

Original paper

Substrate removal kinetics and performance assessment of recirculation sand filters for treating restaurant greywater

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ABSTRACT

Treated wastewater reuse for agriculture is an effective solution to cope with water scarcity conditions in arid and semi-arid areas. The aim of this study was the performance evaluation of a bench scale recirculation sand filter (RSF) for organic matter and nutrients removal from restaurant greywater at the University of Kashan. The average percent removal of 96.9 %, 96.3 %, 98.3 %, 92.8 %, and 70 %, corresponding to five-day biological oxygen demand (BOD₅), chemical oxygen demand (COD), turbidity, total nitrogen, and total phosphorous indicated satisfactory performance of the system for treatment of restaurant greywater with higher concentrations of pollutants compared to typical households greywater. Substrate removal kinetics of the system were assessed by measuring BOD₅ and COD values of septic tank, recirculation tank, and filter bed effluents. First order and second order kinetic models were applied to obtain COD and BOD₅ removal kinetic coefficients for the recirculation tank and the filter bed. Kinetic parameters of the recirculation tank were determined using regression analysis and the results showed that both models were appropriate to describe the substrate removal in the recirculation tank. The reaction rate constants of $K=1.9$ 1/d and 0.4 1/d respectively for BOD₅ and COD were obtained by the first order model, while the corresponding values for the second order model were $K=0.004$ L/mg.d and 0.0003 L/mg.d. For the filter bed, the first-order reaction rate constants $K=1.3$ 1/d and 1.73 1/d were found for BOD₅ and COD, respectively. The second order model was not well qualified for evaluation of the filter bed performance. The results of kinetic models can be used to predict the behavior or design of the recirculation sand filter in full scale applications.

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1. Introduction

Water shortage is one of the environmental challenges in many parts of the world, especially in arid and semiarid areas such as Iran. The use of treated wastewater for agriculture is one of the most environmentally friendly methods to deal with water scarcity. Although the centralized wastewater management is preferred by planners and decision makers in populated areas, this strategy is not economically and reasonably feasible for small communities and decentralized locations such as rural areas. In such cases, the decentralized strategy can be useful for wastewater management. The decentralized wastewater treatment systems are conventionally used for domestic wastewater treatment and they can produce treated effluent meeting the recommended guidelines and standards.

Among various decentralized wastewater treatment systems, Recirculation Bio-Filters (RBFs) are employed in many countries as a reliable and robust decentralized technology, especially in small communities and single family residences (USEPA 2008). RBFs as the secondary treatment systems receive the effluent from septic tanks and treat it through physical, chemical and biological treatment processes. RBFs are the modification form of Intermittent Sand Filters (ISFs) which are extremely effective and reliable for removing biological oxygen demand (BOD), total suspended solid (TSS), Turbidity and ammonia (NH₄) from wastewater (Venhuizen 2005). Biological processes are the main mechanism of pollutants removal in RBFs. A thin layer of microorganisms (biofilm) attaches and grows on the filter media surface, and absorbs soluble and colloidal waste materials in the wastewater as it percolates over the sand surfaces. Physical processes (e.g. straining and sedimentation), and chemical adsorption are among other mechanisms of pollutants removal in RBFs (USEPA 2002). The principle objective of wastewater treatment is the production of an

effluent without harmful effects on human health and the environment. Mathematical modeling of substrate removal is prerequisite to describe the performance of any biological treatment system. Furthermore, it can be used to understand the basic mechanisms of pollutants removal and to estimate bioprocess kinetic coefficients and system characteristics in full scale applications (Senturk et al. 2013). Several kinetic models have been widely presented for different anaerobic upflow filters and fixed bed reactors using Monod first order and Stover-Kincannon and Grau second order models (Akbari et al. 2012; Asadi et al. 2013; Babaei et al. 2013; Rajagopal et al. 2013; Kapdan 2004; Latkar et al. 2003; Ahn and Forster 2000). The performance of RBFs for treatment of single-family residences greywater have been carried out by several researchers based on measuring the quality parameters in the effluent (Zhifei 2006; WSDH 2015; IDNR 2007). However, there is no information about the kinetic processes of substrate removal from this system.

