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Investigation of the simultaneous effects of operating condition in the anaerobic filter with five chambers for the treatment of dairy effluent

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ABSTRACT

Dairy wastewater is one of the most polluted wastewaters due to its high organic load and treating this wastewater is less costly than compensating for eco-system damage. This study aimed to investigate the simultaneous effect of operating conditions on the performance of an anaerobic filter reactor (AFR) in treating dairy wastewater of Kanyar Company (Quchan, Iran). At first, to eliminate the oily materials, the wastewater entered the American Petroleum Institute (API) grease trap pilot; then, the effects of changing parameters, such as hydraulic retention time (HRT), temperature, and pH, on reactor performance were investigated. Response surface methodology was applied to design the experiments of system operating conditions. According to the results, the concentration of oil & grease decreased in the API pretreatment. Further, results indicated that temperature, HRT, and pH were effective on the quality of the AFR performance. In addition, according to the design of experiments results, it was found that only the interaction of HRT and temperature affects the performance of the reactor and should be controlled. Also, on the reactor optimum operating condition, the rate of chemical oxygen demand (COD) removal efficiency was 82%. Finally, this research showed that about 35% COD removal was performed in the first chamber.

Keywords: Anaerobic filter reactor (AFR); Chemical oxygen demand removal; Dairy wastewater; Nitrogen removal; Phosphorus removal

1. Introduction

Dairy wastewater is among the main causes of environmental pollution due to its industrial wastewater with a high organic load. Treating this wastewater is less costly than compensating for ecosystem damage [1,2]. In this respect, biological treatment processes have received a great deal of attention in the last 20 y because of their high efficiency, being performed by both aerobic and anaerobic methods [3]. In these methods, dairy wastewater is not added to the aerobic system at first to prevent a significant decrease in unit efficiency and increase the amount of sludge produced. Therefore, the anaerobic methods are useful due to gas production by anaerobic bacteria. In recent years, using anaerobic processes, especially in treating very strong wastewater, has confirmed their superiority over those of aerobic processes [4].

The increasing use of anaerobic systems is attributed to the development of high-load reactors capable of separating hydraulic retention time (HRT) from solids retention time (SRT). This separation allows the anaerobic microorganisms to remain independent of wastewater with relatively slow growth within the system, increasing the volume loading, and providing relatively significant chemical oxygen demand (COD) removal efficiencies [5]. There are various anaerobic reactors, such as up flow anaerobic sludge blanket (UASB), anaerobic baffled reactors (ABR), septic tank, fluidized bed, and anaerobic filter reactor (AFR) [6]. AFR

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has many advantages, including low HRT, moderate area requirement (can be built underground), low operating costs, long service life, high reduction of BOD and solids, low sludge production, stabilized sludge, and no need for electrical energy and gas/and solid separator [7–9].

The AFR systems are selected since they work simply with the energy-saving process and avoid running costs for their installation [10]. Unlike the traditional aerobic treatment systems, it is challenging to make the AFR systems more efficient in treating. So far, many studies have been conducted on using upflow and single chamber anaerobic filters. In fact, in previous studies, the effect of chamber number on the percentage of COD removal and obtaining the optimal number of chamber in this reactor has not been investigated. However, the effect of more chambers on reactor performance has not been investigated [11,12]. Therefore, these results cannot be considered for anaerobic filter reactors with multiple chambers, and more studies should be done to understand the simultaneous effect of variables on the process. In addition, there have been many studies on dairy wastewater treatment by anaerobic methods, all indicating a high COD removal efficiency [13–15].

Some studies have reported the effect of operating conditions (e.g., HRT and organic loading rate) on anaerobic filter performance. However, in these papers, the simultaneous effect of three variables of temperature, HRT, and pH in the anaerobic reactors has not been investigated [16,17]. Research has also been done on the simultaneous use of anaerobic filter reactors with other methods that have increased COD removal efficiency [18].

In this paper, for the first time, AFR with 5 chambers is used to investigate the simultaneous effect of the temperature, HRT, and pH and define optimum operating conditions in the treatment of dairy wastewater of Kanyar Company in the City of Quchan.

To this end, system performance can be understood and improved using experimental design software and optimized using corresponding models. The response surface methodology (RSM) was used to investigate in parallel the effect of temperature, HRT, and pH on the performance of the anaerobic filter reactor in the treatment of dairy effluent of Kanyar Company, which has not been studied before.

