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Application of response surface methodology in the analysis of parameters influencing the removal of turbidity and nematodes in direct filtration process

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ABSTRACT: Nematodes are well-known due to their resistance to disinfectants and their ability to ingest and carry pathogens to water distribution systems. Coagulation and filtration play significant roles in removing these organisms in water treatment plants. Investigating the effect of different parameters on the nematodes removal has always been an interest to researchers. However, the simultaneous evaluation of these parameters needs a comprehensive statistical analysis. In this study, the effects of ferric chloride dosage, filter media type, and filtration rate were investigated on the removal efficiency of turbidity and nematodes in direct filtration process using response surface methodology and central composite face-centered design. Based on the results, the average removal efficiency of turbidity, motile nematodes and non-motile nematodes in single-media filter were 96.14, 94.02 and 41.39%, respectively. Meanwhile, these numbers for dual-media filter were obtained as 96.61, 95.76 and 46.01%, respectively. With the increase in coagulant dosage, the removal efficiency of nematodes was improved significantly. Furthermore, the removal efficiency of non-motile nematodes was increased as the filtration rate decreased. However, an increase in the filtration rate led to an unexpected increase in the removal efficiency of motile nematodes. This distinct behavior of the nematodes led to the independence of total nematodes removal from the filtration rate. According to the results, using the direct filtration process is suggested, when the turbidity of raw water is lower than 5 NTU. However, primary disinfection must be applied to immobilize the nematodes and compensate the weakness of granular beds in the removal of motile nematodes.

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1. INTRODUCTION

Nematodes with the lengths of 100 to 1000 µm and the widths of 5 to 50 µm can be found in drinking waters that originated from surface water resources. Although nematodes themselves have not been identified as a health threat, they can ingest pathogens such as Shigella, Salmonella, Total coliforms, Cryptosporidium, Escherichia coli, and viruses [1, 2].

The presence of nematodes in finished water shows the poor performance of the treatment process. Nematodes are very resistant to UV radiation, ozone, and chemical disinfectants [3, 4]. If nematodes stay activated, they can resist against settling in the sedimentation basin and can pass through granular filters as well. Accordingly, coagulation as a pretreatment and filtration as the last solid–liquid separation step play significant roles in removing either active (motile) or inactive (non-motile) nematodes.

The treatment method in Mashhad water treatment plant No. 1 (Mashhad, Iran) is a conventional treatment. However, due to the low turbidity of raw water entering this treatment plant, direct filtration can be used instead of conventional treatment. Therefore, the present study investigated the efficiency of direct filtration to replace it with conventional treatment. In this regard, the effect of coagulant dosage, type of filter bed (single and dual-layer) and filtration rate on the removal efficiency of turbidity and nematodes were investigated. Meanwhile, the response surface methodology and the central composite face-centered design (CCFD) were used to design the experiments (DOE) and analyze the data.

2. MATERIALS AND METHODS

Ardak and Kardeh dam reservoirs (with the ratio of 3 to 1) were supplied the raw water of Mashhad No. 1 treatment plant during the experiments. The characteristics of raw water during the experiment are given in Table 1.

To simulate the direct filtration process, a pilot plant including coagulation and filtration units was constructed at Mashhad water treatment plant No. 1. As shown in Fig 1, the raw water was transferred to the filtration unit after injection of specific dosages of coagulant (ferric chloride) and rapid mixing. To evaluate the efficiency of the filtration process in removing motile and non-motile nematodes, the raw water was transferred to the pilot plant without pre-chlorination.

The filtration unit included two physically identical parallel filter columns. Filter columns were made of plexiglass

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Table 1. The characteristics of raw water

Parameter	Unit	Value
Turbidity	NTU	3.9 – 4.1
pH	-	7.6 – 7.9
Electrical conductivity (EC)	µS/cm	670 – 690
Temperature	°C	10 – 12
Motile nematodes	number/liter	18 – 23
Non-motile nematodes	number/liter	37 – 46
Total nematodes	number/liter	56 – 67

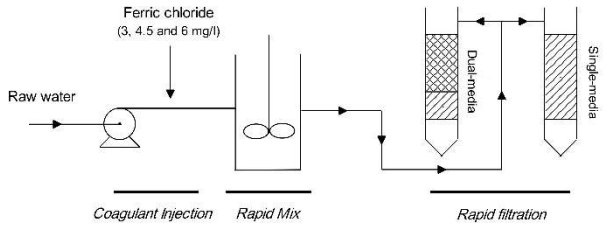

Fig 1. Schematic of direct filtration process

Table 2. Characteristics of the filters media.

