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A theoretical analysis of an air stripper–biofilter system (ASBF) for industrial wastewater treatment

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ABSTRACT

In this study, we focus on the industrial wastewater contaminated with volatile organic compounds (or VOC's) which are carbon-containing compounds such as benzene, toluene, xylene, styrene, etc. VOC's in general are toxic and potentially carcinogenic and they harm aquatic life and the environment. In this research, we focus on a theoretical analysis of VOC removal from industrial wastewater using a hybrid system that combines two processes, namely air-stripping and biofiltration (ASBF). In this system, airstream is first contacted with industrial wastewater in an air-stripping tower and depending on the air stripping efficiency clean water, which is devoid of VOCs, leaves the unit as the effluent. The contaminated air stream is then fed to a biofilter that eliminates VOCs by biological degradation. The theoretical predictions conducted through modeling demonstrate effective removal of VOCs from wastewater can be achieved in the ASBF system under different operating conditions.

Keywords: Air stripping; ASBF system; Biofilter; Packing size; Packing media; VOC; Wastewater

1. Introduction

Depending on the source, volatile organic compounds (or VOC's) may be abundant in the industrial wastewater and many of the VOCs present in the industrial wastewater are toxic, potentially carcinogenic, and harmful to aquatic life and the environment. The VOCs are the main contributors to the smog, formation of tropospheric ozone layer, and to the greenhouse effects [1,2].

In this research, we focus on the removal of VOCs (i.e., styrene, toluene, etc.) using a physical-biological system. Styrene is widely used in the industry in the production of polymers such as plastics, paints and resins. According to United States Environmental Protection Agency, styrene adversely affects human health and when exposed for a long time, it can lead to liver and nerve tissue damage. During a short time exposure, it can cause weakness, weariness and nausea. It is also a suspected carcinogen when consumed at quantities above the maximum contaminant level (MCL). At present, the Environmental Protection Agency (EPA) has regulated the MCL at 0.1 mg/L for styrene [3].

In addition to styrene, other compounds investigated in this study include ethylbenzene, xylene, toluene and hydrogen sulfide. Ethylbenzene is commercially produced by the alkylation of benzene with ethylene. Acute exposures to ethyl benzene cause respiratory and eye problems, headaches and fatigues [4]. Currently, aeration is widely used to remove ethyl benzene from contaminated water.

Major contributors of xylene are from the oil and gas industries. Xylene is not only a component of coal tar and fuel, but it is also a naturally occurring product of plants [5]. Xylene has adverse health effects on humans such as hindrance in mental abilities, damage to kidneys, liver and central nervous system, etc. Thus, the MCL of xylene has been regulated at 10 mg/L for drinking water and the leading method of removing xylene from water is through volatilization [5].

The drinking water standard for toluene is maintained at a MCL of 1 mg/L. Health effects associated with chronic exposure to toluene include tremors and damage to hearing, vision, liver, kidney and memory. Toluene has a wide range of applications, ranging from manufacture of benzoic acid to the production of urethane. Currently the available technologies for treatment of toluene contaminated water

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include use of granular activated charcoal and packed tower aeration [6].

In addition to VOCs, we also investigated removal of hydrogen sulfide (H_2S), which is commonly found in wastewater as one of the major odor causing compounds. H_2S can easily be identified by its rotten egg smell. It is naturally present in crude oil, springs and certain natural gases [7]. The major sources of hydrogen sulfide emission include wastewater treatment facilities, petroleum refining, paper mills, etc. Exposure to hydrogen sulfide causes irritation, effects on the central nervous system, respiratory problems and digestive disturbances. At high concentration, exposure to hydrogen sulfide can lead to coma and death [7].

In this study, we focus on removal of VOCs and hydrogen sulfide from industrial wastewater by a hybrid system that combines two processes, namely air stripping and biofiltration. The hybrid process is illustrated in Figs. 1 and 2. Fig. 1 shows the block flow diagram for the proposed system and Fig. 2 illustrates a schematic diagram of the air-stripping biofilter system (ASBF). In this process, airstream is first contacted with industrial wastewater in an air-stripping tower and depending on the VOC stripping efficiency clean water, which is devoid of pollutants leaves as the effluent. The contaminated air stream effluent from the air stripper is then fed to a biofilter, which eliminates VOCs, by biological oxidation [8].