About 35 % of total water consumption at the University of Kashan is allocated for landscape irrigation. Moreover, the university restaurant produces about 40 m³/d greywater, which after treatment can provide part of the water requirement for irrigation. As RBFs can provide a high-level treatment of greywater for single family residences (USEPA 2002), the aim of this study is to evaluate the efficiency of a bench-scale RBF for the treatment of restaurant greywater with higher concentrations of pollutants compared to typical domestic greywater. Five quality parameters including BOD₅, COD, Turbidity, TN and TP in raw greywater and system effluent were measured, and the percent removal of quality parameters were determined and compared with emission standards. Furthermore, the first order and second order kinetic models for recirculation tank and filter bed were developed to obtain the kinetic coefficients of BOD₅ and COD removal.

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2. Material and methods

2.1. Recirculation sand filter (RSF) experimental setup

RSF system consisted of a cylindrical septic tank with 30 cm depth and 10 cm diameter, a cylindrical recirculation tank with an operating volume of 1.5 times of the septic tank, and a cylindrical filter with 45 cm depth and 20 cm diameter as shown in Fig. 1. About 35 cm of the filter depth was filled with crushed sand media with an effective size (d_{10}) of 2 mm and uniformity coefficient (C_u) of unity. Twelve 3-mm holes drilled in the bottom of the filter column allowed the wastewater to percolate through the filter bed. A layer of washed pea gravel was placed over the drilled holes to prevent the clogging of the underdrain system. The raw greywater was poured into the septic tank, allowing gross solids to settle

and scum to float. The septic tank effluent flowed by gravity into the recirculation tank and then into the sand filter column. The filter effluent was collected in the storage tank where a portion of the filter effluent was pumped back into the recirculation tank and the rest was discharged as treated effluent. The recirculation tank effluent was dosed periodically onto the surface of the sand at a constant frequency 48 times/day with an 8-min running time for each dose and 22-min off between doses, which was controlled by an electronic timer controlled valve. In each dose, 75 % of the filter effluent was pumped back to the recirculation tank for re-dosing onto the filter. The hydraulic loading rate (HLR) 0.20 $m^3/m^2/day$, corresponding to the flow rate of 1.57 liters per day was selected in the experiment. The values of the design parameters used in this RSF are presented in Table 1.

Table 1. A summary of design parameters for RSF.

Parameter	HLR, $m^3/m^2.d$	HRT, d	R	Dosing frequency, times/day	Filter media (Fig. 1b) crushed sand
Value	0.2	1	3:1	48	$D_{10}=2\text{ mm}$ $C_u=1$

* Effective size
** Uniformity coefficient

2.2. Sampling and measurement

The efficiency of filter medium for greywater treatment was studied using a single-medium crushed sand filter. The RSF was operated at a constant room temperature 25 ± 2 °C. To examine the system performance, four sampling points were selected: raw greywater from the restaurant, septic tank effluent, recirculation tank effluent, and sand filter effluent. The samples were collected in 500mL plastic bottles and stored at a temperature of 4 °C for less than 24 hours before analysis. Five parameters including COD, BOD_5 , Turbidity, TN and TP were measured based on the Standard Methods (Rice et al. 2012) according to Table 2. Table 3 shows the results of influent and effluent quality parameters in comparison with the Iranian standard of wastewater reuse for irrigation (IRNDOE 2002). For TN and TP which are not specified in IRNDOE, the standard limits were selected from USEPA (2004). The results of the tests revealed good performance of the system and the suitability of effluent for agricultural usage.

septic tank effluent, recycled flow, and recirculation tank effluent, respectively.

Table 2. Methods used for the analysis of quality parameters (Rice et al. 2012).

Parameters	Method used
BOD_5	Winkler (B 5210)
COD	Reflux method (B 5220)
Total nitrogen	Spectrophotometer (38405 DIN)
Total phosphorus	Spectrophotometer (38405 DIN)
Turbidity	Turbidity meter (B 2130)

2.4. Kinetic reaction in the recirculation tank

During the dosing operational periods, mass balance analysis of the recirculation tank can be carried out by modelling of this unit as a Continuous Stirred Tank Reactor (CSTR) where a portion of filter bed effluent (recycled effluent) returns to the reactor, it mixes with the septic tank effluent, and doses onto the surface of the sand filter. The uniform concentrations of reactants in the reactor are supposed under steady state conditions. Therefore, the reactants concentrations in the reactor and in the recirculation effluent are the same, and the change of mass accumulation in the reactor becomes zero, i.e. $V (dC_r/dt) = 0$. The mathematical form of mass balance equation for the recirculation tank can be defined as:

$$V \left[\frac{dC_r}{dt} \right] = Q_s C_s + Q_r C_r - Q_r C_r - \gamma_1 V = 0 \tag{1}$$

where, γ_1 is the rate of substrate reduction in the reactor (mg/L.d) and V is the volume of the recirculation tank (L^3).