Media	Density (kg/l)	Porosity	d_{10} (mm)	d_{60} (mm)	UC
Sand	2.44	0.510	0.75	1.05	1.4
Anthracite	1.45	0.560	1.15	1.96	1.7

Table 3. Level of independent variables in terms of the actual and coded units

Variables	Range and levels		
	Low (-1)	Middle (0)	High (+1)
X_1, Filtration rate (m/h)	5	7	9
X_2, $FeCl_3$ dosage (mg/l)	3	4.5	6

Table 4. Design matrix of central composite face-centered for the study of two experimental variables and obtained results

Run	Design of experiments		Response (Percent Removal %)							
			Single-media				Dual-media			
			Nematode			Turbidity	Nematode			Turbidity
	Filtration rate	$FeCl_3$ Dosage	Total	Non-motile	motile		Total	Non-motile	motile	
1	9 (+1)	3 (-1)	68.12	83.86	34.45	92.25	71.43	87.10	37.92	93.90
2	7 (0)	6 (+1)	81.92	96.93	48.27	96.60	84.04	98.45	51.73	96.78
3	5 (-1)	6 (+1)	80.80	98.54	40.00	97.08	81.82	98.54	43.35	97.25
4	7 (0)	4.5 (0)	78.73	95.16	46.88	96.95	80.85	96.78	49.98	97.08
5	7 (0)	4.5 (0)	79.58	96.67	48.50	96.88	81.71	98.33	51.50	97.00
6	7 (0)	4.5 (0)	79.56	95.31	44.80	97.08	82.81	96.88	51.73	97.20
7	7 (0)	3 (-1)	72.62	89.55	32.14	96.10	75.80	92.55	35.73	96.30
8	9 (+1)	4.5 (0)	75.83	91.53	46.88	94.25	79.11	93.21	53.12	95.30
9	7 (0)	4.5 (0)	79.77	96.50	44.44	97.38	83.32	98.24	51.83	97.60
10	9 (+1)	6 (+1)	78.40	93.10	50.00	93.75	80.69	94.83	53.35	95.17
11	5 (-1)	3 (-1)	67.78	91.67	20.00	96.75	71.10	93.33	26.65	96.88
12	7 (0)	4.5 (0)	79.77	96.44	46.44	97.22	82.14	98.21	50.03	97.50
13	5 (-1)	4.5 (0)	76.00	96.98	35.29	97.58	79.00	98.48	41.20	97.97

with a total height of 400 cm and a diameter of 20 cm. Sand depth in single-media filter was 75 cm while the depths of sand and anthracite in dual-media filter were 25 and 50 cm, respectively. Other media properties are given in Table 2.

In this study, the central composite face-centered design (CCFD) and response surface methodology (RSM) were applied to design the experiments and analysis of data. Ferric chloride dosage and filtration rate were chosen as the independent variables. The range of these variables in terms of the actual and coded units were shown in Table 3. The effect of independent variables on the dependent variables of total nematodes removal, non-motile nematodes removal, motile nematodes removal and turbidity removal in single and dual-media filters were evaluated using RSM.

3. RESULTS AND DISCUSSION

Central composite face-centered design with the results are shown in Table 4.

Quadratic regression models developed according to the CCFD where each response was evaluated as a function of filtration rate and coagulant dosage. The adequacy of the quadratic models was justified through ANOVA. Accordingly, both terms of filtration rate and ferric chloride dosage are significant variables (p-value < 0.05) in removing turbidity,

