Biofiltration performance and kinetic study of hydrogen sulfide removal from a real source

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Abstract

Purpose Biofiltration is one of the most accepted technologies in odor control in wastewater facilities. A biofilter system consists of a bed of organic material providing both as the carrier for the active microorganisms and as nutrient supply. This study was aimed to evaluate and model a biofilter performance operated under real conditions of odor emission from a wastewater pump station located in Khorramabad, Iran.

Methods The media was a mixture of compost and wood chips with a weight ratio of 5:1. The treatment performance of the biofilter was assessed during a 90-day operation period and the gathered data were utilized to develop and determine the best fit kinetic model based on Michaelis-Menten and Ottengraf models. The best fit model was used in the analysis of scenarios defined based on inlet H₂S loading fluctuations. Also, the effectiveness of the main parameters in biofilter performance was evaluated using a dimensionless sensitivity coefficient.

Results The best fit model was found the Ottengraf zero-order type limited by diffusion based on the values of R-square (0.98) and mean square error (MSE) (0.002). The results demonstrated a high H₂S removal efficiency of about 98% in an EBRT (empty bed residence time) of 60 s. despite high fluctuations of inlet concentration under real conditions. The system was able to meet the effluent standard limit of 10 ppm even if the inlet H₂S loading increases up to two times the base level. According to the results of the defined sensitivity coefficient, the system performance was more sensitive to the inlet concentration than EBRT with a ratio of 1.4.

Conclusions In addition to the acceptable efficiencies of biofilter in odor removal, the results proved the worth of using a kinetic model in forecasting the system performance which is a useful tool in the design and operation of such systems.

Keywords Biofilter · Hydrogen sulfide · Kinetic model · Michaelis-Menten model · Ottengraf model

Introduction

One of the main problems in municipal wastewater facilities (MWFs) is the emission of offensive odorous gases such as hydrogen sulfide which is both a malodorant with a distinctive rotten egg smell and an environmental pollutant [1]. Wastewater treatment workers and habitats located near wastewater pump stations are two common groups which usually exposed to H₂S emission from MWFs. The production mechanism of this gas is driven by sulfur-reducing-bacteria which utilizes sulfate (SO₄⁻²) as the electron acceptor in anaerobic respiration, reducing it to hydrogen sulfide [2]. Factors affecting the production mechanism consist of concentration of organic matter and nutrients, level of dissolved oxygen (DO), pH, temperature, flow rate, surface area, and

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hydraulic retention time [3]. H_2S concentration up to 100 ppm has been reported in the literature for air emissions from MWFs [4]. The clinical effects of H_2S depend on the exposure duration and its concentration. Exposure to low H_2S concentration (2 ppm) can cause bronchial constrictions in asthmatic people [5] whereas higher concentrations (10–500 ppm) lead to various respiratory symptoms that range from rhinitis to acute respiratory failure [6]. According to Occupational Safety and Health Administration (OSHA), 10 ppm is the permissible exposure limit (PEL) for 8 h time-weighted average and 50 ppm is the acceptable maximum peak above the ceiling concentration for an 8-h shift, with a maximum duration of 10 min [7].

Negative effects on ecological systems and human health by H_2S emission has driven development of various physical and chemical technologies for treatment at its source. These are including hybrid solvents (ionic liquids) for selective sorptive separation of H_2S from a gas stream [8, 9], scrubbing [10], adsorption [11, 12], thermocatalytic processes [13], and electrochemical technologies [14]. High operating and process costs, generation of hazardous byproducts, and high pressure/temperature requirements are the main bottlenecks for developing these technologies [15]. Hence, recent research in this field has focused on simple, efficient, and environmentally benign treatment methods. In this respect, biofiltration has been proposed as a cost-effective and easy-maintenance method for removal of odors [16–19].

Many factors affect the performance of a biofilter such as packing media and the environmental conditions for bacterial growth like residence time, humidity, and biomass. This system often needs an approximately constant inlet H_2S loading to keep microbial activities in a sufficient level [20]. Hence, this factor can cause a limitation in biofilter implementation at some specific emission sources, such as wastewater pump stations (WPSs). WPSs are an integral component of sewage systems. As wastewater flows into a pump station before a pumping cycle begins, the water level rises and physically displaces air. The displaced air carries its odorous compounds such as H_2S .