2. Materials and methods

2.1. Experimental set-up

First, to eliminate the oily materials, the wastewater entered the American Petroleum Institute (API) grease trap pilot, with an effective capacity of 328 L and a dimension of 135 cm length, 27 cm width, and 90 cm height, made of iron. This pilot had an oil collection system and a bottom valve for discharging sediment materials. The temperature sensor was installed inside the pilot for detecting and controlling wastewater temperature. Then, the effluent of the grease trap pilot was directed to the anaerobic filter reactor (AFR), as shown in Fig. 1. The AFR was made of polyethylene material with 5 identical baffled chambers with an effective capacity of 1,500 L and an external dimension of 250 cm length, 60 cm width, and 100 cm height. In all chambers, valves were

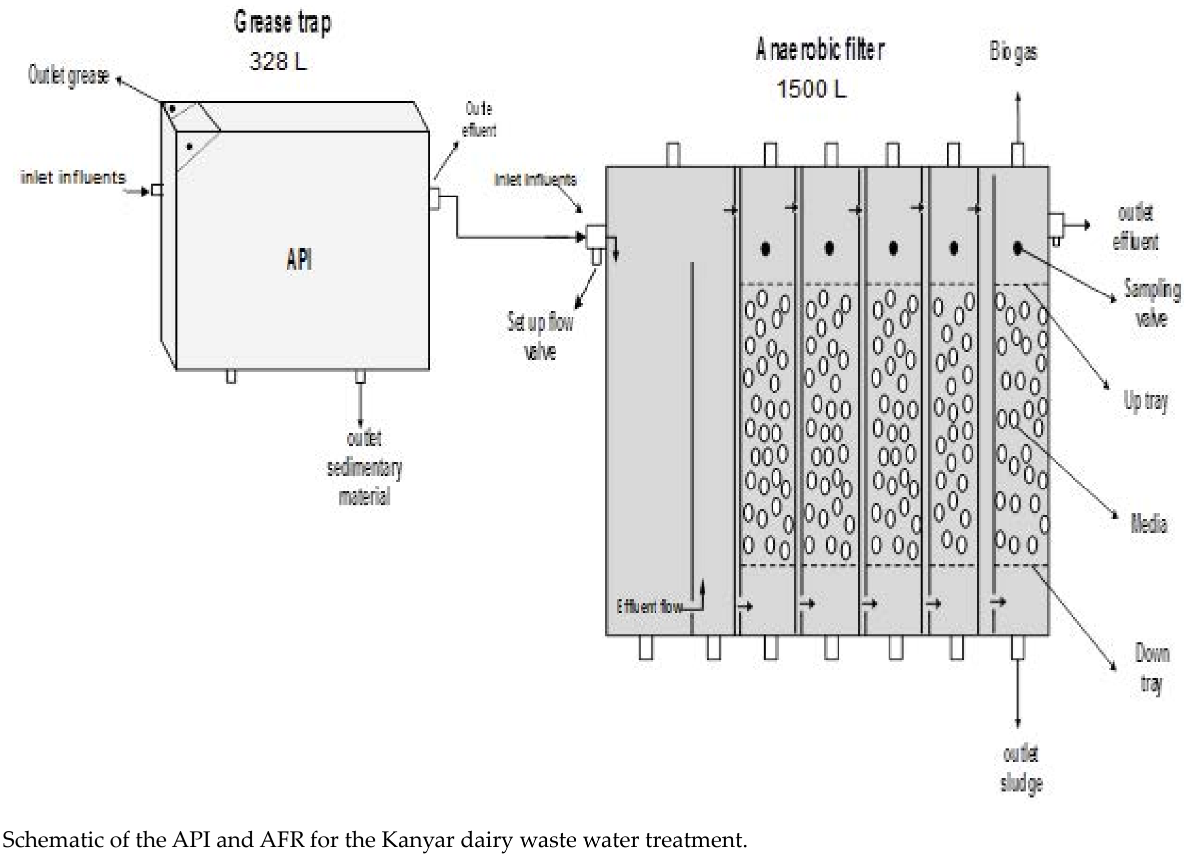


Fig. 1. Schematic of the API and AFR for the Kanyar dairy waste water treatment.

used for sampling and determining the quality of effluent. In addition, to measure the amount of produced biogas in each chamber, a valve is individually fitted on its top. The flow diagram and the view of API and AFR are shown in Figs. 1 and 2.

Each chamber of AFR was filled up to 40% of capacity with plastic flexible corrugated conduit pipe hose media with a specific surface area of 500 m^2/m^3, a height of 2.5 cm, a diameter of 1.5 cm, and a density of 0.96 g/cm^3.

2.2. Material

The materials used in this project included the following:

- Raw wastewater (the effluent from the plant's primary treatment)
- Sulfuric acid (provided by Merck, Germany) with a purity of 98%
- Alkali (NaOH-provided by Arax Shimi, Iran) with a purity of 98.5%

2.3. Wastewater properties

The raw wastewater was collected from Kanyar Dairy Company, located in Quchan, Iran. The characteristics of this wastewater are presented in Table 1. Dairy effluents contain large amounts of nutrients such as nitrate and phosphate due to their constituents.

2.4. Analytical methods

An API pilot was installed after the last grease trap lagoon available at Kanyar Dairy Company, Ghochan, Iran, to overcome the problems of operation resulted in flow variation. The wastewater was discharged into the API grease trap pilot, and after removing the sediment materials and oil, a part of the effluent was directed to an AFR.

The AFR was then seeded with waste sludge with total suspended solids (TSS) = 30,980 mg/L and volatile suspended solids (VSS) = 20,880 mg/L from an anaerobic rector placed in the wastewater treatment plant, Quchan Industrial Park. This sludge filled 50% of the reactor capacity, and the remaining section was then filled by the wastewater from the grease trap pilot. At the time of system start-up, the reactor was first operated discontinuously for two weeks for familiarity and compatibility of sludge with wastewater. Then, the system was launched with the organic loading rate (OLR) of 1.2 kg $COD/m^3\cdot d$ with HRT = 24 h for three months, continuously.

