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Temperature and air–water ratio influence on the air stripping of benzene, toluene and xylene

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ABSTRACT

Volatile organic compounds in water and wastewater can be removed using air stripping. The effects of temperature and air-water ratios on the air stripping of benzene, toluene and xylene (BTX) from wastewater have been examined at a temperature range of 30–50˚C and air-water ratios of 20–100. Removal efficiencies of >99%, >93% and 93% for BTX, respectively, were obtained at 50˚C and air-water ratios of 100. The removal efficiencies increase non-linearly with temperature and air-water flow ratio. The effects of increasing temperature on the removal efficiency were found to be more significant at temperatures between 30 and 35˚C than at 45 and 50˚C. The effects of increasing water-air ratios on the removal efficiency were more significant at air-water ratios of 20–60 than at 80–100. The results indicate that a high removal of BTX can be achieved by operating the air stripper at high temperature conditions even at relatively low air-water ratios and vice versa.

Keywords: Air stripping; Volatile organic compounds; Removal efficiency; Wastewater treatment

1. Introduction

The removal of benzene, toluene and xylene (BTX) from wastewater using a pilot-scale packed column air stripper has been studied. In particular, the influences of temperature and air-water ratio on the removal efficiency have been examined experimentally. Industrial wastewater containing volatile organic compounds (VOCs) will seriously affect water supplies. Abdullah and Chian studied VOCs in drinking water in peninsular Malaysia and detected 54 different VOC species in the samples analysed from 11 states [1]. This was attributed to improper disposal practice. VOCs are contained in many manufactured products, including paints, adhesives, gasoline, plastic, pharmaceuticals and refrigerants. Many are also compounds of fuels, solvents, hydraulic fluids and dry cleaning agents commonly used in urban settings such as bleach [2]. An epidemiological study by the United States Environmental Protection Agency has identified

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some of the VOCs as air toxics or carcinogens [3]. Exposure to high VOC concentrations usually results in acute and chronic health effects. These include eye, nose and throat irritations, headache, vomiting, dizziness, cancer, damage of the liver, kidney or nervous system as well as asthma exacerbation [4]. The presence of odours is also associated with VOC emissions [5].

Growing public concern about environmental protection/sustainability and public health have led to the enactment of environmental laws and setting up of emission standards. The manufacturers are therefore faced with the need to reduce the release of these pollutants into the environment by treating effluents before discharge. The treatment methods are air stripping, absorption, adsorption, reverse osmosis, biological, thermal and catalytic oxidation [4,6–8]. Other methods include sonochemical and other advanced oxidation processes like Fenton, photo-Fenton, wet oxidation, ozonation, photo catalysis [9,10], electrochemical [4], membrane-based separation [11] and non-thermal plasma [12].

The basic principle of air stripping is the removal of VOCs from wastewater by increasing the surface area of the contaminated water that is exposed to air. Air stripping remains the most useful technique especially where there is an economic interest in higher concentrations of valuable VOCs [13]. It involves trapping these compounds and removing them from the system for possible reuse. In biological, thermal and catalytic oxidation methods, however, the VOCs are destroyed. Air stripping is commonly used due to its simple technology, cost effectiveness and high removal efficiency [14–17].

Previous studies show that VOC removal efficiency depends on temperature, air-to-water ratio, hydraulic loading rates, packing materials and size, column height and diameter, gas pressure drop and Henry's constant of the contaminant [6,14–16,18]. Efficient and economic combination of these factors to achieve the maximum removal of VOCs remains a challenge [18]. A common feature of the previous researches on air stripping of VOCs is that mostly single VOCs species are considered [19]. Only few reported works involve mixture of VOCs [18]. This however, focused only on the determination of the condition at which low levels of BTX could be effectively stripped from water using low air-water ratios (G/L) of 0–0.06 [18]. Therefore, there is a need for further attention in this direction, specifically considering high levels of BTX contamination and high air-water ratios (G/L). This is because practical situations in the industries such as pharmaceutical wastewater usually consist of mixture of VOCs at higher concentrations [20].

2. Materials and methods

2.1. Materials

BTX were obtained from Merck Sdn Bhd. Malaysia with greater than 99.5% purity. Synthetic wastewater containing 1,500 ppm of BTXs was prepared. The study was carried out in a custom-made pilot-scale packed column air stripper (Model 2T4H) from Branch Environmental Corp., USA. The stripping column is made of a 1.5 m stainless steel tube of 0.05 m internal diameter filled with 6 mm ceramic raschig rings packing. The height of the packing is 1.15 m which is equivalent to a packing volume of $2.26 \times 10^{-3}\ m^3$. The process flow diagram (PFD) is shown as Fig. 1.