Various studies have evaluated the emission pattern of H_2S from WPSs [3, 21]. The main common point in these studies is high fluctuation in emitted H_2S concentration during a day, usually between 0 and 30 ppm. This is due to the variation of inflow rate per hour within a day. Despite relatively strong literature regarding the implementation of biofilters in H_2S treatment from MWFs, however, they mostly investigate the biofilters under laboratory conditions or a relatively constant H_2S loading [1, 22, 23]. There is a scientific gap in the literature about this question: to what extent biofiltration can be effective for implementing in WPSs with a high fluctuation in

H_2S emission concentration? How will removal performance and kinetic parameters be affected?

To address these questions a pilot-scale biofilter was installed in a WPS and the polluted air containing H_2S was pumped from the wastewater well. For selecting a proper biofilm medium which is an important step toward a successful biofilm, several factors were considered including (i) suitable environment for microorganisms to thrive, (ii) high moisture-holding capacity, (iii) large surface area, and (iv) stable compaction properties. The mixture of compost and wood chips has been implemented as a proper medium in the literature for H_2S containing gas flow [24–26]. It is due to providing a variety of microbial community and available sources of nutrients by compost, as well as increasing medium porosity and moisture-holding capacity by wood chips.

Alongside the H_2S removal performance, kinetic parameters of the biofilter have been studied in this research to quantify the microbial activity in the biofilter during removal of the target pollutant under real emission conditions. Also, using experimental data to develop a kinetic model is useful in the prediction of the biofilter efficiency and optimization of the design parameters and operating factors. To achieve these purposes two kinetic models were used including (i) Michaelis-Menten model which involves first-order and zero-order reactions, and (ii) Ottengraf's model which has been presented in three forms of zero-order reaction-limited and diffusion-limited and first-order reaction. Eventually, the advantages of the best fit model were demonstrated by scenario analysis and the effectiveness of different parameters on biofilter performance was studied.

Material and methods

Experiment setup and operation

A pilot-scale biofilter unit was constructed at a wastewater pump station in the city of Khoramabad, Iran. To set up the pilot, a column made of galvanized steel was used with 160 cm in height and 26 cm as internal diameter. Figure 1 illustrates the photo and a schematic of the constructed pilot. The height of media in the column was 70 cm and the internal surface of the column was covered by a foam layer as a barrier against heat and humidity. A metal grating of two mm thickness was used for the maintenance of the media bed and the uniform distribution of inlet airflow through the media.

As shown in Fig. 1, five sampling valves were installed at the top of the biofilter column with equal distances of 17.5 cm. These valves were used to sample the effluent H_2S

Fig. 1 An image and schematic of the biofilter pilot

representing five different EBRTs (empty bed residence time) based on Eq. (3).

According to the measurements, the incoming air from the wet well of wastewater pump station had a relative humidity of 70–80%. However, for reliable operation, a sprinkler at the top of the column regulated the humidity and nutrient concentration in the reactor media. The sprinkler injected settled wastewater with a flowrate of 30 mL/min and an average concentration of BOD₅ = 135 mg/L, TKN = 26 mg/L, and TP = 3.5 mg/L.

A vacuum pump was used to pull out the airflow from the top of the media. The inlet airflow was controlled by a manual valve and determined by measuring the flow velocity.

The media was a mixture of municipal waste compost and wood chips with a weight ratio of 5:1. The compost was obtained from Kermanshah composting facility and wood chips from a carpentry workshop. The compost had a size range of 2–10 mm with a C:N:P ratio of 100: 9.8: 2.1, 39% organic matter and a pH value of 7.5 [27]. One advantage of compost as a biofilter media is no necessity of microbial inoculation because it contains a variety of microorganism communities which can be adapted to the removal of a specific pollutant such as H₂S.

Wood chips with a size of 50–100 mm were used to improve the media porosity and decrease the head loss and prevention of media canalization. Overall density and porosity of the mixed media was 590 kg/m³ and 77% respectively.

Measurement of H₂S gas concentration was done by a portable device (BW Technologies Co. Gas Alert Micro 5) based

on the method EPA7783-06-4 CAS [12]. The total period of sampling was 90 days and 450 samples were analyzed.

Biofilter kinetic models

In a biofilter system, biofilm layer is the main place that all biological processes occur in. Therefore, in the assessment of the process kinetics, the main focus is on the physical and biological processes that happen in this layer. A biofilm is characterized by its ability to adhere to the medium through the fixed film of polymers that protects the bacteria against sloughing off.