To control the ratio of COD:N:P to 350:5:1, phosphate and urea fertilizers were used as a source of phosphorus and nitrogen.

In the last two weeks of the start-up period, there were not many changes in the COD output of the reactor.

The temperature varied in the range of 40°C, 35°C, 30°C by the element embedded in the grease trap pilot equipped with a temperature control sensor. Temperature was measured every hour at the inlet and outlet of the reactor to ensure stability. pH was measured during the examination and changed by acid and alkali in a feed tank before the API grease trapping to the three range of 6, 7, and 8.

The HRT measured in the range of 12, 22, and 32 h was changed by controlling the inlet and outlet flow rate to the AFR in the three ranges of 0.5, 1.5, 2 L/min. The outlet and inlet flow rate of the reactor was measured several times every day. Once each level of independent parameters was set, and the reactor reached the steady-state after a period of operation, the wastewater properties, including COD, TSS, and turbidity content, were evaluated and compared with the initial properties of the wastewater. To determine COD, a German-made AL125 reactor was used to heat the COD vial; then, a German-made AAS240 spectrophotometer was applied to measure the COD value. The turbidity was determined by TURB355, a German-made turbidity meter. The pH was measured by the pH meter TES1381 made in Taiwan, and the TSS, total phosphorus, nitrate, and oil & grease were determined according to the standard method [19–21].

2.5. Statistical analysis of data

To optimize the operating conditions of the reactors and reduce the number of tests, first all the parameters as well as

Fig. 2. The view of the API and AFR for the Kanyar dairy waste water treatment.

Table 1
Characteristics of wastewater

Row	Parameters	Avg. result	Standard deviation
1	Temperature, °C	25	
2	pH	4.53	0.5
3	COD, mg/L	6,834	5.7
4	Total suspended solids (TSS), mg/L	910	5
5	Total phosphorus (TP), mg/L	52.8	2.5
6	Nitrate, mg/L	1,467	3.8
7	Oil & grease, mg/L	372	4.6
8	Turbidity, NTU	850	3.2

the effect of the parameters on each other were investigated using the test design. Thus, the number of required tests was significantly reduced.

Design-Expert Software (version 11 released in 2018) is used for statistical analysis. The response surface model is the Central Composite method that is Quadratic [22].

This project was performed using a central composite design with 3 independent variables, each of which changed in 3 levels, and the type of regression model was selected from the quadratic equation type, which includes 17 experimental stages for AFR reactor (Table 2). Analysis of variance was used to evaluate the importance of the parameters and their effect. In this study two-way ANOVA was used because in this study there were three independent variables, each of which had several levels.

3. Results and discussion

3.1. ANOVA analysis of the model

Since the most important response to show the performance of the AFR in treating dairy effluent is the COD removal percentage, and TSS and turbidity are its functions, the following information is provided for the COD removal rate.

The *p*-value is a function of the observed experimental results to test a statistical hypothesis [23,24].

As shown in Table 3, *A* is pH, *B* is temperature, and *C* is HRT. The *p*-value less than 0.05 indicates that the model terms are significant, and all of the three independent factors (i.e., temperature, HRT, and pH) have a significant impact on the test process; thus, they should not be ignored.

Furthermore, according to the *p*-values, HRT-temperature interaction is also important, affecting the system response. Lack of fit indicates the amount of data mismatch obtained from the focal point duplication. The lack of fit *F*-value of 2.79 is nonsignificant relative to the pure error.

The value of adjusted R^2 shows that the used model is well capable of covering the data. In this model, the predicted R^2 of 0.9339 is in reasonable agreement with the adjusted R^2 of 0.9848. The coefficient of determination (R^2) reported in quantitative studies was more than 0.8, indicating that the regression model was well consistent with the data [25,26]. The second-order polynomial models were used to express dependent variables according to independent variables.

The following equation obtained by regression analysis is used to establish a relationship between the parameters and their interaction with the response. The system response is the COD removal percentage.

$$\begin{aligned}\text{COD Removal} = {} & +80.81 + 10.00\text{pH} + 5.30\text{Temperature} + 11.10\text{HRT} - 1.13\text{pH} \times \text{Temperature} + 0.8750\text{pH} \times \text{HRT} \\ & - 2.63\text{Temperature} \times \text{HRT} - 12.54\text{pH}^2 - 20.04\text{Temperature}^2 - 8.04\text{HRT}^2\end{aligned} \quad (1)$$

After the analysis of variance (ANOVA) and removing parameters with no effect on the response, Eq. (1) and its constants are changed as Eq. (2):

$$\begin{aligned}\text{COD Removal} = {} & +80.81 + 10.00\text{pH} + 5.30\text{Temperature} + 11.10\text{HRT} - 2.63\text{Temperature} \times \text{HRT} \\ & - 12.54225\text{pH}^2 - 0.801690\text{Temperature}^2 - 0.080423\text{HRT}^2\end{aligned} \quad (2)$$

A positive sign for temperature, HRT, and pH coefficients indicates that three factors have a direct effect on the COD removal percentage. Also, a positive sign for the interaction between HRT and temperature coefficient shows that their interaction has an opposite effect on the system response. In other words, by increasing this interaction, the COD removal percentage decreases.

