymmetric
Surface property	Hydrophilic
Pore size (nm)	<0.1
Max. P (bar)	9
Max. T (?C)	50

ology coupled with Box-Behnken response surface experimental design (BBD) was employed to investigate the individual and interactive effects of process variables on the responses. Initial pH (A), feed flow rate (B) and operating pressure (C) were selected as independent variables; whereas permeate flux (Y_1) and TDS rejection (Y_2) is selected as responses. After selection of process (independent) variables and their ranges, experiments were established based on a BBD and the complete design consists of 17 experiments with five centre points. The total number of experiments was calculated from the following equation

$$N = 2K(K-1) + C_0 \qquad (1)$$

where, K is number of factors and C_0 is the number of central point. For predicting the optimal point after performing experiments, a second-order polynomial equation was fitted to correlate the relationship between independent variables and responses. The general mathematical form of second-order polynomial equation is given below

$$Y = \beta_0 + \sum_{j=1}^{k}\beta_j X_j + \sum_{j=1}^{k}\beta_{jj} X_j^2 + \sum_{i}\sum_{<j=2}^{k}\beta_{ij} X_i X_j + e_i \qquad (2)$$

where, Y is the response; X_i and X_j are variables (i and j range from 1 to k); β_0 is the model intercept coefficient; β_j, β_{jj} and β_{ij} are interaction coefficients of linear, quadratic and the second-order terms, respectively; k is the number of independent parameters (k = 3 in this study); and e_{-i} is the error. After fitting the data to the models, the models were validated and used for the construction of three dimentional (3D) response surface contour plots to forecast the relationships between independent and dependent variables. After analyzing the polynomial equation depicting the effect of independent variables on the responses, optimization process parameters was carried out by Derringer's desired function methodology[16]. All the statistical analyses were done with the help of Stat ease Design Expert 8.0.7.1 statistical software package (Stat-Ease Inc., Minneapolis, USA).

RESULTS AND DISCUSSION

Influence of initial pH

pH is one of the important parameter which affects the RO treatment efficiency effectively. In order to study the effect of initial pH over the permeate flux and TDS rejection from chicken mill wastewater using RO treatment method, experiments were carried out in various pH ranges (5-9) and it was shown in Figure 2a-b. From the results, it was observed that, the permeate flux and TDS rejection were increased linearly with increasing initial pH from 5 - 8. This is mainly due to the fact that, increases in pH creates a strong affinity of membrane surface towards maximum removal efficiency of toxic matters present in the wastewater and enhance performance of RO treatment method. Thereafter, there is a drastic decrease in permeate flux and TDS removal due to the decline in membrane stability[17].

Influence of feed flow rate

Feed flow rate is the key parameter which affects the performance of the RO method to treat chicken wastewater. Hence, in this present study, the influence of feed flow rate (40 - 90 LPH) on the permeate flux and TDS removal were studied in various ranges of feed flow rate (40-90LPH) and results are shown in Figure 2c-d. It can be seen from the results, permeate flux and TDS rejection were increased linearly with increasing feed flow rate up to 75 LPH. This is mainly due to the fact that, higher feed flow rate generated an effective contact of wastewater to membrane module, which could enhance the permeate flux and TDS rejection [18]. However, beyond feed flow rate of 76 LPH shows the decline in permeate flux and TDS removal.

Influence of operating pressure

Operating pressure is one of the important factors affecting the permeate flux and TDS rejection in RO treatment method. In order to investigate the effect of operating pressure on permeate flux and TDS rejection, various ranges (4-8 bars) of operating pressure were applied to treat chicken mill wastewater and results were shown in Figure 2 a-d. As shown in Figure 2 a-d, the permeate flux and