For the first order kinetic reaction ($\gamma_1 = K_1 C_r$), equation (1) can be written as follows:

$$V \left[\frac{dC_r}{dt} \right] = Q_s C_s + Q_r C_r - Q_r C_r - K_1 C_r V = 0 \tag{2}$$

where, K_1 is the first order reaction rate constant in the recirculation tank (1/d). The relationship between flow rates in the septic effluent, recirculation tank effluent and filter effluent can be expressed by equations 3 and 4.

$$Q_f = R Q_s \tag{3}$$

And effluent

$$Q_r = Q_s + Q_f = (1 + R) Q_s \tag{4}$$

From the above equations, the mathematical kinetic model of substrate removal in the recirculation tank can be derived as:

$$C_s = (K_1 \theta_h + R + 1) C_r - R C_f \tag{5}$$

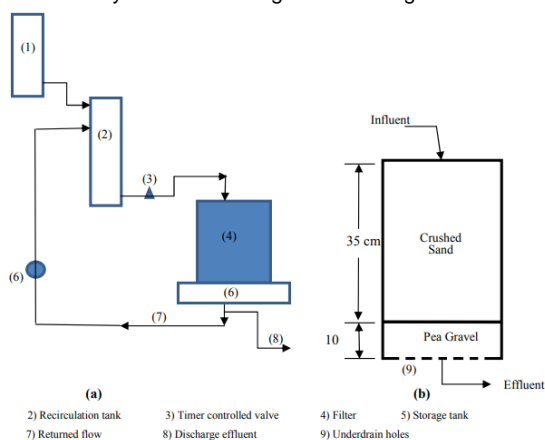


Fig.1. (a) The schematic view of RSF, (b) Details of the filter bed.

2.3. Kinetic models

Determination of the major quality parameters, prediction of the RBF performance, and interpretation of the experimental data for substrate removal are the main purposes of employing the mathematical models. A conceptual model of the RBF is illustrated in Fig. 2.

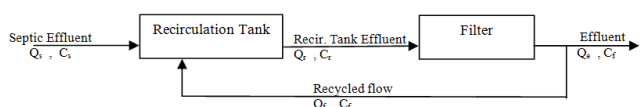


Fig. 2. A conceptual model of the RSF.

where Q_s , Q_r , Q_f and Q_e (L/d) are flow rates of septic tank effluent, recycled flow, recirculation tank effluent, and filter bed effluent, respectively. C_s , C_r , and C_f (mg/L) are the reactant concentrations in

where R is the recirculation ratio and θ_H (d) is the hydraulic retention time defined as the volume of recirculation tank divided by the influent flow rate.

The mathematical kinetic model of second order reaction ($\gamma_1=K_2C_r^2$) is prescribed by the equation given as:

$$C_s = K_2\theta_H C_r^2 + (R+1)C_r - RC_r \tag{6}$$

where, K_2 (d.mg/l)⁻¹ is the second order reaction rate constant.

2.5. Kinetic reaction in the filter bed

During the dosing periods, the recirculation tank effluent feeds to the surface of filter media, percolates through the filter bed and the concentration of reactants varies along the depth of the reactor. Hence, the filter system can be modelled as a Plug-Flow Reactor (PFR). Assuming a first order kinetic reaction, the mathematical form of mass balance can be defined as equation 7.

$$-\frac{dC_e}{dt} = K_f C_e \tag{7}$$

The negative sign on the left hand side of equation 7 implies a decrease of reactant concentrations during the time. The mathematical kinetic model of substrate removal in the filter bed is derived as follows.

$$\theta_H K_f = \left[\ln \frac{C_r}{C_e} \right] \tag{8}$$

or

$$C_e = C_r \exp(-\theta_H K_f) \tag{9}$$

where, $\theta_H = \frac{V}{Q_r}$ is the hydraulic retention time (d) and K_f is the reaction rate constant for the filter bed (1/d). Similarly, the mathematical model of second order kinetic reaction is expressed by equations 10 or 11.

$$\theta_H K_f = \frac{1}{C_e} - \frac{1}{C_r} \tag{10}$$

or

$$\theta_H K_f = \frac{1}{C_r} \left[\frac{C_r}{C_e} - 1 \right] \tag{11}$$

Table 3. Quality properties of the raw greywater and the filter effluent.