There are several advantages of using the proposed ASBF system: (a) VOCs are removed from industrial wastewater by purging clean air and the treated water can be returned for reuse. This is accomplished by a simple air stripper (b) As compared to conventional biological treatment, ASBF system eliminates the need for additional process units such as aeration, flocculation, coagulation tanks, etc. (c) In ASBF system, there is no excess biomass growth, therefore problems related to removal of biomass can be avoided. (d) Air stripping unit has a dual purpose of stripping VOCs from water as well as humidifying the influent air to the biofilter unit. Thus, ASBF arrangement eliminates the need for a humidifier; in a conventional biofilter system, humidifier is a required component that keeps biofilter media moist. The objective of this work is to demonstrate theoretically, efficient removal of VOCs from industrial wastewater using the proposed ASBF system under various operating conditions.

2. Materials and methods

2.1. Model equations for air stripper

The process model and design equations guiding the operation of an air-stripping unit have been previously developed [9–11]. These equations are presented here to discuss the results. The equation that relates to the height (Z) of a stripping tower is as follows:

$$Z = \mathrm{HTU} * \mathrm{NTU} \tag{1}$$

where Z = height of stripping tower packing (m), HTU = height of a transfer unit (m), NTU = number of transfer units.

Height of a transfer unit HTU defined as:

$$\mathrm{HTU} = \frac{L}{\rho K_{La}} \tag{2}$$

where L = water loading rate, kg/(m²·s), defined as

$$L = \frac{Q_w \rho}{A} \tag{3}$$

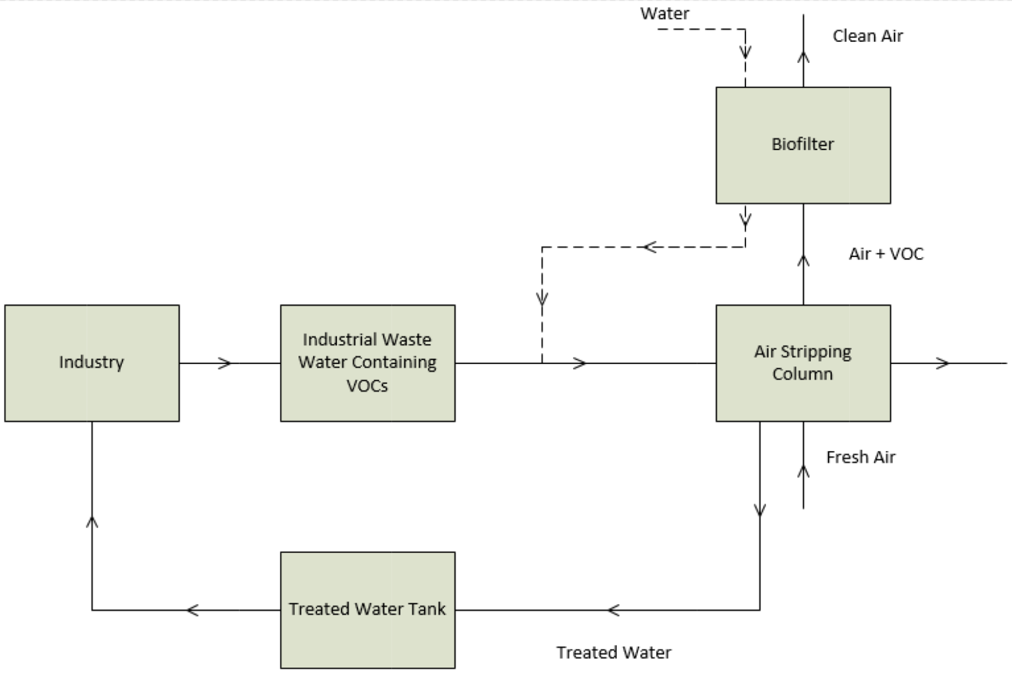

Fig. 1. Block diagram of the air stripping-biofiler (ASBF) process.