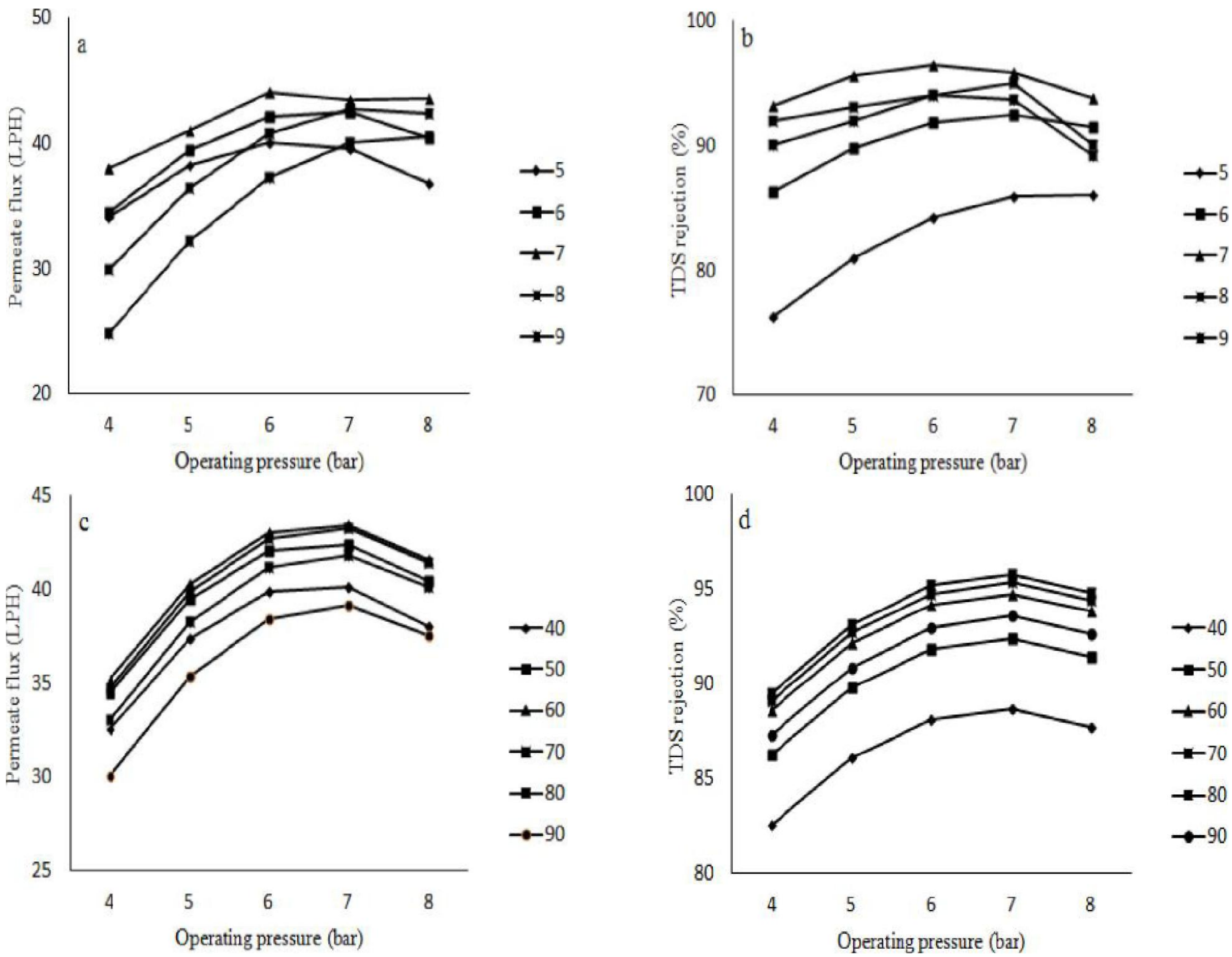


Figure 2 : Effect of process variables on the permeate flux and TDS removal, (a) Effect of pH on the permeate flux (Condition: Flow rate: 50LPH), (b) Effect of pH on TDS removal (Condition: Flow rate: 50LPH), (c) Effect of flow rate on permeate flux (Condition: pH:7), (d) Effect of flow rate on TDS removal (Condition: pH:7)

TDS rejection were increased with increasing operating pressure up to 7 bar. This is mainly due to the fact that, optimum operating pressure (7 bar) generates a effective driving force for maximum permeate flux and TDS rejection. Beyond that, there is a negative effect on the RO treatment process[19].