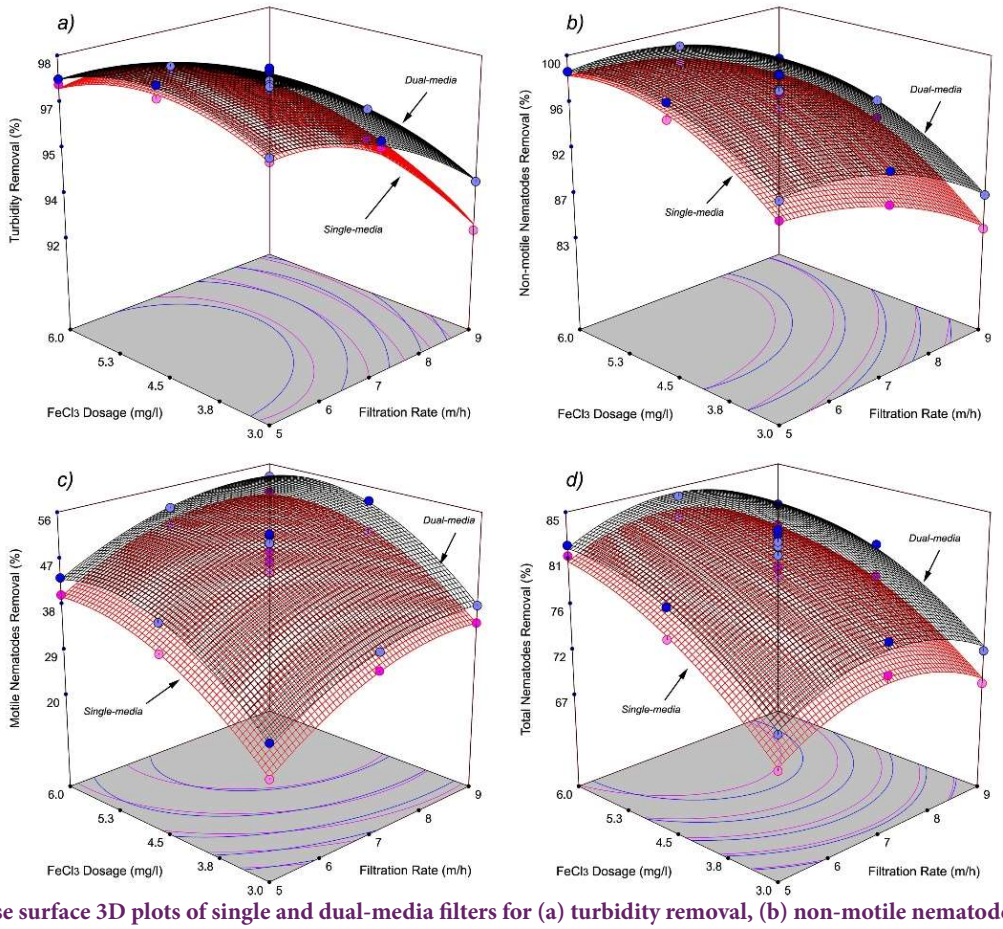

Fig. 2. Response surface 3D plots of single and dual-media filters for (a) turbidity removal, (b) non-motile nematodes removal, (c) motile nematodes removal and (a) total nematodes removal

motile nematodes and non-motile nematodes in single and dual-media filters. However, the filtration rate term for the removal of total nematodes is not significant (p-value > 0.05).

3.1. Effect of media type on filter performance

The average removal efficiency of turbidity, motile nematodes and non-motile nematodes in single-media filter were 96.14, 94.02 and 41.39%, respectively. Meanwhile, these numbers for dual-media filter were obtained as 96.61, 95.76 and 46.01%, respectively. Accordingly, the dual-media filter showed a better performance in removing turbidity and nematodes.

3.2. Effect of coagulant dosage and filtration rate on filter performance

For a better explanation of the interactive effects of coagulant dosage and filtration rate on the turbidity and nematodes removal, response surface 3D plots are represented in Fig 2. According to this Fig, regardless of filtration rate, the removal efficiency of non-motile, motile and total nematodes was increased by increasing the ferric chloride dosage. This trend was also observed for turbidity. However, as shown in Fig 2a, injecting coagulant with dosages greater than 4.5 mg/l, reduces the removal efficiency of turbidity. It can also be concluded that further increase in ferric chloride dosage above 4 mg/l does not considerably improve nematodes removal in both filters. In fact, by injecting concentrations greater than the optimal value, the excess amounts of the coagulant cause additional positive charge and particles stabilized again [5].

According to Figs. 2a and 2b, removal of turbidity and non-motile nematodes increased with the decrease in filtration rate. In fact, non-motile nematodes behaved similar to any other impurities. Fig 2c shows that the percent removal of motile nematodes increases with the increase in filtration rate in both filters. The unexpected behavior of the motile nematodes could be due to turbulence and subsequent battering at higher filtration rates which leads to the motility loss of motile nematodes. A motile nematode by losing its motility became non-motile and could be removed more easily by the filter. If the magnitude of motility loss is greater than the decrease in the removal of non-motile nematodes due to the increased filtration rate, increased removal of motile nematodes will be observed. Consequently, by increasing the filtration rate, the removal efficiency of motile and non-motile nematodes was increased and decreased, respectively. These two counteracting factors result in the percent removal of total nematodes to be independent of the filtration rate (Fig. 2d).

4. CONCLUSIONS

The most important results obtained from this research are:

- An increase in coagulant dosage (up to the optimum

dosage) improved the removal efficiency of turbidity and nematodes, significantly.

• Increasing the filtration rate had a negative effect on the effluent turbidity. Also, an increase in filtration rate decreased the removal efficiency of non-motile nematodes

• The percent removal of motile nematodes was increased with the increase in filtration rate.

• The counteracting impact of filtration rate on the removal of motile and non-motile nematodes led to the insignificant impact of filtration rate on total nematodes removal.

• Using the direct filtration instead of conventional treatment is recommended in low turbidity waters if the pre-oxidation process is initiated to immobilize the motile nematodes.

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