Figure 5 in Appendix presents a schematic of the components of a biofilm system. As shown in the figure, biofilm consists of two layers of base film and surface film with an irregular surface enclosed by a uniform layer of liquid. In most of biofilm models, the surface film is ignored and only the base film is considered responsible for performing all the treatment processes [28, 29].

Pollutant removal in a biofilter takes place in two steps. First, diffusion conveys the pollutant to the biofilm, and then biodegradation reaction occurs in the biofilm. For a zero-order model, one of these steps confines the total removal. The removal process is called diffusion-limited if the rate of diffusion is less than the rate of reaction. Additionally, the process is reaction-limited if the rate of reaction is less than the rate of diffusion. In the first order kinetics, diffusion or reaction is not an important factor in the model equations. These three kinds of biofilter models are known as Ottengraf models, which will be discussed further.

Ottengraf's model

Ottengraf's model [17, 18] is one of the most accepted kinetic models for gas removal in a biofilter. The basic assumptions used in this model are as follows [30]:

- 1) Biodegradation occurs in the liquid phase-biofilm, 2) Biofilm thickness is small compared to packing material diameter, 3) Biomass concentration is homogeneous in the reactor volume, 4) Gas flow pattern is plug flow, 5) There are no reactions between the chemical species, 6) Mass transfer resistance in the gas phase is negligible, 7) Regime is steady-state. Based on the above assumptions, Ottengraf (1977) presented his model in three forms of zero-order reaction-limited and zero-order diffusion-limited and first-order reaction. The related equations are presented as follows [16]:

- Zero-order reaction-limited

$$C_{out} = C_{in} - K_0 \times EBRT \quad (1)$$

where, C_{in} and C_{out} are inlet and outlet gas concentration in kg/m^3 respectively, and K_0 is the zero-order reaction rate constant ($\text{kg} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$), which is defined in (Eq. 2):

$$K_0 = \mu^* X_v A_s \delta / Y \quad (2)$$

where μ^* = specific growth rate (s^{-1}), X_v = biofilm density ($\text{kg} \cdot \text{m}^{-3}$), A_s = biofilm surface area or unit volume of biofilter (m^{-1}), δ = biofilm depth (m) and Y = yield coefficient equal to the ratio of biomass produced to the substrate consumed.

EBRT is calculated based on (Eq. 3):

$$EBRT = H / U_g \quad (3)$$

where H is the height of biofilter column (m) and U_g is the velocity of air (m/s) through the column.

- Zero-order- diffusion-limited

$$C_{out} = C_{in} \left(1 - \beta_1 \frac{EBRT}{\sqrt{C_{in}}} \right)^2 \quad (4)$$

where β_1 is a constant defined as in (Eq. 5):

$$\beta_1 = A_s \sqrt{\frac{K_0 f(X_v) \cdot D_{H_2S.w}}{2m}} \quad (5)$$

where $f(X_v)$ is the ratio of diffusivity of the pollutant in the biofilm to that in water, $D_{H_2S.w}$ is diffusivity of H_2S in water ($\text{m}^2 \cdot \text{s}^{-1}$), and m is dimensionless Henry's constant of the pollutant.

- First-order reaction

$$C_{out} = C_{in} \exp(-K_1 EBRT) \quad (6)$$

where K_1 is the reaction rate constant (s^{-1}) given as (Eq. 7):

$$K_1 = \frac{A_s}{m} \sqrt{\frac{X_v \cdot \mu^* f(X_v) \cdot D_{H_2S.w}}{KY}} \tanh(\beta_2) \quad (7)$$

β_2 , is defined as Eq. (8):

$$\beta_2 = \delta \sqrt{\frac{X_v \mu^*}{KY f(X_v) \cdot D_{H_2S.w}}} \quad (8)$$

where K is the Monod kinetic constant ($\text{kg} \cdot \text{m}^{-3}$) [19].