Mathematical modelling

As stated earlier, performance evaluation of reverse osmosis (RO) membrane to treat chicken mill wastewater were carried out according to the BBD experimental design and the total number of 17 statistically designed experiments were performed for different combinations of the process variables in order to optimize and study the combined effect of independent variables (initial pH, feed flow rate and operating pressure) on the maximum permeate flux and TDS removal (TABLE 2). Then the BBD experimental data was fitted to the various models (linear, interactive (2FI), quadratic and cubic) to obtain regression equation. Multi regression analysis such as sequential model sum of squares, and model summary statistics were carried out to decide about the adequacy of various mathematical models. From the results (TABLE 3), linear and interactive (2FI) models were exhibited lower R^2 and high *p*-values, compared to quadratic model. Cubic model was found to be aliased. Therefore the quadratic model[20] was selected to describe the effects of process variables on the permeate flux and TDS rejection.

(a) Fitting of second order polynomial equation and verification

By applying multiple regression analysis on the BBD experimental data, the coefficients of individual and interactive process variables were determined and it was fitted to second-order polynomial equation that can express the relationship between process variables and the responses[21]. The final equation obtained in terms of coded factors are given below

$$Y_1=44.00+0.13A+0.50B+4.88C+2.50AB+3.25AC+0.50BC-3.63A^2-3.88B^2-4.62C^2 \quad (3)$$

$$Y_2=98.61+4.48A+1.01B+0.32C-2.83AB-4.61AC+0.057BC-6.07A^2-4.31B^2-3.00C^2 \quad (4)$$

Where, Y_1 and Y_2 are permeate flux and TDS rejection respectively; A, B and C are the coded values of initial pH, feed flow rate and operating pressure respectively. Then the statistical analysis was used to analysis the significance of the developed mathematical via Pareto analysis of variance (ANOVA). The statistical significance of the developed regres-

TABLE 2 : Box-Behnken response surface design

S.No	Initial pH (A)	Feed flow rate (B)	Operating pressure (C)	Permeate flux (Y_1)	TDS removal (Y_2)
1	9	65	4	27	98.04
2	7	90	4	31	92.54
3	7	40	4	31	90.24
4	7	65	6	44	98.65
5	7	90	8	41	92.48
6	5	65	4	34	79.58
7	5	65	8	38	90.24
8	9	90	6	40	90.54
9	9	40	6	34	94.58
10	7	65	6	44	98.45
11	7	40	8	39	89.95
12	5	40	6	38	80.26
13	7	65	6	44	98.65
14	9	65	8	44	90.28
15	5	90	6	34	87.54
16	7	65	6	44	98.65
17	7	65	6	44	98.65

TABLE 3 : Multi regression analysis results of BBD experimental data

Source	Sum of Squares	Df	Mean Square	F Value	Prob > F	Remarks
Sequential model sum of squares						
Sequential model sum of squares for permeate flux						
Mean	24929.47	1.00	24929.47			
Linear	192.25	3.00	64.08	2.75	0.0854	
2FI	68.25	3.00	22.75	0.97	0.4455	
Quadratic	232.78	3.00	77.59	241.40	< 0.0001	Suggested
Cubic	2.25	3.00	0.75	6366.00	< 0.0001	Aliased
Residual	0.00	4.00	0.00			
Total	25425.00	17.00	1495.59			
Sequential model sum of squares for TDS removal						
Mean	144868.54	1.00	144868.54			
Linear	169.34	3.00	56.45	1.75	0.2056	
2FI	116.87	3.00	38.96	1.29	0.3304	
Quadratic	299.90	3.00	99.97	379.82	< 0.0001	Suggested
Cubic	1.81	3.00	0.60	75.43	0.0006	Aliased
Residual	0.03	4.00	0.01			
Total	145456.50	17.00	8556.26			

Model	Model summary statistics					
	Std.Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	Remarks
Permeate flux						
Linear	4.8300	0.3880	0.2467	0.0357	477.9	
2FI	4.8480	0.5257	0.2411	-0.1199	554.9	
Quadratic	0.5669	0.9955	0.9896	0.9274	36.0000	Suggested
Cubic	0.0000	1.0000	1.0000		+	Aliased
TDS removal						
Linear	5.6746	0.2880	0.1237	-0.1651	685.0	
2FI	5.4931	0.4868	0.1789	-0.2847	755.3	
Quadratic	0.5130	0.9969	0.9928	0.9506	29.0160	Suggested
Cubic	0.0894	0.9999	0.9998		+	Aliased

sion equation was evaluated by the corresponding *F* and *p*-values and it is presented in TABLE 4, which shows the model *F* and *p*-value of >150 and <0.0001 for both the mathematical models. Then, the suitability of the fitted model was also evaluated by the determination co-efficient (R^2), adjusted determination co-efficient (Adj-R^2), predicted determination co-efficient (Pre-R^2) and co-efficient of variance (CV). From the results it was found that the form of the mathematical model chosen to explain the relationship between the process variables and the responses are well-correlated[22].