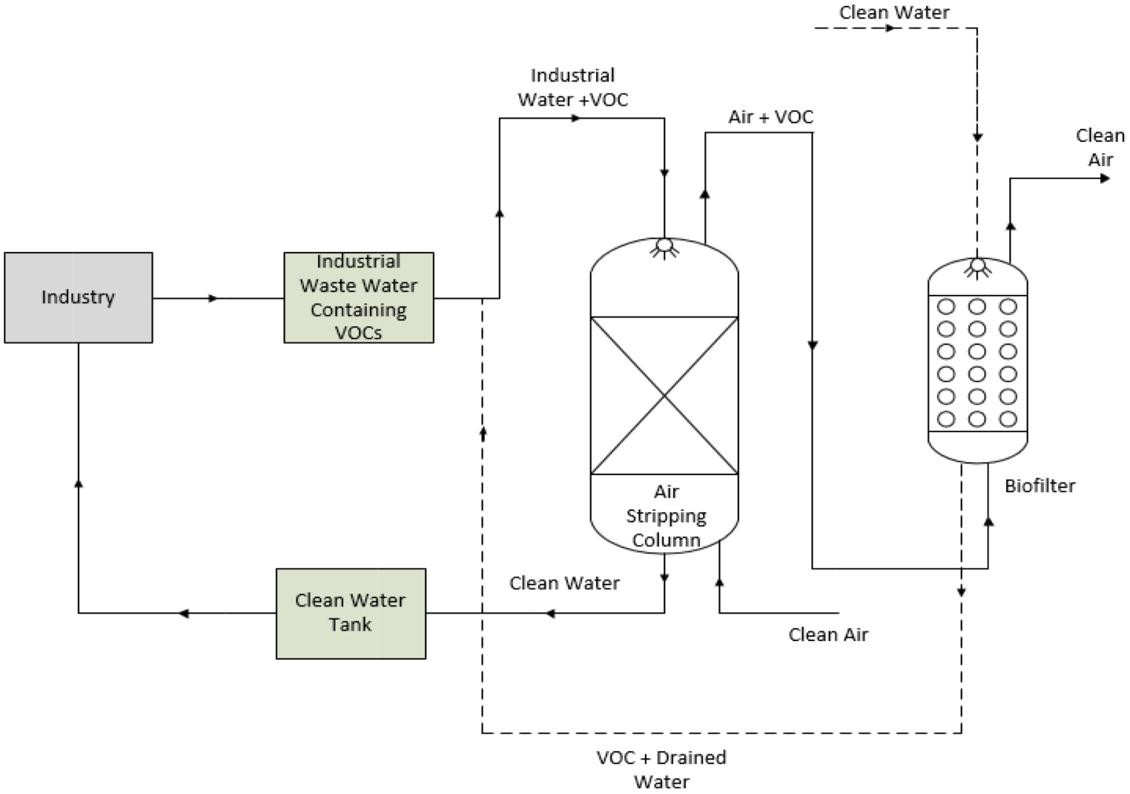

Fig. 2. Schematic diagram of an air stripping-biofilter (ASBF) system.

where Q_w = water flow rate (m^3/s), ρ = density of water, (kg/m^3), A = cross sectional area (m^2).

The overall mass transfer rate constant (K_{La}), (which determines the rate at which the VOCs are transferred from water to air), is estimated using Sherwood and Holloway empirical correlations [9].

$$K_{La} = \alpha * D_L * \left(0.305\frac{L}{\mu}\right)^{1-n}\left(\frac{\mu}{\rho D_L}\right)^{0.5} \tag{4}$$

where α, n = constants based on packing type, D_L = VOC diffusion coefficient in water (m^2/s), μ = viscosity of water (1.002 × 10^{-3} Pa·s at 20°C), ρ = density of water (1000 kg/m^3 at 20°C).