Parameters	Unit	Standard value	Raw greywater		Filter effluent		Removal, %
			Mean±SD	Range	Mean±SD	Range	
COD	mg/L	200 (IRNDOE)	5097.5±2397	2040-8176	187.9±67.4	91-287	96.3
BOD ₅	mg/L	100 (IRNDOE)	3450.4±1755.2	1045-6060	105.3±38	54-156	96.9
Turbidity	NTU	50 (IRNDOE)	523.6±303.9	245-1000	9.1±2.9	4.8-15	98.3
TN	mg/L	30 (USEPA)	144±17.3	47.7-415	10.4±2.2	7.8-14	92.8
TP	mg/L	10 (USEPA)	30.8±12.9	15-50	9.2±4.6	6-17	70

standard deviation

3. Results and discussion

3.1. System performance

According to Table 3, RSF provides an average percent removal of 96.6 % and 96.3 % for BOD₅ and COD, respectively. It is observed that COD concentration in the filter effluent is less than the maximum permissible level of COD in wastewater for irrigation and agricultural purposes according to the IRNDOE Standard. Therefore, the RSF effluent can be used safely for landscape irrigation from the COD viewpoint. The mean value of BOD₅ in the filter bed effluent is about 5 % more than the maximum allowable level of BOD in wastewater for irrigation according to the IRNDOE Standard. The IRNDOE Standard has set 50 NTU as the maximum permitted value of turbidity. The average turbidity removal in the system is 98 %, which indicates the high performance of the RSF for restaurant greywater treatment. Nutrients removal from any wastewater treatment system is one of the important issues especially when the treated wastewater is released back into the environment. The average TN removal in the present system is 92.8 %. According to the USEPA Standard, the maximum permissible level of TN in treated wastewater for irrigation is 50 mg/L, while the IRNDOE Standard has no recommendation of TN limit for treated wastewater reuse in agriculture. The average total percent removal of 70 % for phosphate is provided according to Table 3. The USEPA Standard has set 10 mg/l as the maximum level of phosphate in wastewater for irrigation, while the IRNDOE Standard has no restriction on the presence of phosphate in treated wastewater.

3.2. Correlation between BOD₅ and COD

The BOD₅/COD helps to quantify the biodegradability of wastewater. Typical values for the ratio of BOD₅/COD for untreated municipal wastewater are in the range from 0.3 to 0.8, and wastewater with the ratio greater than 0.5 is considered to be effectively treatable by biological methods. The relation between BOD₅ and COD for the restaurant greywater and the filter effluent are shown in Fig. 3. It is observed that the biodegradability index (BOD₅/COD) of 0.68 (R²=0.95) is obtained for raw greywater. The linear regression analysis for the filter bed effluent derives the biodegradability index of 0.52 (R²=0.90).

3.3. Kinetic evaluation of BOD₅ and COD removal

To evaluate the kinetic models presented in this study, BOD₅ and COD values at three points of the system (septic tank effluent,

recirculation tank effluent and filter bed effluent) were measured. The mean values with standard deviations of quality parameters are summarized in Table 4.

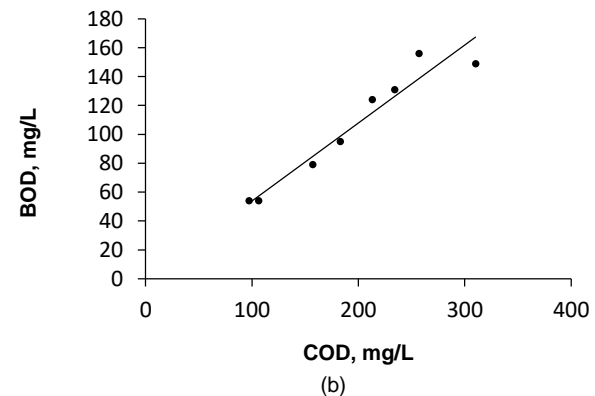
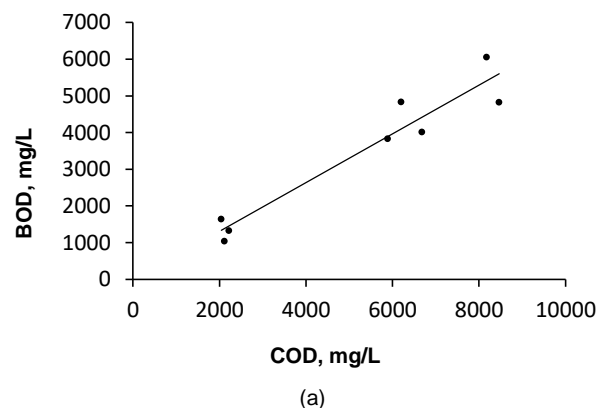