2.2. Methods

The effects of temperature and air flow rate on BTX removal were investigated according to the following procedure: The air flow rate (2.4 L/min) was set using a rotameter and the wastewater inlet was also set to 0.12 L/min by adjusting the rotameter, while the wastewater and air heaters were set to 30℃. The air and contaminated water were then pumped into the air stripper in counter-current operation. The VOC rich air was collected at the top while the treated wastewater was collected at the bottom. This procedure was repeated for other runs using air flow rates of 4.8, 7.2, 9.6 and 12 L/min; and temperatures of 35, 40, 45 and 50℃, respectively, at a fixed wastewater flow rate of 0.12 L/min. These air and wastewater flow rates are equivalent to G/L ratios of 20, 40, 60, 80 and 100, respectively. The quantities of BTX in the treated wastewater samples were determined using Ultraviolet–visible spectrophotometer (Perkin–Elmer

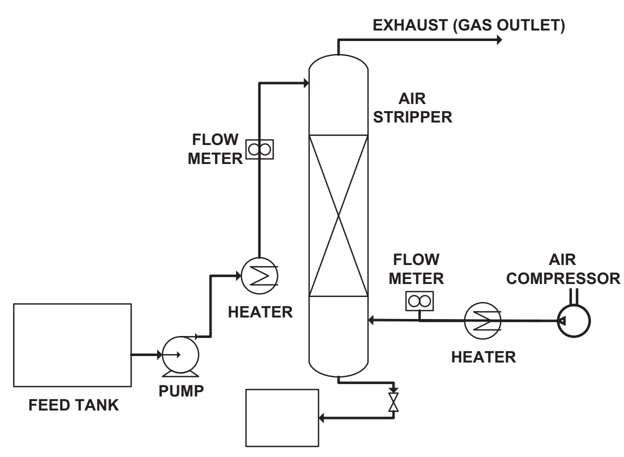


Fig. 1. PFD of the air stripping process.

Lambda 25). BTX removal efficiencies (η) of the air stripper were calculated:

$$\text{Efficiency} = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100\ (\%) \quad (1)$$

where C_{in} and C_{out} are VOC concentrations in influent and effluent water in ppm, respectively.

3. Results and discussion

The percentage removal of the contaminant is used to evaluate the efficiency of the air stripper. Figs. 2 and 4 represent the experimental results showing the performance removal efficiencies of BTX at the temperature range of 20–50˚C and air-water ratios of 20–100. The results show that for the various combinations of temperature and air-water ratio, removal efficiencies of between 84% to above 99, 85–93 and 79–93% were obtained for BTX, respectively. The high removal efficiencies speak favourably for the air stripping system. Other studies have reported similar results of high VOC removal efficiencies using air stripping as shown in Table 1. Samadi et al. compared the performance of air stripper to granulated activated carbon (GAC) in the removal of chloroform from Tehran drinking water. The average of variations of removal efficiencies for air stripper and GAC columns with deionized water samples were, 90, 71% and for chlorinated Tehran tap water were 91 and 76%, respectively [21]. This result shows that air stripper is more effective in chloroform removal.

3.1. Comparison of removal efficiencies of BTX

The transfer of VOCs in air stripping is not only affected by the system variables such as temperature, air flow rate and column height but is also a function of the physical chemistry of the contaminants. The removal efficiencies of BTX depend on physical