Michaelis-Menten model

The kinetics of H_2S removal by a biofilter system given by Michaelis-Menten is as follows [20, 21]:

$$-\frac{dc}{dt} = \frac{V_m \times C \times B}{K_m + C} \quad (9)$$

where C is the substrate concentration (g/m^3), B is the microbial population density, V_m is theoretical maximum specific reaction rate ($\text{g} / \text{m}^3 \text{ h}$), K_m is the half-saturation constant (ppm) and t is the reaction time (h). The main kinetic parameters in this model are V_m and K_m which can be obtained from a modified Michaelis–Menten equation [29]:

$$\frac{1}{R} = \frac{K_m}{V_m} \cdot \frac{1}{C_{Ln}} + \frac{1}{V_m} \quad (10)$$

where R is removal rate which is equal to $R = \frac{SV(C_{in} - C_{out})}{\alpha}$ ($\text{g} / \text{m}^3 \text{ h}$) and SV is space velocity equal to $\frac{Q_{in}}{V_{biofilter}} \text{h}^{-1}$, C_{in} and C_{out} are inlet and outlet gas concentrations and Q_{in} is the air flow rate, (m^3 / h).

α = conversion coefficient

$$= \left[\frac{22.4 \times (273 + T)}{273} \times \frac{10^6}{\text{mole} \times 10^2} \right] \times \frac{V_{media}}{V_{biofilter}}$$

C_{Ln} is logarithmic mean concentration (ppm) calculated as:

Coefficients V_m and K_m are obtained by a linear regression plot of $1/R$ versus $1/C_{Ln}$. In the steady state, the three following conditions are possible:

- a) Substrate concentration is highly greater than half-saturation constant ($C \gg K_m$), in this case (Eq. 9), simplifies to (Eq. 11) and (Eq. 12) and the kinetics becomes a zero-order type.

Fig. 2 Daily inlet, outlet H_2S concentrations, and efficiency removal with real data and seven moving average

$$-\frac{dc}{dt} = V_{\max} \times B = K_0 \quad (11)$$

$$C = C_0 - K_0 t \quad (12)$$

where K_0 is the zero-order coefficient and C , C_0 are outlet and inlet concentrations respectively.

- Substrate concentration is much less than K_m ($C \ll K_m$), in this case, (Eq. 9) simplifies to a first-order kinetic similar to (Eq. 6):
- Substrate concentration C and K_m have little difference. In this case, the reaction follows fractional-order kinetics. Therefore, complex equations must be derived from Eq. 9. Since this case did not occur in the present study, more discussion is not provided.

Model calibration and validation

The aim of this study is to determine the best fit model, apply it in the prediction of biofilter performance, and analyze the effectiveness of important factors. Therefore, a calibration validation process is used to evaluate the robustness of each model according to the data set. In this regard, the data set is divided into two parts: the first part is used to calibrate the model and determine the coefficients of the model equation. The second part is used for validation of the obtained equations' fitness.

Two criteria are used to show the degree of adjustment of model predictions to the observed data. R-squared (R^2) (the coefficient of determination) and MSE (mean square error) are calculated based on Eq. (13) and (14).

$$R^2 = 1 - \frac{\sum (y_i - y_m)^2}{\sum (y_i - \bar{y})^2} \quad (13)$$

$$MSE = \frac{\sum (y_i - y_m)^2}{n} \quad (14)$$

where $\bar{y}$ is the average of observed data, y_i , observed data, y_m , simulated by model and m , the total number of data.

Scenario analysis

One of the most useful applications of the simulation models is the prediction of the system response under different loading situations that occurs in a real operation. Therefore, in this study, after the determination of the best fit model, scenario analysis is done to evaluate the behavior of the system under input loading variations. The ratio of input concentration in scenario (i) ($C_{in}(i)$) to the reference input concentration ($C_{in(ref)}$) is defined as the loading factor (α) that specifies each scenario according to the Eq. (15).

$$\alpha = \frac{C_{in}(i)}{C_{in(ref)}} \quad (15)$$

The response of the system to each loading scenario can be assessed by a parameter namely “response factor” (R_f) which is defined as the ratio of outflow H_2S concentration of the scenario with (α) loading factor ($C_{out}(\alpha)$) to the outflow concentration at base scenario ($C_{out(base)}$) as shown in Eq. (16).

$$R_f = \frac{C_{out}(\alpha)}{C_{out(base)}} \quad (16)$$

Dimensionless sensitivity coefficient

To determine the sensitivity and effectiveness of parameters such as EBRT and influent concentration on the output predicted by the model, a dimensionless sensitivity coefficient (F_{sa}) is defined according to Eq. (17) [31]:

Table 1 Average inlet/outlet concentration at different EBRTs

EBRT (s)	C_{in} (ppm)	C_{out} (ppm)
15	18.84	10.76
30	18.84	5.01
45	18.84	2.71
60	18.84	1.63