(b) Diagnostics of model adequacy

Generally, it is essential to evaluate the adequacy of developed mathematical model; otherwise the developed model may gives poor or misleading results. In addition to statistical analysis, the adequacy of the models was also evaluated by Normal probability plots which are a suitable graphical method for judging residuals normality. The observed residuals are plotted against the predicted values and they lie reasonably close on a straight line and show no deviation of the variance (Figure 3 a-b). Moreover, construction of internally studentized residuals plot was also used to analyze the experimental data to find out the satisfactory fit of the developed

TABLE 4 : Analysis of variance results

Source	Permeate flux		TDS removal	
	F value	*P* value	F value	*P* value
Model	170.52	< 0.0001	247.43	< 0.0001
A	0.39	0.5527	609.37	< 0.0001
B	6.22	0.0413	30.93	0.0008
C	591.50	< 0.0001	3.09	0.1223
AB	77.78	< 0.0001	121.72	< 0.0001
AC	131.44	< 0.0001	322.28	< 0.0001
BC	3.11	0.1211	0.05	0.8290
A^2	172.13	< 0.0001	590.16	< 0.0001
B^2	196.70	< 0.0001	296.66	< 0.0001
C^2	280.20	< 0.0001	144.10	< 0.0001
CV	1.48		0.56	
AP	37.37		47.51	
PRESS	36.00		29.02	

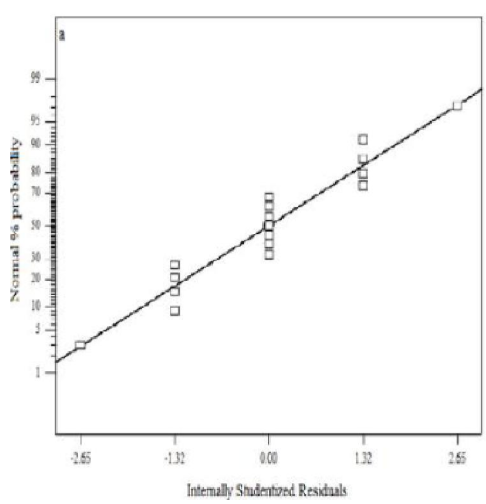
models and the plot shows that, all the data points lie within the limits (Figure 3 c-d). Diagnostic plots such as predicted versus actual (Figure 4 a-b) help us to investigate the model fitness and find out the affiliation between predicted and experimental values. The data point on this plot lie reasonably close to the straight line and indicates that a sufficient agreement between experimental data and the data obtained from the models. These results confirm that the developed mathematical model has the ability to describe the present RO treatment process very robustly[23].

(c) Interactive effect of process variables on responses

To understand the interaction between the independent variables and estimate the permeate flux and TDS rejection over independent variables, three dimensional (3D) response surface plots were plotted from the developed models, which were shown in Figure 5. In this present study, the model has more than two factors. So, the 3D plots have drawn by maintaining one factor at constant level, whereas the other two factors were varied in their range. From the results, it was observed that all the combined process variables shows the significant effect on the RO treatment process and the trends obtained in the 3D response contour plots are closely agreed with Figure 2[24].

(d) Optimization of process parameters

According to the BBD results, the optimal operating conditions to obtain maximum permeate flux and TDS rejection were determined by Derringer's desired function methodology[25] as follows: initial pH of 7, feed flow rate of 70 LPH and operating pressure of 6 bars. Under these conditions, the predicted permeate flux and TDS rejection was found to be 44.54 LPH and 99.05 % respectively with a desirability value of 0.98. Then the suitability of the optimized conditions for predicting the optimum response values was compared with experimental values. The good correlation between observed results and predicted values indicates the reliability of BBD incorporate desirability function method and it could be effectively used to optimize the operating parameters on the maximum permeate flux and TDS rejection[26].