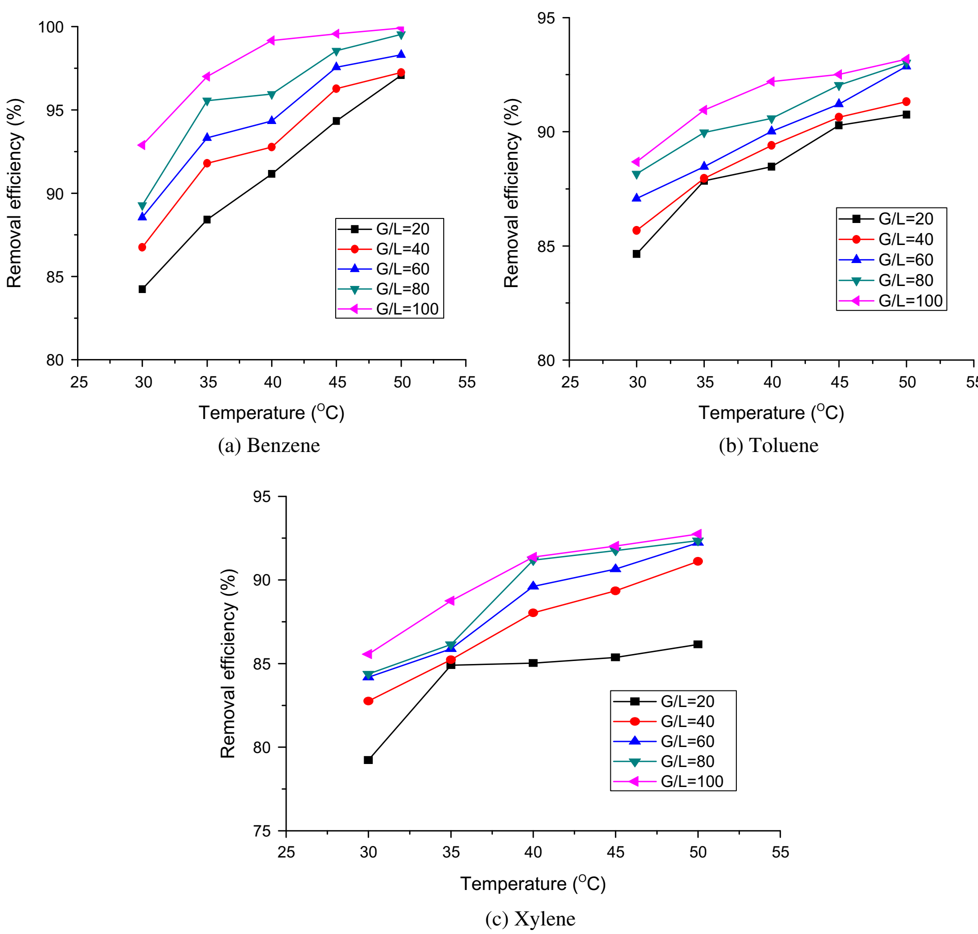


Fig. 2. Effect of temperature on BTX removal efficiency.

Table 1
Removal efficiency of air stripping for various VOCs

Compound	Removal efficiency (%)	Reference
Chlorobenzene	99	[19]
Chloroform	87	[21]
1,2–dichloroethane (DCE)	>90	[22]
1,2-dibromo-3-chloropropane	89–96	[23]
1,1,1-trichloroethane (TCE)	99	[24]
1,1,2,2-tetrachloroethane	94–98	[24]

properties such as Henry's constant, enthalpy of hydration (heat of solvation) and vapour pressure [25]. In general air stripping of VOCs occurs through volatilization which may be induced by mechanical surface aeration. The process of removal of dissolved gas from liquid proceeds through the following consecutive steps [26];

(1) transfer from the bulk fluid to the interface;
(2) transfer across the interface; and
(3) transfer away from the interface into the bulk of new phase.

The rate of mass transfer of a VOC from wastewater to the atmosphere across an air-wastewater interface (dM/dt) can be described by the following equation [26,27].

$$\frac{dM}{dt} = -K_{\mathrm{La}}\left(\frac{C - C_g}{H}\right) A \tag{2}$$

where K_{La} is the overall mass transfer coefficient (s^{-1}), C is VOC concentration (g/m^3), C_g is the gas phase VOC concentration (g/m^3), H is Henry's constant (atm) and A is surface area (m^2). K_{La} increases with temperature. Compounds with Henry's constant value greater than 0.001 atm m^3/mole are considered volatile and amenable to air stripping.

It can be observed from the result that the order of removal efficiency was benzene > toluene > xylene. The removal efficiencies of BTX at 30˚C and G/L = 20 are 84, 84 and 79%, respectively, while at 50˚C and G/L = 100 the removal efficiencies are > 99%, > 93% and 93%, respectively. Henry's constants for BTX are similar: 0.25, 0.286 and 0.32, respectively. The observed trend in removal efficiency can be attributed to the high vapour pressure of benzene (12.64 kPa at 25˚C) compared to that of toluene and xylene, 3.79 and 0.88 kPa at 25˚C, respectively [28,29]. When more than one VOC is found in a wastewater supply system, air stripping is designed to treat the least volatile compound to a level below the regulatory contaminant concentration. At this level, it is expected that the more volatile components would have been stripped off earlier since the partial pressure of each compound provides the driving force for its volatilization. As remarked, the distribution of a VOC between the aqueous solution phase and air is influenced by its enthalpy of hydration. This explains why benzene with a lower enthalpy of hydration value of 28 kJ/mol was stripped off faster than toluene and xylene with enthalpy of hydration values of 37 and 32.4 kJ/mol, respectively.