Table 2 Values of R^2 and MSE in the calibration/validation stage and the Model equations

No.	Model	Calibration		Validation		Equation
		R^2	MSE	R^2	MSE	
1	Zero-order- reaction-limited	0.888	0.011	0.865	0.019	$\frac{C_{out}}{C_{in}} = -0.2167 \frac{EBRT}{C_{in}} + 0.8679$
2	Zero-order- diffusion-limited	0.980	0.002	0.927	0.009	$\left(\frac{C_{out}}{C_{in}}\right)^{0.5} = -0.0525 \frac{EBRT}{C_{in}^{0.5}} + 0.9553$
3	First-order reaction	0.932	1.972	0.701	1.620	$-\ln\left(\frac{C_{out}}{C_{in}}\right) = 0.0843 * EBRT - 0.4711$
4	Michaelis-Menten Model	0.818	8.483	—	—	the same as first model (Zero-order- reaction-limited)

$$F_{sa} = \frac{\partial O}{\partial P} \cdot \frac{P}{O} \quad (17)$$

where O is the model output and P is the input parameter, ∂O and ∂P are the variation of output/input parameters with respect to the base values. Since F_{sa} is dimensionless, it is comparable with various parameters of different units.

Result and discussion

The inlet, outlet concentrations with the system removal efficiency at EBRT = 60s are shown in Fig. 2. The points in the graph present the real data while the curves show the seven-day moving average due to high fluctuations of field data. As shown in the figure, it takes about 15 days for the system to proceed with the adaptation period. Then, a significant increase in removal efficiency may represent the logarithmic phase of bacterial growth. Finally, after the day 20th, the system was reached to a steady state with a removal efficiency of nearly 98%.

To determine the model of best fit for H_2S removal and average H_2S concentrations at each EBRT were used [28]. Table 1 shows the average inlet and outlet concentration (C_{in} , C_{out}) at four EBRT.

Best fit model

To determine the best fit model, a calibration/ validation process is needed for each model and then R^2 and MSE values are compared. In this regard, among 450 data sets, 300 data were used for calibration and 150 for validation. Figures 6, 7 and 8 (Appendix) show the results of the calibration and validation of the Ottengraf models for zero and first-order kinetics. Five data points represent the average values of each data set for the five EBRTs. As shown in the figures the model equation is obtained in the calibration phase and then the model validation is assessed based on the difference between the observed and simulated data.

As mentioned before, in the Michaelis-Menten model the kinetic parameters are not directly used in the simulation but used to determine the kinetic order. Therefore, all data set are used in calibration to obtain half-saturation constant, which should be compared with the inlet substrate concentration. Figure 9 (Appendix) shows the best fit line through the data points. The kinetic parameters are obtained as follows:

$$\frac{1}{v_m} = 36.359 \rightarrow v_m = 0.0275 \quad \& \frac{k_m}{v_m} = 59.038 \rightarrow k_m = 1.623$$

By comparing the average inlet H_2S concentration ($C_{in} = 18.8$ ppm) and the half saturation coefficient ($k_m = 1.623$) it is concluded that ($C_{in} \gg k_m$). Therefore, the model simplifies to a zero-order reaction-limited type.

Fig. 3 Comparing the response factor of scenarios at different EBRTs (a) Decrease inlet loading ($\alpha < 1$) (b) Increase of inlet loading ($\alpha > 1$)

Table 3 Average simulated outflow concentration (in ppm) at different scenarios and EBRTs

EBRT	$\alpha = 0.25$	$\alpha = 0.5$	$\alpha = 0.75$	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$	$\alpha = 4$
15	1.7	4.7	8.0	11.5	26.1	41.3	56.8
30	0.4	2.1	4.4	7.0	18.9	32.1	45.9
45	0.3	0.7	2.0	3.7	13.0	24.2	36.3
60	0.3	0.5	0.8	1.7	8.3	17.5	27.9

Table 2 shows the results of comparing the fitness models using the criteria R^2 and MSE. It is obvious that the second model i.e., Zero-order diffusion-limited has the maximum R^2 and minimum MSE at both calibration and validation phases. Therefore, this model is chosen as the best fit model for H_2S removal of the biofilter.

Scenario analysis

To predict the biofilter behavior under different loading conditions, the best fit model is used in scenario analysis. In this regard, six scenarios are defined in addition to the base scenario (i.e., existing data); three scenarios for the loading increase with loading factor (“ α ” in Eq. 15) equal to 2, 3, 4 and the other three scenarios refer to loading decrease with $\alpha = 0.25, 0.5$ and 0.75 .