Fig. 3. Correlation between BOD₅ and COD in raw greywater and filter effluent (R of 3:1, HLR of 0.2 m³/m²d and HRT of 1 d).

Table 4. BOD₅ and COD Values at different points of the system.

Parameter	BOD ₅ , mg/L	COD, mg/L
Septic tank effluent (C _s)	1987.6±757	3182.8±1036.1
Recirculation tank effluent (C _r)	387.2±130.8	1053.4±353.8
Filter bed effluent (C _f)	105.3±38	187.9±67.4

The first order models of BOD₅ and COD removal in recirculation tank are shown in Fig. 4 a, b. The reaction rate constant values (K) of 1.9 1/d and 0.4 1/d for BOD₅ and COD with correlation coefficients of R²=0.90 and R²=0.89, respectively are obtained from the slope of the straight line illustrated in Fig. 4 a, b. The calculated K value of BOD removal is about 4.75 times more than the corresponding value for COD removal which may be due to non-biodegradable organic matter in the restaurant greywater. In the same way, the second order reaction rate constants for BOD₅ and COD removal in the recirculation tank were obtained by plotting C_s+RC_f versus C_r as shown in Fig. 4 c, d which are

0.004 (L/mg.d) and 0.0003 (L/mg.d) for BOD₅ and COD, respectively. In the second order model, the determined K value of BOD₅ removal is about 13 times more than the corresponding value for COD removal. Fig. 5 a, b represents the graph plotted of first order reaction of BOD₅ and COD in the filter bed. The first order reaction rate constants 1.3 1/d for BOD₅ removal and 1.73 1/d for COD removal were observed in the filter bed effluent. Table 5 shows BOD₅ and COD removal coefficients with corresponding correlation coefficients for the recirculation tank and the filter bed effluent.

The results reveal that both first order and second order kinetic models are appropriate for prediction of the recirculation tank performance. The presented first order model is suitable to assess the efficiency of filter bed for BOD₅ and COD removal, while the second order model is inadequate for the evaluation of filter bed performance.