The HTU is a measure of the mass transfer characteristics of the packing medium. The number of transfer unit is defined as:

$$NTU = \left(\frac{R}{R-1}\right)\ln\left(\frac{\left(\frac{C_{in}}{C_{out}}\right)(R-1)+1}{R}\right) \tag{5}$$

where R = stripping factor which is defined as

$$R = H' * \left(\frac{Q_a}{Q_w}\right) \tag{6}$$

where Q_a = air flow rate (m^3/s), H' = dimensionless Henry's law constant, C_{in} = influent concentration of VOC in water, kg/m^3, C_{out} = effluent concentration of VOC in water, kg/m^3.

Concentration of VOC in exiting gas phase

$$A_{out} = \left(C_{in} - C_{out}\right) * \frac{Q_w}{Q_a} \tag{7}$$

The exiting air laden with VOCs from the stripping tower is the inlet air to the biofilter.

2.2. Biofilter sizing using elimination capacity

$$V = \frac{Q_a \times \left(C_{in} - C_{out}\right)}{EC} \tag{8}$$

where Q_a = air flow rate (m^3/s) exiting from the stripper outlet, C_{in} = concentration (kg/m^3) exiting the air stripping column and entering the biofilter, C_{out} = concentration leaving the biofilter, (kg/m^3), V = volume of biofilter, (m^3), EC = elimination capacity of the packing material (kg/m$^3_{\text{biofilter}}$·s).

3. Results and discussion

3.1. Air stripping column

First, we investigated the removal of VOC (i.e., styrene) and optimum design heights of the stripping column for a variety of packing types. The two main parameters, the height of the stripping tower (Z) and the concentration of the outlet air stream (A_{out}), are dependent on various factors such as, flow rate of water (Q_w), flow rate of air Q_a, concentration of VOCs in water and the types of packing used in the stripping tower.

Sherwood and Holloways's constants (α, n) vary for different packing types and sizes. We determined values of K_{La} for different types of packing and sizes that are commonly available and used. The air stripping model equations have been solved by MATLAB software. All the parameters used in solving the air-stripping model equations are given in Table 1. Using the parameters in Table 1, stripping column heights are calculated for three types of common packing materials namely, Raschig rings, Berl saddles and tiles. The results are presented in Table 2. Predicted height of the stripping column versus particle size is plotted in Fig. 3.

From Fig. 3 it is evident that Raschig ring packing of 25 mm size gives the minimum height for the stripping column. Hence, for optimal height, the Raschig ring packing of 25 mm size is subsequently used for the rest of the analysis.

3.2. Effect of air to water flow rate ratio (Q_a/Q_w) on size of the stripping column

The air to water flow ratio (Q_a/Q_w) is one of the main parameters that affect the height of the stripping column. We have evaluated the effect of Q_a/Q_w on the height of the stripping column for different pollutants. As seen in Fig. 4, as the values of Q_a/Q_w increases, the height of the stripping column decreases. Furthermore, in comparison to the other VOCs considered, stripping column height is the highest for styrene.

Table 1
Parameters used in solving the air stripping model

Parameters	Value	References
H'	0.27	[12]
Q_a/Q_w	20	(This work)
D_L, m^2/s	8.1E-10	[12]
A, m^2	2.92E-1	(This work)
C_{in}, kg/m^3	1.0E-3	(This work)
C_{out}, kg/m^3	3.5E-5	(This work)

Table 2
Sherwood and Holloway's constant for different packing sizes along with the predicted stripping tower heights

Packing	Size (mm)	α	n	K_{La} (s^{-1})	Z (m)
Raschig rings	12	920	0.35	0.2235	11.0
	25	330	0.22	0.0802	9.6
	38	295	0.22	0.0717	10.8
	50	260	0.22	0.0632	12.2
Berl saddles	12	490	0.28	0.1191	11.1
	25	560	0.28	0.1361	9.7
	38	525	0.28	0.1276	10.3
Tile	75	360	0.28	0.0850	15.1