The response of the system to each scenario is assessed by “response factor” (R_f) as defined in Eq. (16). Figure 3 shows the response factors of the scenarios at different EBRTs. To be more comparable, the results are illustrated in Fig. 3. It can be observed

that for the increasing scenarios ($\alpha > 1$), response factor increases at higher EBRTs which shows that biofilter is more sensitive to the shock loads at higher EBRTs. For example, if the input load is increased by three times, the output concentration at EBRT = 60s is increased 10.49 times the base level while this ratio is 3.6 for EBRT = 15 s. It also implies that increasing the input load decreases the removal efficiency ($1 - C_{out}/C_{in}$) in higher EBRT. However, it should be noted that the effluent H_2S concentration is decreased in higher EBRT as shown in Table 3 and Fig. 4.

In the scenarios of loading decrease ($\alpha < 1$), generally, the response factor does not display a regular pattern due to small changes in the inlet/outlet concentration. However, for $\alpha = 0.75$, response factor slightly declines at higher EBRTs which implies that the biofilter is more sensitive to the inlet fluctuations when EBRT increases.

Table 3 shows the average simulated outflow concentration (C_{out}) at different scenarios and EBRTs. As mentioned before, according to OSHA a ceiling of 10 ppm (PEL for 8 h time-weighted average) was considered in different scenarios [7].

Therefore, the outflow concentrations higher than 10 ppm are highlighted in Table 3. It is obvious that the biofilter system is not able to meet the standard limit with shock loads higher than two times the base concentration ($\alpha > 2$). As it is seen, in scenario $\alpha = 2$ only at EBRT = 60s the effluent concentration is less than 10 ppm.

Figure 4 illustrates the dynamic results of scenarios during the 90 days of pilot operation at two EBRTs of 15 and 60 s. The main finding from these graphs is that the response of inlet loading fluctuations magnifies at peak points. As shown in Fig. 4b in scenario $\alpha = 2$ there are some days that the effluent concentration exceeds the permissible 10 ppm, but according to Table 3, the average is 8.3 ppm which is below the limit.

Fig. 4 Simulated outflow concentrations of scenarios during 90 days of operation at (a) EBRTs = 15 s (b) EBRT = 60s

Table 4 Comparison with previous studies

Reference	Media	pollutant	study scale	Media diameter*height (cm*cm)	Inlet concentration/load rate	EBRT (s)	RE (%)	Operation time (d)	Best fit model
current research	wood chips: compost(1:5)	H ₂ S	field scale	26*160	18.8 ppm	15–60	98%	90	Zero-order-diffusion-limited First-order model
Shareefdeen et al. 2011 [28]	porous aggregate+compost	H ₂ S	field scale	13*324	100 ppm	20–60	98.5%	NA	
Shareefdeen, 2014 [32]	+iron powder	H ₂ S	lab scale	10*150	7–35 g/m ² .h	30	97%	NA	Haldane model
Lestari et al., 2016 [33]	Expanded schist	H ₂ S	lab scale	8*80	142	240	97%	NA	Monod equation and mass balance
Jaber et al., 2016 [34]	Expanded schist	H ₂ S, CO ₂ , CH ₄	lab scale	30*100	250 ppm	60	99%	280	Haldane model
Leili et al. 2017 [35]	compost	BTEX and Hg	lab scale	4.5*50	663 gBTEX/m ³ .h & 12.6 gHg/m ³ .h	60	>86%	170	Michaelis–Menten
Das et al. 2019 [36]	compost & biochar	H ₂ S	lab scale	34*150	0.1 to 2.9 g/m ³	119	99%	110	Michaelis–Menten
Wang et al. 2018 [37]	compost	H ₂ S	lab scale	15*70	0–429 mg/m ³ .h	600	64%	28	NA

Analysis of the effectiveness of the parameters

The main independent parameters that are effective in biofilter performance and considered in the modeling study are EBRT and inlet H₂S concentration. To compare the effectiveness of these two parameters for the effluent H₂S concentration, dimensionless sensitivity coefficient (F_{sa} as in Eq. (17)) is calculated. To calculate the coefficient, a range of 5–65 s for EBRT and 5–55 ppm for inlet concentration is selected. Then each range is divided to ten parts of equal size and the sensitivity coefficient (F_{sa}) is calculated for each part. Finally, the overall coefficient is obtained by averaging the calculated values. The result indicates that inlet concentration is more effective than EBRT with a ratio of $F_{sa}(C_{in})/F_{sa}(EBRT) = 1.790/1.244 = 1.4$.