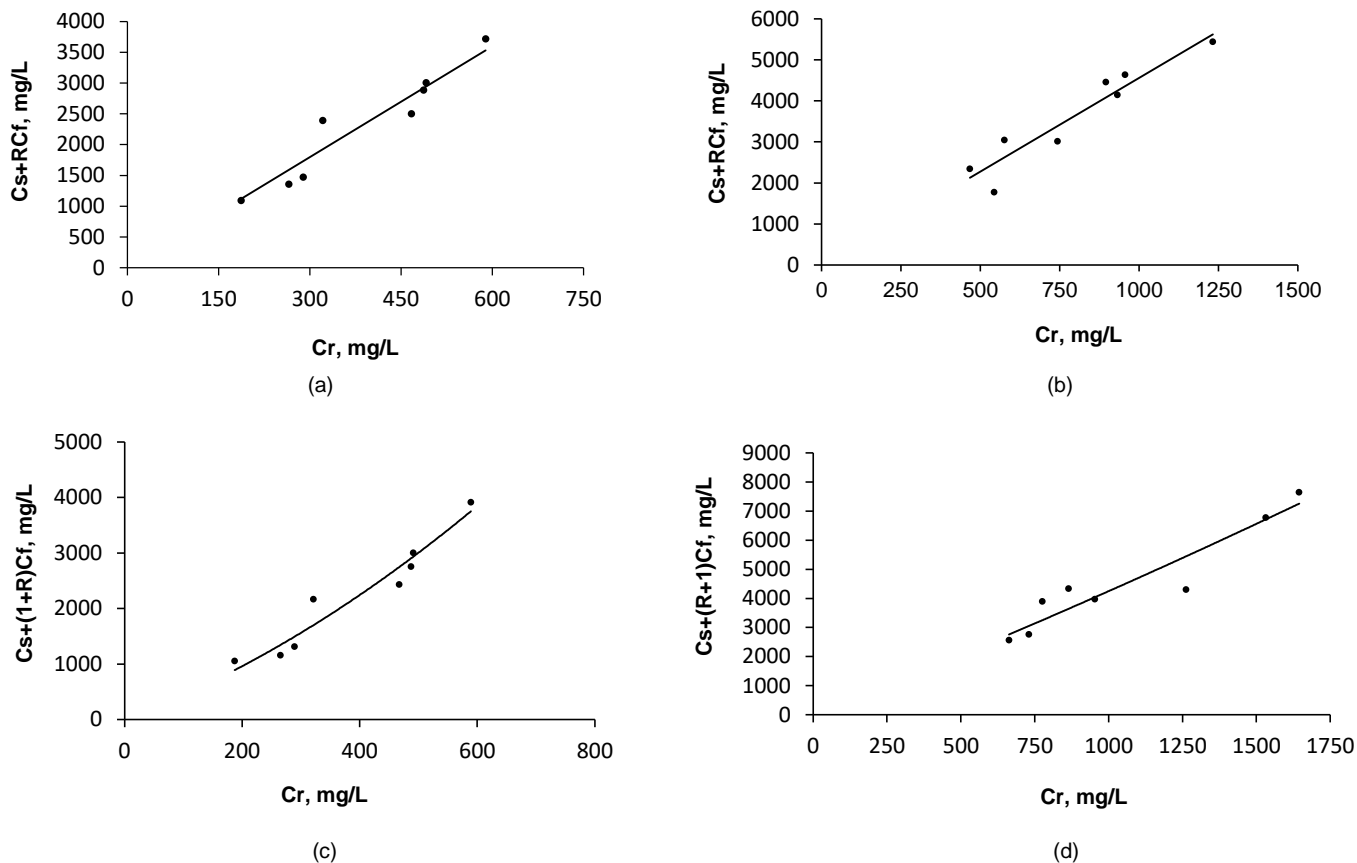
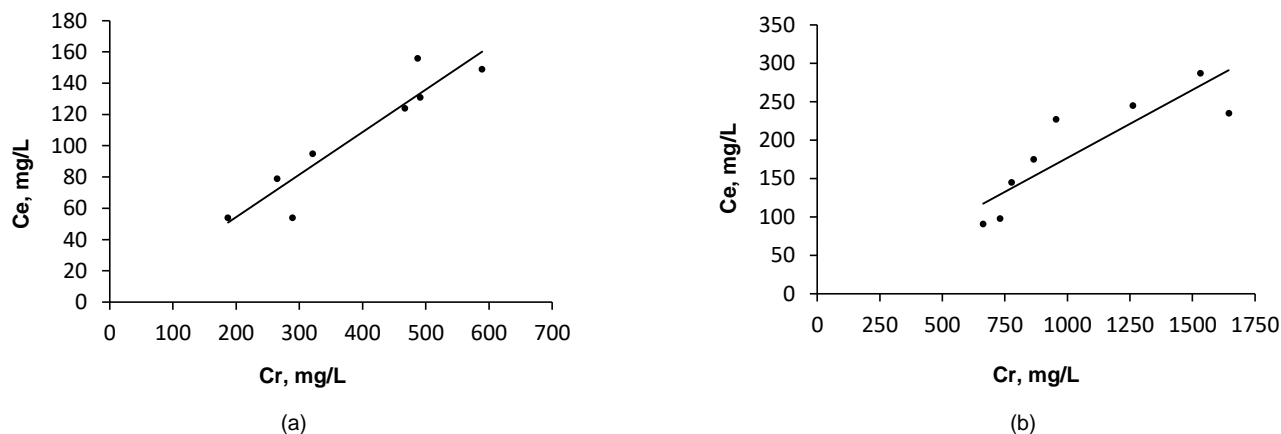


Fig. 4. Graphical analysis for substrate removal in the recirculation tank, (a) the first order kinetic reactions of BOD₅, (b) the first order kinetic reactions of COD, (c) the second order kinetic reactions of BOD₅ and, (d) the second order kinetic reactions of COD (R=3 of 1, HLR of 0.2 m³/m²d and HRT of 1 d).