Fig. 3 presents the interaction of HRT and temperature parameters are displayed. As can be seen, the COD removal percentage increases at low HRT at high temperatures and it is higher at high HRT at low temperatures.

Fig. 4 shows the normal distribution of the main variables and all their interactions. The normal probability diagram is used to evaluate graphically the intrinsic deviation from the normal state. The deviation of the straight line in each parameter represents a deviation from the normal state. The model accuracy was determined using a residual normal distribution graph.

The wastewater entered the API pilot with a flow rate of 1.66 L/min. Then, after separating, the floating and settable material was discharged to AFR about 8 h later. According to Table 3, the wastewater properties at the outlet of the API pilot improved, that is, the concentration of oil and grease decreased from 372 to 220 mg/L.

3.2. Experimental results

The rest of the effluent properties were also reduced. For example, as presented in Table 4, COD decreased from 6,834 to 5,508 mg/L.

Temperature is an important environmental factor in the growth and survival of microorganisms. The minimum and maximum growth temperatures for different microorganisms are highly different, usually indicating the temperature range of the microorganism habitat. HRT is also an important factor in effluent treatment efficiency.

As presented in Fig. 5, the efficiency of treatment with AFR was measured at three temperature levels of 30°C, 35°C, and 40°C and three HRT levels of 12, 22, and 32 h. After each temperature and flow rate change, the reactor worked for about 1 week in that state, and its properties were examined in three steps until it reached the steady state in new conditions; then, the wastewater properties were measured. The optimum temperature in these conditions was 35°C.

According to Fig. 5, in the temperature of 35°C and HRT of 22 h, the COD removal efficiency was 82%, and TSS and turbidity rates were 165 mg/L and 274 NTU, respectively.

When the temperature increased, the COD removal efficiency improved to the optimum temperature, varying based on the microorganism type present in each sludge. Thus, as illustrated in Fig. 5, the rates of COD, TSS, and turbidity removal at a temperature of 30 were 54%, 529 mg/L, and 491 NTU, respectively. Afterward, the COD removal efficiency gradually decreased with increasing temperature until the treatment stopped. The rates of COD, TSS, and turbidity removal at a temperature of 40°C were 66%, 344 mg/L, and 389 NTU, respectively. When sludge is inactivated for long periods under inappropriate temperature conditions, it cannot be activated even after being brought to the appropriate temperature. Also, lowering the temperature reduces the traditional growth rate and biological reaction speed, consequently decreasing the efficiency. A similar result can be observed in a study conducted by Bouted and Ratanatamskul on AFR [7].

The COD removal rate was increased by increasing HRT. At the temperature of 35°C and HRT of 12 h, the COD removal efficiency was 56%, and also TSS and turbidity rates were 408 mg/L and 448 NTU, respectively. The AFR performance improvement in COD, TSS, and turbidity removal was up to 22 h, with a COD removal efficiency of 82%, and TSS and turbidity rates of 185 mg/L and 271 NTU, respectively. Further, the COD removal efficiency, TSS, and turbidity at a temperature of 35°C and HRT 32 hr were 85%, 171 mg/L, and 227 NTU, after which COD removal was slowed down at an HRT of 32 h. Therefore, it is not economically feasible to increase HRT further. This result is consistent with those of some other studies [7,11]. The high percentage of COD removal in this reactor compared to similar studies is due to using 5 chambers instead of one chamber [24–26]. As can be observed, the removal efficiency increases with increasing HRT. Nevertheless, it does not exceed a certain limit since, in the case of strong wastewater with a high organic load, large amounts of CO_2 and long-chain volatile fatty acids are produced during hydrolysis and acidification, inhibiting methane growth in the reactor. This result is in line with those of Vashi et al. [27]. As can be seen in Fig. 6, increasing the OLR reduces the COD removal percentage. In fact, due to the constant value of COD inlet and the volume of the reactor, the amount of OLR is inversely related to the HRT.

As illustrated in Fig. 7, pH = 7 is selected as the optimum pH value, maintained constant in subsequent experiments.