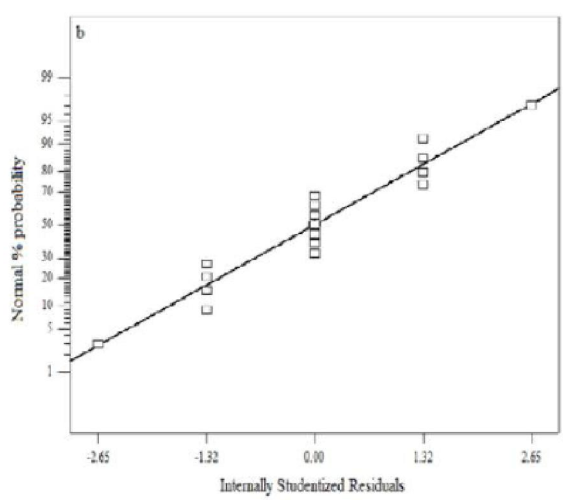


Figure 3 : Normal probability plot for responses. a) Permeate flux b) TDS removal

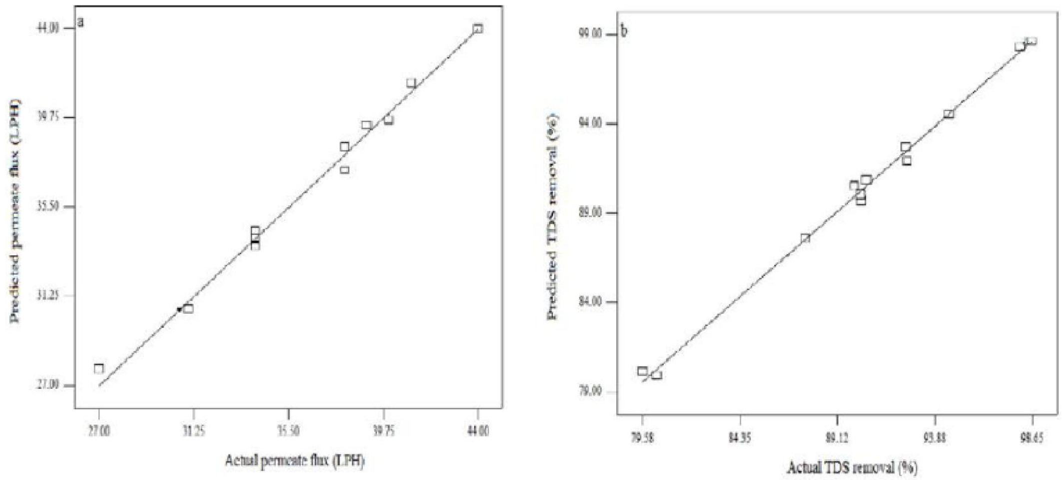


Figure 4 : Predicted versus actual plot for responses

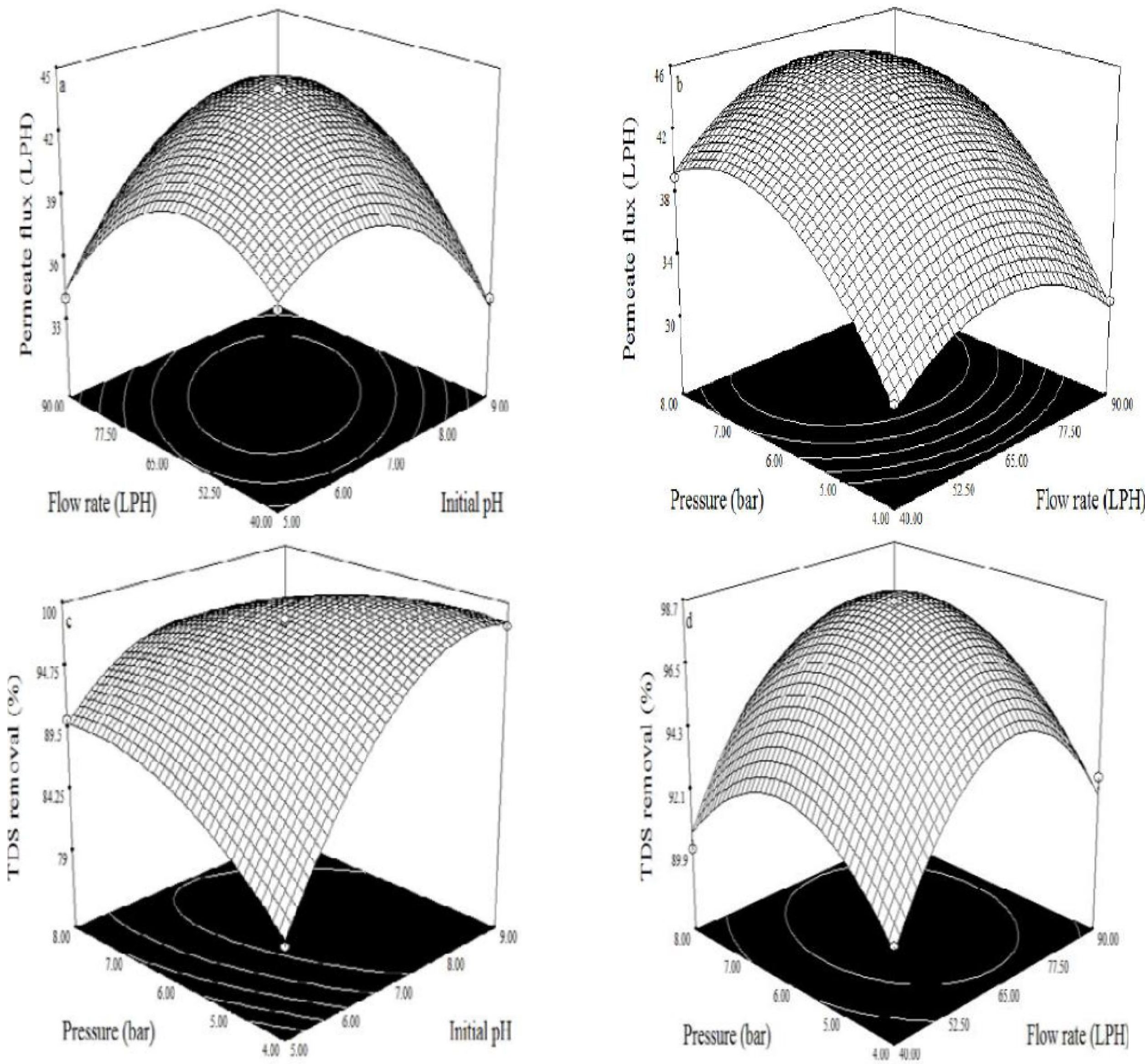


Figure 5 : Three dimensional (3D) response surface plot for on responses

TABLE 5 : Characteristics of wastewater before and after treatment

Characteristics	Raw chicken industry wastewater	Pre-treated chicken industry wastewater	Post-treated chicken industry wastewater	Indian standards (IS: 10500)
pH	4.98	5.25	6.98	5.5-9.0
Turbidity (NTU)	658	105	5	---
BOD (mg/l)	954	148	32	100
COD (mg/l)	4200	66	10	250
TDS (mg/l)	2548	637	7	100

Investigation on reusability of RO treated chicken industry wastewater

In order to verify the reusability of recovered water from the RO treatment, the characteristics of wastewater was determined and compared with Indian standard specifications (IS: 10500) for general standards for discharge[27] of environmental pollutants (TABLE 5). From the results, it was found that the recovered water from can be used to land irrigation and its characteristics falls under the *IS*: 10500 standards.

CONCLUSIONS

Initial pH, feed flow rate and operating pressure on the maximum permeate flux and TDS rejection from chicken mill wastewater by reverse osmosis (RO) treatment method was investigated to recover the reusable water. The obtained results indicated that the factors selected in this study had a significant effect on the performance of RO treatment method. Three factors at three levels Box-Behnken response surface design (BBD was successfully employed to optimize and study the individual and interactive effect of process variables From the ANOVA results, a high correlation second-order polynomial regression models were developed and this could be employed to optimize the process parameters. The optimal conditions were found to be initial pH of 7, feed flow rate of 70 LPH and operating pressure of 6 bars. Under these conditions, the permeate flux and TDS rejection was found to be 44 LPH and 99 % respectively. Finally, the recovered water standard falls under the IS: 10500 Indian standards for the discharge of treated wastewater to land irrigation.

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