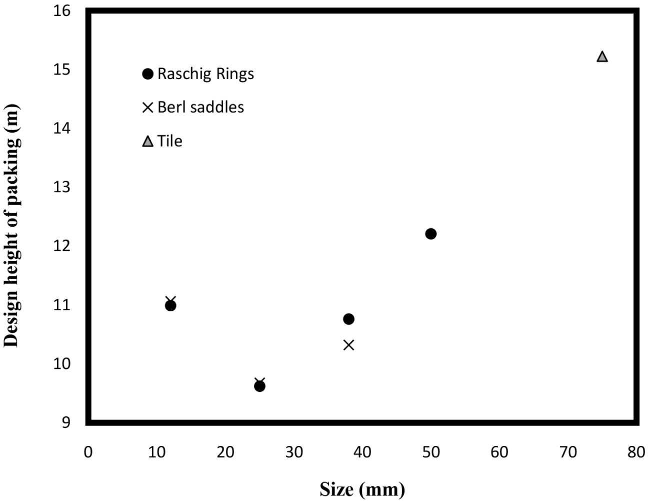

Fig. 3. Comparison of the height of a stripping column (Z) for different packing sizes.

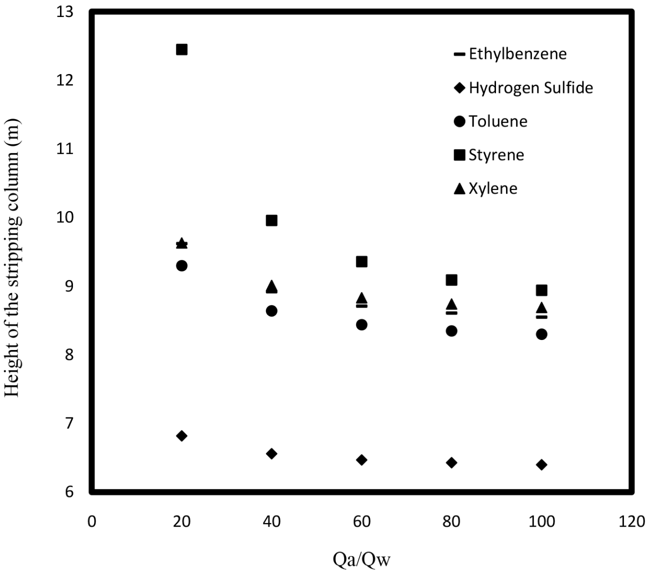

Fig. 4. Comparison of the stripping column height for different air to water ratio (Q_a/Q_w).

3.3. Height of the stripping column for different removal efficiency

Keeping Q_a/Q_w constant at 20, stripping column height versus removal efficiencies (R.E) from 70% to 100% is varied and plotted in Fig. 5.

As expected, from Fig. 5 it is evident that as the R.E. increases with the height. The Fig. 5 shows for higher than 95% removal, stripping height should be substantially increased. It is not economical to have a very high stripping column; thus stripping alone is not sufficient and addition of a biofilter unit becomes necessary, thus, ASBF has advantages over stand-alone stripping tower. Testing with other VOCs further clarified this point and discussed in the following section.

3.4. Evaluation of the stripping effects for different compounds

Compounds that we studied consisted of acetone, ethyl acetate, methyl isobutyl ketone, xylene, ethanol, styrene,

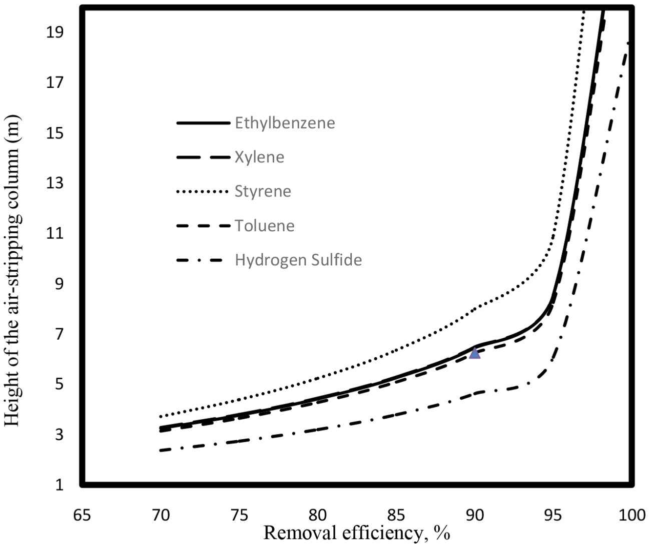

Fig. 5. Heights of the stripping column versus removal efficiencies for different compounds.

methanol, isopropyl alcohol, toluene, ammonia and hydrogen sulfide. In order to determine the stripping tower height (*Z*) for these compounds, we obtained the diffusivities of these compounds (D_L) and dimensionless Henry's law constants (*H*′), from the *GSI Environmental database* [12]. For consistencies we kept airflow rate, removal efficiencies, water flow rate and temperature (@20°C) the same for all simulation runs.