Table 2
Arrangement of experiments designed by RSM method and response obtained in AFR

		Factor 1	Factor 2	Factor 3	Response 1
Std.	Run	*A*: pH	*B*: Temperature	*C*: HRT	COD removal
			°C	h	%
1	10	6	30	12	10
2	5	8	30	12	34
3	13	6	40	12	30
4	12	8	40	12	45
5	2	6	30	32	37
6	15	8	30	32	60
7	11	6	40	32	42
8	14	8	40	32	65
9	3	6	35	22	60
10	7	8	35	22	75
11	8	7	30	22	54
12	17	7	40	22	66
13	16	7	35	12	59
14	6	7	35	32	85
15	4	7	35	22	82
16	1	7	35	22	83.5
17	9	7	35	22	80

Table 3
ANOVA analysis

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	
Model	7,326.98	9	814.11	115.97	<0.0001	
A-pH	1,000.00	1	1,000.00	142.45	<0.0001	
B-Temperature	280.90	1	280.90	40.01	0.0004	
C-HRT	1,232.10	1	1,232.10	175.52	<0.0001	
AB	10.13	1	10.13	1.44	0.2688	significant
AC	6.13	1	6.13	0.8725	0.3814	
BC	55.13	1	55.13	7.85	0.0264	
A^2	421.47	1	421.47	60.04	0.0001	
B^2	1,076.23	1	1,076.23	153.31	<0.0001	
C^2	173.29	1	173.29	24.69	0.0016	
Residual	49.14	7	7.02			
Lack of fit	42.97	5	8.59	2.79	0.2848	not significant
Pure error	6.17	2	3.08			
Cor. total	7,376.12	16				

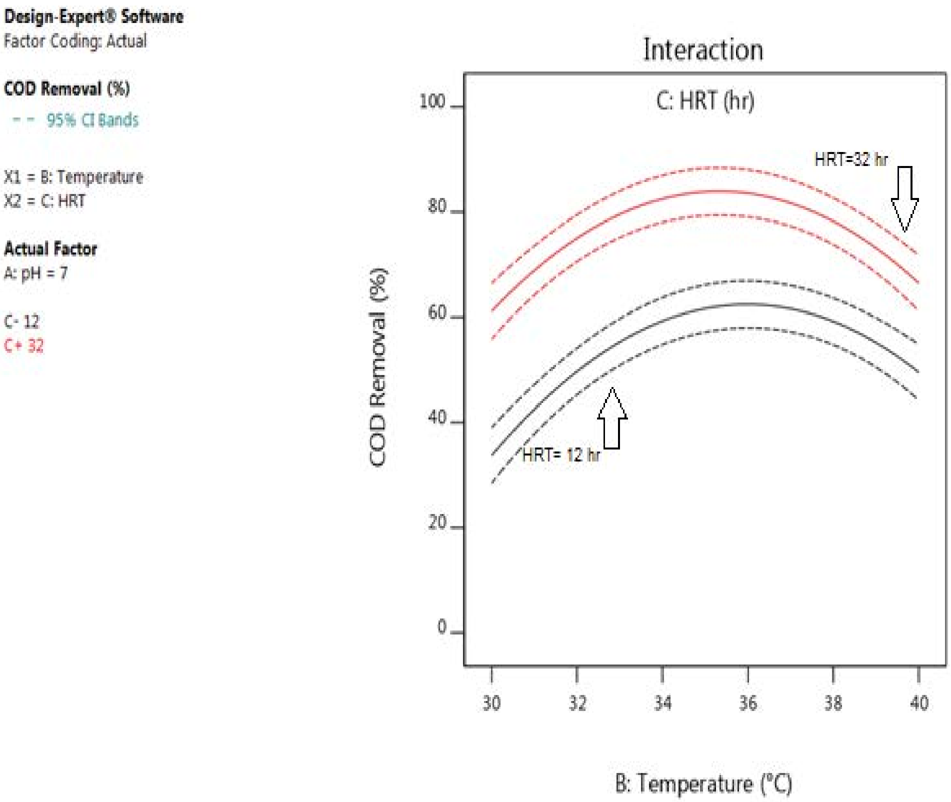


Fig. 3. Effect of HRT and temperature interaction on COD removal at pH of 7.

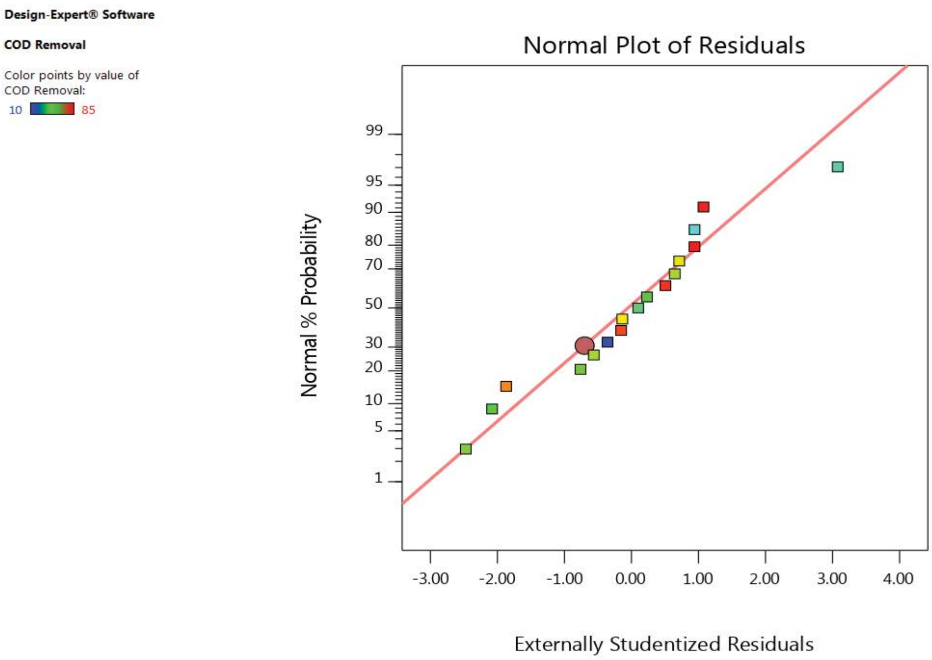


Fig. 4. Normal scatter chart.