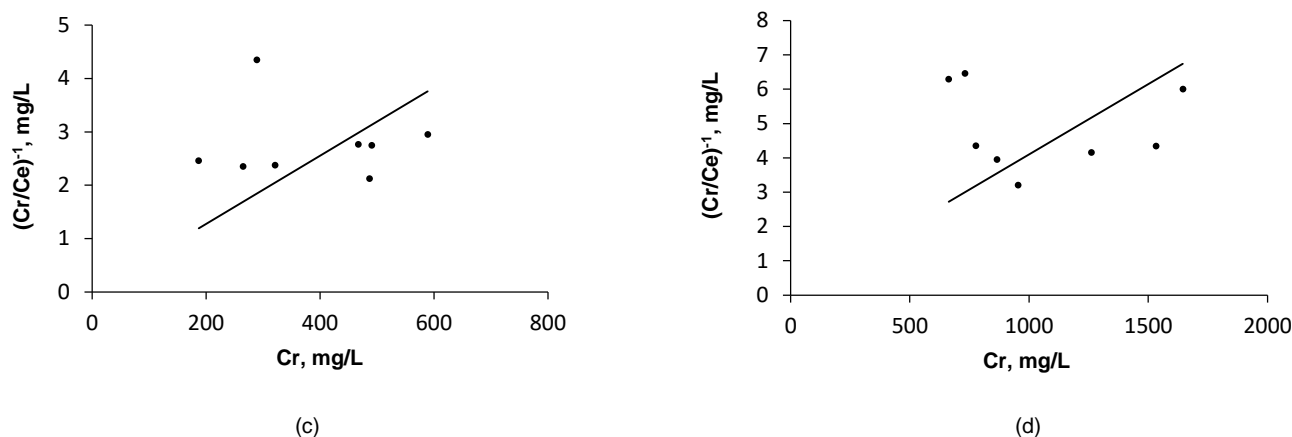


Fig. 5. Graphical analysis for substrate removal in the filter bed, (a) the first order kinetic reactions of BOD₅, (b) the first order kinetic reactions of COD, (c) the second order kinetic reactions of BOD₅ and (d) the second order kinetic reactions of COD (R of 3:1, HLR of 0.2 m³/m²d and HRT of 1.

Table 5. Summary of kinetic parameters in recirculation tank and filter bed for BOD and COD removal.

Reactor	Kinetic models	Quality parameter	K	R ²
Recirculation tank	First order	BOD ₅	1.9 1/d	0.9
		COD	0.4 1/d	0.89
	Second order	BOD ₅	0.004 L/mg d	0.94
		COD	0.0003 L/mg d	0.89
Filter bed	First order	BOD ₅	1.3 1/d	0.88
		COD	1.73 1/d	0.74
	Second order	BOD ₅	0.0079 L/mg d	-0.40
		COD	0.0046 L/mg d	-0.80

4. Conclusions

The performance of a bench-scale recirculation sand filter for restaurant greywater treatment was investigated in this study. The constant values of hydraulic retention time 24hr, hydraulic loading rate 0.2 m³/m²d, and the recirculation ratio R=3:1, and a constant surface area and depth of the filter bed were selected for the system and the experiments were carried out at a constant room temperature of 25±2 °C. The average percent removal of 96.3 %, 96.9 %, 92.8 %, 70 %, and 98.3 % were obtained for chemical oxygen demand (COD), 5-days biological oxygen demand (BOD₅), total nitrogen, total phosphorous, and turbidity, respectively. The results indicated considerable efficiency of the system for restaurant greywater treatment to produce an effluent with suitable quality for landscape irrigation according to the Iranian standard of wastewater reuse for irrigation and the United States Environmental Protection Agency standard. First order and second

order kinetic models of substrate removal were applied to the recirculation tank effluent. Both kinetic models were found appropriate to assess the efficiency of recirculation tank for BOD₅ and COD removal. The first order model of substrate removal in the filter bed showed the recognized results with R²=0.88, but the second order model was not acceptable to evaluate the filter bed performance. The results of kinetic models can serve as a basis to improve the design and operation of recirculation sand filter in full scale applications.

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