Out of the several compounds tested (see Table 3), acetone, ethyl acetate, methyl isobutyl ketone, ethanol, methanol isopropyl alcohol and ammonia gave us unacceptable values for the height of the stripping column. This can be explained by the fact that these compounds are not "volatile". Low values for Henrys constant and other contributive parameters make it difficult for these compounds to be removed by air stripping at 20°C. However, at higher temperature air stripping is possible. According to the equation for Henry's constant, $[H' = [e^{A-\frac{B}{T}}]/RT]$, H′ increases with T (*A*, *B* are regression constants, *T* is the temperature, *R* is the gas constant and *H*′ is the dimensionless Henry's law constant) [9]. The effect of temperature is discussed in the next section.

Table 3
Estimated height of stripping column (Z) for different hydrocarbons

Group	Compound	D_L (m^2/s)	*H*′ (@20°C)	*Z* (m)
1	Ethyl benzene	8.1E–9	2.7E–1	9.62
	Acetone	1.1E–9	1.6E–3	N/A
	Ethyl acetate	9.7E–10	5.5E–3	N/A
	Methyl isobutyl Ketone	7.8E–10	5.8E–3	N/A
	Xylene	7.8E–10	3.1E–1	9.63
2	Ethanol	1.2E–9	2.7E–4	N/A
	Styrene	8.0E–10	1.1E–1	12.45
	Methanol	1.6E–9	1.9E–4	N/A
3	Isopropyl alcohol	1.0E–9	3.7E–4	N/A
	Toluene	8.6E–10	2.8E–1	9.30
	Ammonia	6.9E–9	1.4E–2	N/A
	Hydrogen sulfide	1.4E–9	4.8E–1	6.83

3.5. Effect of temperature on air-stripping toluene from industrial wastewater

In many cases, industrial processes discharge water at elevated temperatures and hence temperature effects need to be considered in stripping column design. The diffusivity coefficient (D_L), dimensionless Henrys constant (*H*′), density and viscosity of water are also affected by the changes in temperature. The height of the air-stripping column for varying temperatures is presented in Fig. 6, which shows height of the stripping column decreases significantly due to increase in temperature or high volatility rate.

3.6. Effect of air to water flow rate ratio (Q_a/Q_w) on biofilter height

Once the VOC is removed from water, the pollutant that is transferred to the air needs to be cleaned. Styrene is listed as one of the 189 hazardous contaminants mentioned in the Clean Air Act Amendment (CAAA) of 1990 [13]. In order to

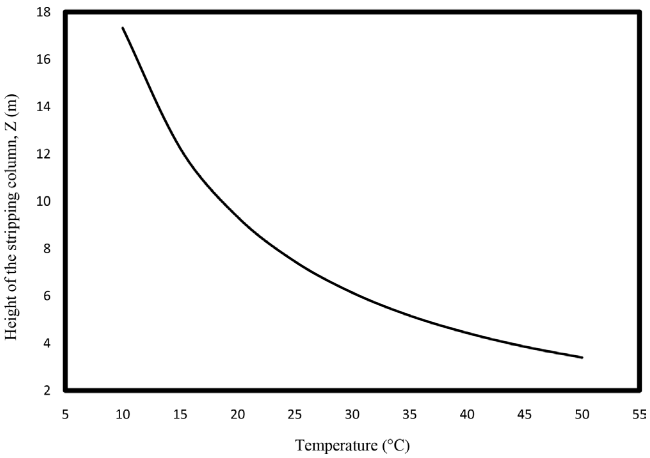

Fig. 6. Height of the stripping column (Z) versus temperature.