The pH changes during the wastewater treatment process; thus, its value must be controlled. Studies have shown that in all cases, the performance of AFR increases by increasing pH. At the temperature of 35°C, HRT of 22 h, and pH = 6, the COD removal efficiency is 60%, and also TSS and turbidity rates are 399 mg/L and 440 NTU L/d, respectively; these properties at pH = 7 are 82%, 185 mg/L, and 271 NTU, respectively.

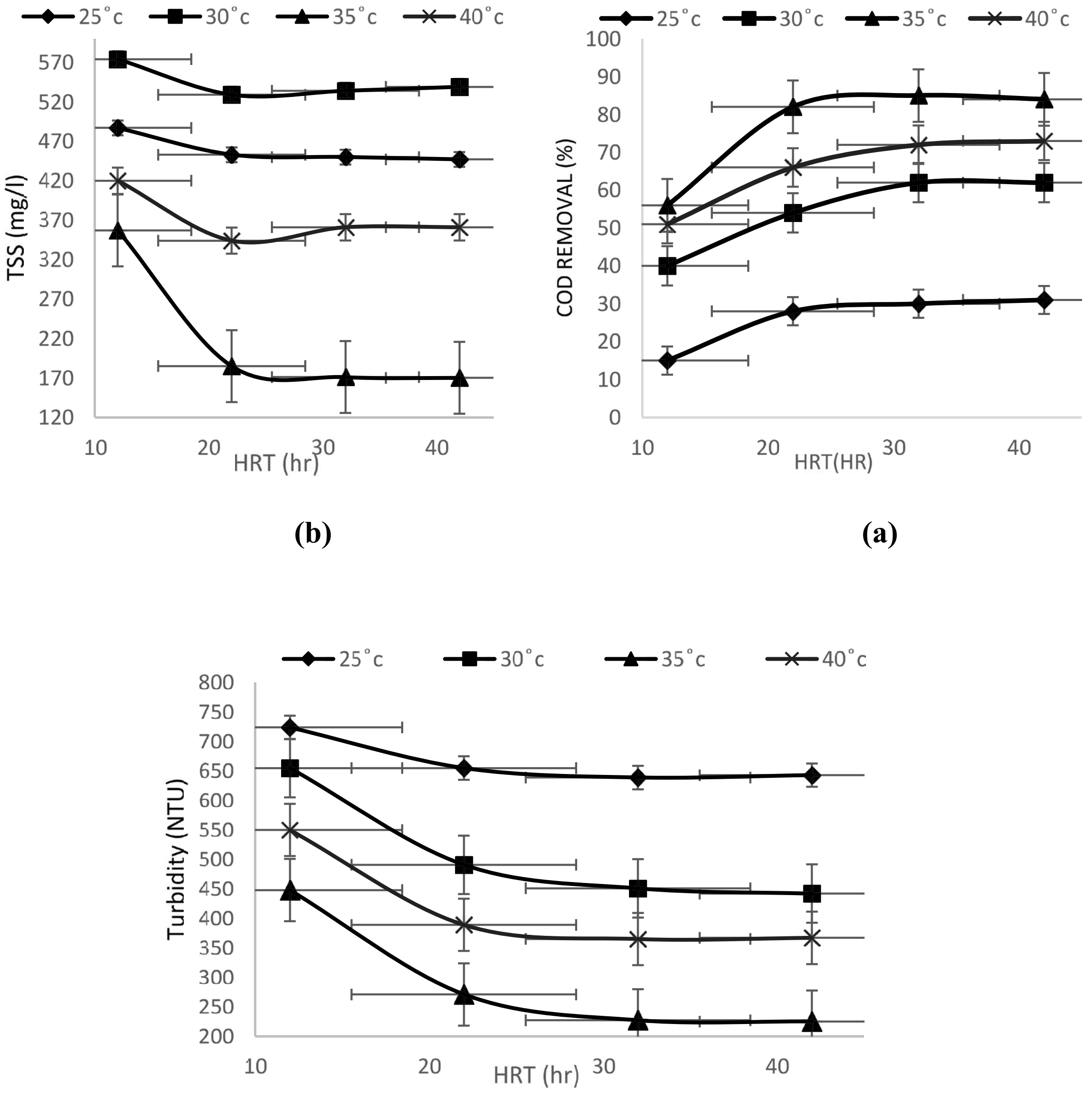
Table 4
Properties of inlet and outlet effluents of API pilot

Properties	Before API	After API
Temperature, °C		25
pH	4.53	4.55
COD, mg/L	6,834	5,508
TSS, mg/L	910	740
TP, mg/L	52.8	40.88
Nitrate, mg/L	1,467	1,395
Oil & grease, mg/L	372	220
Turbidity, NTU	850	774

After the optimum point, pH = 7 again causes the COD reduction to decrease gradually until the purification process is deactivated. As shown in Fig. 5, in pH = 8, the COD removal efficiency is 75%, and TSS and turbidity rates are 262 and 312 mg/L, respectively. Appropriate pH has also been obtained in most previous studies for microorganisms in the same range [27,28].