Comparing results with the previous studies

Table 4 shows a summary of the results compared with the previously published researches. The comparison was made based on media type, pollutant (mostly H₂S), study scale (mostly lab scale), pilot dimensions, inlet concentration, EBRT, removal efficiency, operation duration, and the best fit model. A brief review of the results approves the validity of the obtained results of this study compared with the literature.

Conclusions

In this study, modeling the performance of a biofilter system in the removal of H₂S gas released from a municipal wastewater pump station was assessed. The data of 90 days of pilot operation were used to evaluate the removal efficiency and the reaction kinetics. Two models of Ottengraf and Michaelis–Menten were used to evaluate and determine the best fit model according to R-square and MSE values in calibration and validation stages. The best fit model was applied in scenarios analysis based on inlet load fluctuations. Also using a sensitivity coefficient, the effectiveness of the main parameters in biofilter performance was determined. According to the results of scenario analysis, the present biofilter system is able to reduce the H₂S concentration to below the standard limit up to the maximum two times the base inlet H₂S load. Also, the inlet concentration is about 40% more effective than EBRT in the performance of the system. The results demonstrate the advantage of applying a validated model in the prediction of the system performance which can be an effective tool for the operators and designers.

Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

Abbreviations

EBRT	Empty bed residence time	K	the Monod kinetic constant (kg.m^{-3})
MWF	Municipal wastewater facilities	C	the substrate concentration (g/m^3),
DO	Dissolved oxygen	B	the microbial population density,
OSHA	Occupational Safety and Health Administration	V_m	theoretical maximum specific reaction rate ($\text{g/m}^3 \text{ h}$)
PEL	Permissible exposure limit	K_m	the half-saturation constant (ppm) and t is the reaction time (h)
WPS	Wastewater pump stations	R	removal rate
C_{in}, C_{out}	inlet and outlet gas concentration in kg/m^3	SV	space velocity
K_0	the zero-order reaction rate constant ($\text{kg.m}^{-3}.\text{s}^{-1}$)	Q_{in}	the air flow rate, (m^3/h)
μ^*	specific growth rate (s^{-1})	C_{Ln}	logarithmic mean concentration (ppm)
X_v	biofilm density (kg.m^{-3})	K_0	the zero-order coefficient
A_s	biofilm surface area or unit volume of biofilter (m^{-1})	C, C_0	outlet and inlet concentrations respectively
δ	biofilm depth (m)	$\bar{y}$	average of observed data
Y	yield coefficient equal to the ratio of biomass produced to the substrate consumed	y_i	observed data
H	the height of the biofilter column (m)	y_m	simulated value by model
U_g	the velocity of air (m/s) through the column.	n	the total number of data
β_1	a constant defined as in (Eq. 5)	$C_{in(ref)}$	the reference input concentration
$f(X_v)$	the ratio of diffusivity of the pollutant in the biofilm to that in water	α	the loading factor
$D_{H_2S,w}$	diffusivity of H_2S in water ($\text{m}^2.\text{s}^{-1}$)	R_f	response factor
m	dimensionless Henry's constant of the pollutant	F_{sa}	sensitivity coefficient
K_1	the reaction rate constant (s^{-1}) given as (Eq. 7)	F_{sa}	the sensitivity coefficient
β_2	defined as Eq.8	O	the model output
		P	the input parameter
		$\partial O, \partial P$	the variation of output/input parameters with respect to the base was

Appendix

Figure 5, presents a schematic of the biofilm system. A base film is overlaying with an irregular surface film that is enclosed by a uniform water boundary layer in turn. Figures 6, 7 and 8 show the calibration for the Ottengraf model and Fig. 9 presents the best fit line through the data points for the Michaelis-Menten model.

Fig. 5 Schematic of the components of a biofilm system

Fig. 6 **a** Calibration / **b** validation of zero-order reaction-limited model

Fig. 7 **a** Calibration / **b** validation of zero-order diffusion-limited model

Fig. 8 **a** Calibration / **b** validation of first-order model

Fig. 9 Best fit line through the data points for the Michaelis-Menten model

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