Table 4
Different packing used in biofilter and their respective elimination capacities [14]

Packing media	Elimination capacity (g·m^3/h)
Peat	30
Compost	334
Peat + Glass bead	63
Peat + Ceramic	175

remove styrene, several methods such as catalytic oxidizer, thermal oxidizers, etc. can be used. However, thermal oxidation is expensive and requires a lot of energy. In the biofilter system, bacteria degrade styrene at ambient conditions at much lower cost [14].

The odor threshold value for styrene in air is 0.32 ppm [14]. In calculating biofilter height, we set odor threshold value as the biofilter outlet concentration. The inlet concentration to the biofilter is the same as the exit concentration of the air-stripping unit. VOC removal efficiency in a biofilter is dependent on the type of biofilter media used and it greatly influences the biofilter height. Table 4 shows some of the commonly used packing media along with experimentally determined styrene elimination capacities from the literature [14]. In this work, we compared biofilter height versus Q_a/Q_w for different types of packing for styrene removal in Fig. 7, which shows that compost gives the lowest biofilter height.

Using the biofilter parameters listed in Table 5, we determined the height of the biofilter necessary to reduce the pollutant concentration to odor threshold level, for the other VOCs as shown in Fig. 8.

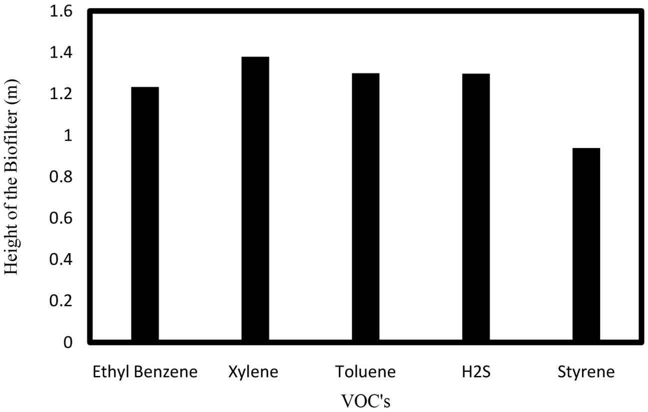

Fig. 8. Biofilter height for different volatile organic compounds.

4. Conclusion

In this work, we have theoretically evaluated an air stripping-biofiltration (ASBF) system to remove VOCs and H_2S from industrial wastewater. The design equations of the ASBF system are analyzed and several influencing parameters were varied to estimate optimal operating conditions. Appropriate packing size, effect of air to water flow ratio (Q_a/Q_w) and types of VOCs present in the wastewater are investigated. The proposed ASBF system has many advantages and eliminates several process units that are used in traditional wastewater treatment systems. Furthermore, ASBF system eliminates the use of a humidifier, which is otherwise a required component for the biofilter. Thus, employment of ASBF system in place of standalone air stripper or biofilter can substantially reduce costs and give better performance. Although the results presented in this work are promising, experimental validations of the proposed ASBF system in lab and pilot-scale units are needed and such studies are our future scope of research.

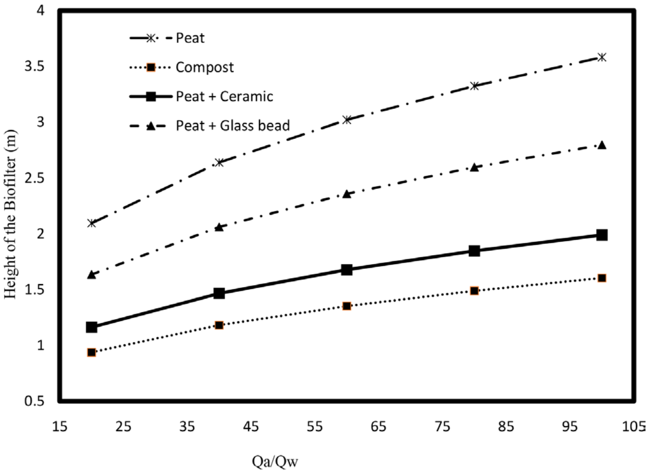

Fig. 7. Height of the biofilter for different packing media versus Q_a/Q_w ratio.