It is of note that by increasing the pH above 6, the treated effluent starts producing sludge. However, once pH exceeds 7, the sludge becomes highly productive so that the effluent goes out of its normal state and becomes toxic.

This study tried to determine the role of each AFR chamber in the overall reactor performance and the status and location of the most active bacteria in the reactor. To this end, the COD removal percentage from each chamber was



(c)

Fig. 5. Effect of HRT and temperature at pH = 7 on COD removal efficiency, TSS, and turbidity removal. (a) HRT via COD, (b) HRT via TSS and (c) HRT via turbidity.

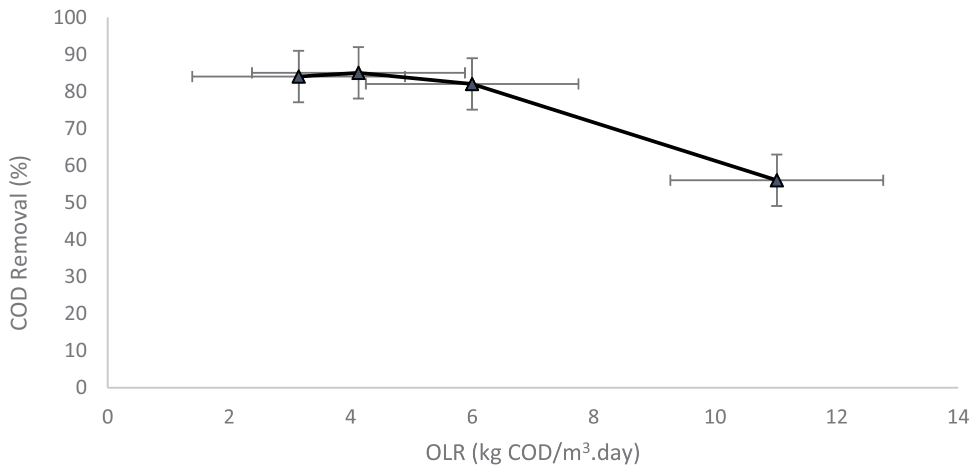


Fig. 6. Effect of OLR at pH = 7 and temperature = 35°C on COD removal efficiency.

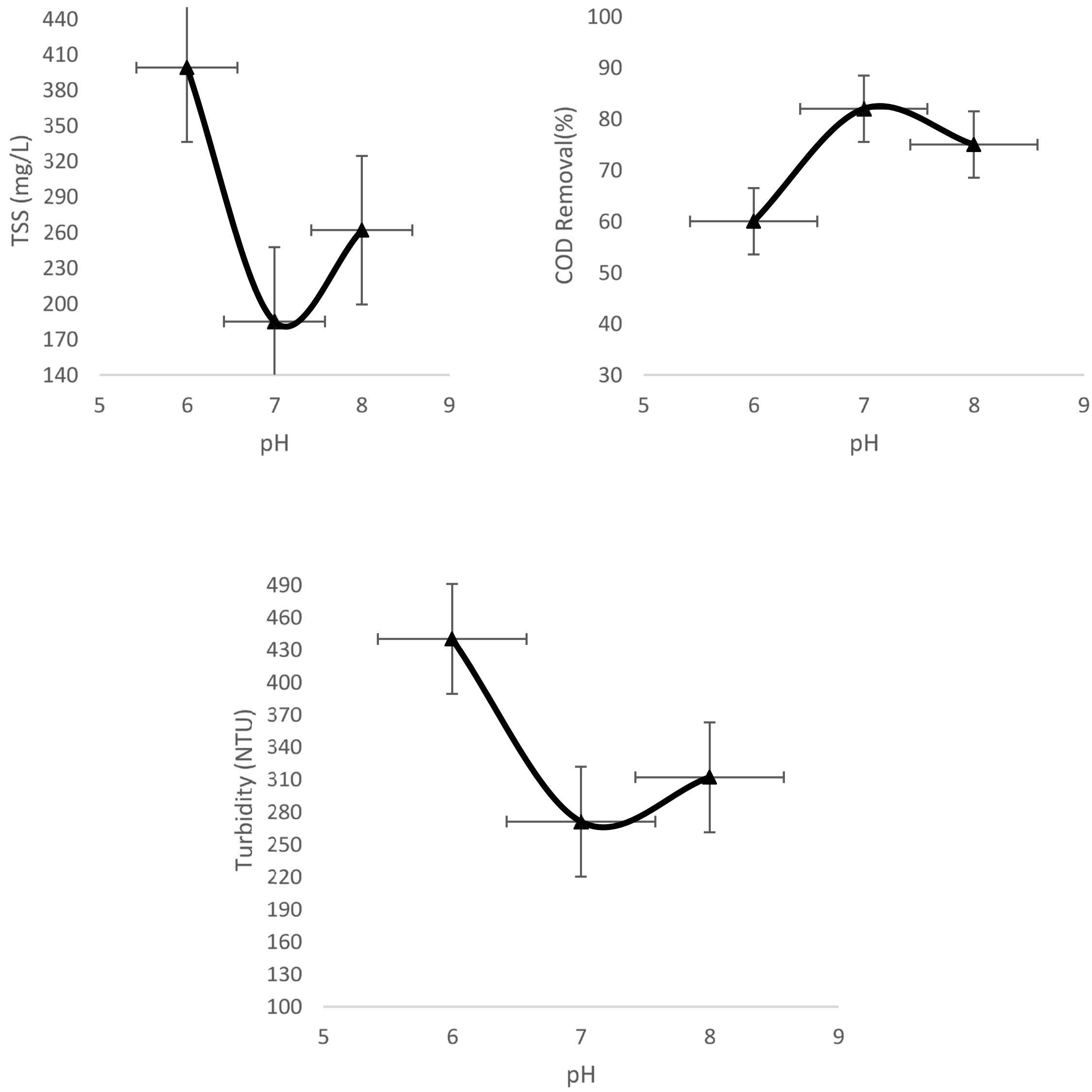


Fig. 7. Effect of pH 7 on COD removal efficiency, TSS, and turbidity removal at temperature of 35°C and HRT of 22 h.

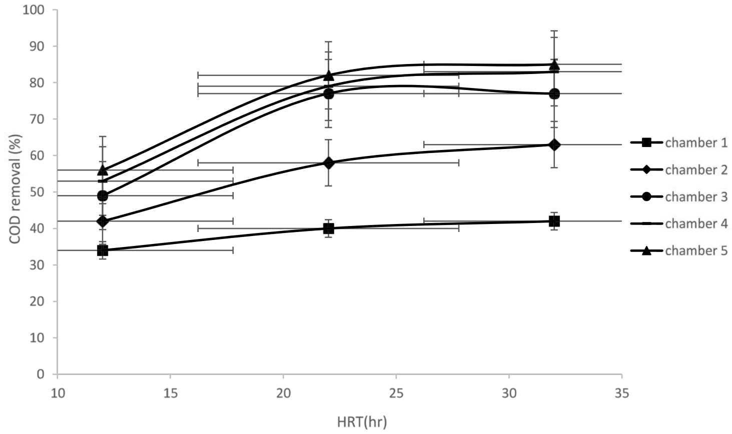


Fig. 8. COD removal rate per chamber of the reactor for different HRT at pH = 7 and 35°C.

evaluated at the end of each period of HRT changes and for 3 consecutive days (Fig. 8). For this purpose, at 35°C and pH = 7, sampling was performed from each chamber at different HRT. As shown in Fig. 8, the COD removal activity in the first three chambers of the reactor is much higher than in the two end chambers. The results show that more than 80% of the activity occurs in the first three chambers of the reactor since the intermediate products (e.g., acetate) are formed in the reactor's starting chambers.

As can be observed, about 35% of COD removal occurs in the first chamber. Similar studies in environments with high acetate concentration show the increase in the growth of bacteria such as Methanosarcina [18].

4. Conclusion

This study demonstrated the feasibility of the AFR process for the treatment of dairy industry wastewater after removing oily and sediment materials by simple gravity settling in an API grease trap pilot.

Based on the obtained results, in the API pilot, the oil and grease were reduced by about 60%, and effluent COD decreased by about 21%.

The effluent of the API pilot entered the AFR setup for approximately 3 months and seeded with sewage sludge from an anaerobic reactor in the wastewater treatment plant of Quchan Industrial Park.

According to the results, the COD removal percentage increased by increasing HRT but did not exceed a certain limit. As the temperature increases, the COD removal percentage increases until reaching the desired temperature. Also, lowering the temperature reduces the growth synthesis and speed of biological reactions and thus reduces the removal efficiency. The highest COD removal efficiency in AFR was obtained at pH = 7, 35°C, and an HRT of 22 h, with 82% removal. Experiments showed that in all cases, the COD removal percentage increased with increasing pH, and after the optimum pH = 7, the COD removal rate decreased again until the deactivation of the purification process. According to the statistical analysis of the results, interactions between variables were not affected by the process response. Therefore, they were negligible, except for temperature and HRT. Moreover, the three independent variables of the experiment, including temperature, HRT, and pH, affected AFR performance.

Examining each chamber revealed that the COD removal activity in the first three chambers of AFR was much higher than in the two end chambers. The results showed that 35% of the COD removal was in the first reactor chamber. Considering that about 77% of the COD is removed in the first three chambers, increasing more than three chambers in this reactor will not be very efficient. In brief, the AFR reactor exhibited a good performance because of its high COD removal efficiency, good stability, low pH changes, and operating in a short start-up time since it does not need to form any granules and biofilms.

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