References

[1] S.O.L. Jonathan, C. Hanks, Volatile Organic Compounds, New York: Nova Science Publishers, Inc. (2011).

[2] B.L. Rowe, P.L. Toccalino, M.J. Moran, J.S. Zogorski, C.V. Price, “Occurrence and Potential Human-Health Relevance of Volatile Organic Compounds in Drinking Water from Domestic Wells in the United States,” Environmental Health Perspectives, 115(11) (2007) 1539–1546.

[3] USEPA, “National Primary Drinking Water Regulations: Styrene,” Office of Water, Washington D.C. (1995).

[4] N.J. Ayscough, W. Young, P. Whitehouse, Proposed Environmental Quality Standards for Ethylbenzene, Environmental Agency, Bristol. (2002).

[5] USEPA, Xylenes (Mixed Isomers), Environmental Protection Agency, Washington D.C. (2000).

Table 5
Parameters for evaluating biofilter heights for different compounds

Compounds	Odor threshold in air (ppm)	Ref	Packing media	EC (g/m^3.h)	Ref.
Ethyl benzene	2.3	[15]	Fibrous peat	120	[16]
Xylene	1.1	[5]	Scoria/Compost	97.5	[17]
Toluene	2.9	[6]	Compost	100	[18]
Hydrogen sulfide	0.0005	[19]	Compost	130	[18]
Styrene	0.32	[14]	Compost	334	[14]

[6] USEPA, National Primary Drinking Water Regulations: Toluene, Office of Water, Washington D.C. (1995).

[7] OSHA, OSHA Fact Sheet: Hydrogen Sulfide, United States Department of Labor, Washington D.C. (2005).

[8] C. Rahul, A. Mathur, C. Balomajumder, Biological treatment and modeling aspect of BTEX abatement process in a biofilter, Bioresour. Technol., 142 (2013) 9–17.

[9] M.D. LaGrega, P.L. Buckingham, J.C. Evans, Hazardous Waste Management, New York: McGraw-Hill (2011).

[10] G. Tchobanoglous, F.L. Burton, H.D. Stensel, M. Eddy, Wastewater Engineering: Treatment and Reuse, 4 ed., New York: McGraw-Hill (2003).

[11] Z. Shareefdeen, M. Ogunlaja, A. Elkamel, Process intensification and modeling of a hybrid air stripping – biofilter (ASBF) system for removal of Benzene from produced water, Desal. Water Treat., 57(33) (2015) 1–8.

[12] GSI Chemical Properties Database, GSI Chemical Database, California (2015).

[13] USEPA, Clean Air Act, Environmental Protection Agency, US (1990).

[14] M.-C.D. St-Pierre, A.A. Ramirez, M. Heitz, Biofiltration of air contaminated by styrene vapors on inorganic filtering media: an experimental study, J. Air Waste Manage. Assoc., 59(5) (2009) 568–578.

[15] USEPA, National Primary Drinking Water Regulations: Ethylbenzene, Environmental Protection Agency, Washington D.C. (1995).

[16] F. Álvarez-Hornos, C. Gabaldón, V. Martínez-Soria, M. Martín, P. Marzal, J. Penya-roja, Biofiltration of ethylbenzene vapours: Influence of the packing material, Bioresour. Technol., 99(2) (2008) 269–276.

[17] A. Rahimi, B. Bina, F.M. Moghadam, M. Heidari, M. Amin, Performance evaluation of a scoria-compost biofilter treating xylene vapors, J. Environ. Health Sci. Eng., 12(1) (2014) 1–10.

[18] J.S. Devinny, M.A. Deshusses, T.S. Webster, Biofiltration for Air Pollution Control, New York: Lewis Publishers (1998).

[19] F.L. Colomer, H. Espinos-Morato, E.M. Iglesias, T.G. Perez, A. Campos-Candel, C.C. Lozano, Characterization of the olfactory impact around a wastewater treatment plant: Optimization and validation of a hydrogen sulfide determination procedure based on passive diffusion sampling, J. Air Waste Manage. Assoc., 62(8) (2012) 863–872.