3.2. Effect of temperature on BTX removal efficiency

The effect of temperature on BTX removal efficiency was studied at a temperature range of 20–50˚C and air-water ratio of 20–100 as represented by Fig. 2(a)–(c) for BTX, respectively. It is demonstrated that BTX removal efficiency increases with the temperature at all air-water ratios.

The results are in agreement with other findings [18,19,30]. Henry's constant plays an important role for the removal process [16]. The temperature dependence of the Henry's constant is modelled by the Van't Hoff-type relation [26].

$$\log(H) = \left(\frac{-\Delta H^{\circ}}{RT}\right) + C \tag{3}$$

where T is temperature, $-\Delta H^{\circ}$ is enthalpy change, R is universal gas constant and C is a constant of Van't Hoff's equation.

The decrease in the solubility of organic compounds in water as the temperature increases can be explained using the second law of thermodynamics [30]. The vapour pressure of various substances increases with the temperature. The rate of increase also increases with temperature. If it is assumed that the effect of temperature on Henry's constant is due almost entirely to changes in vapour pressure, the relationship between Henry's constant and temperature can be approximated by Clausius–Clapeyron equation:

$$\ln\left(\frac{H_1}{H_2}\right) \approx \ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_v}{R}\ \left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{4}$$

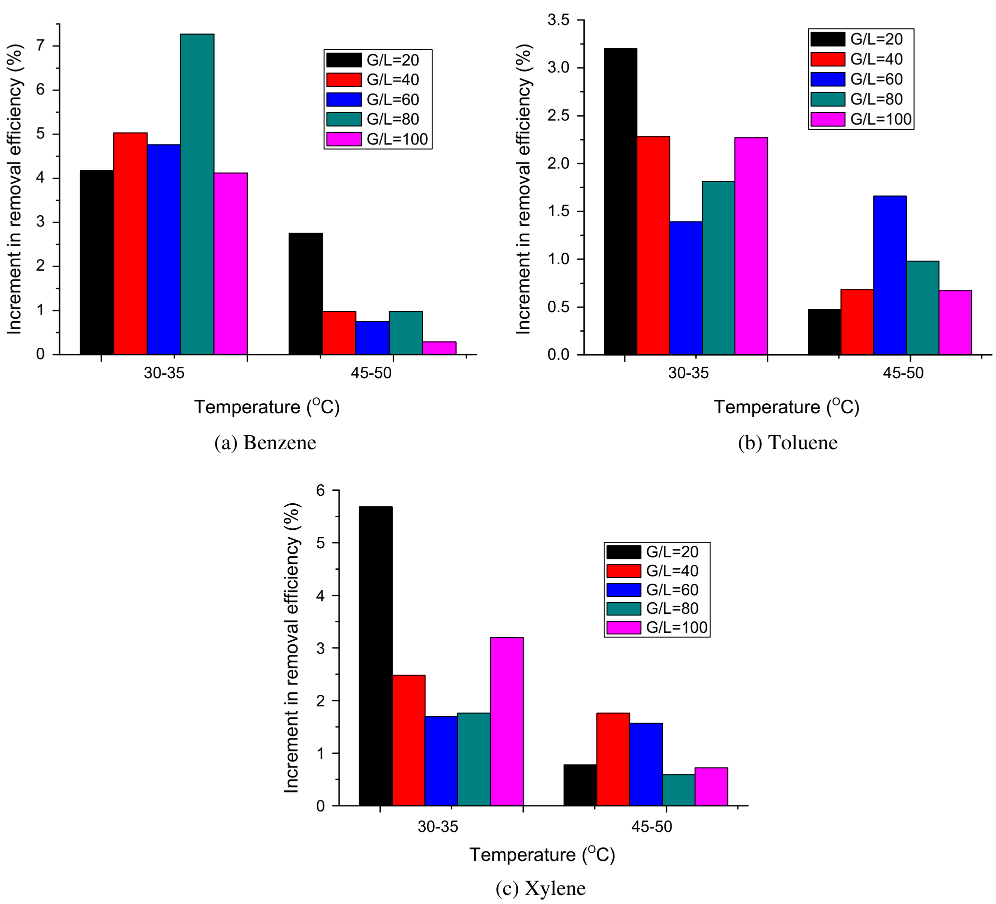
where H is Henry's constant, T is temperature, R is universal gas constant, P is pressure, ΔH_v is enthalpy change and 1,2 denotes initial and final conditions. Bass and Sylvia reported that the Henry's constant for methyl tert-butyl ether is doubled by a 17˚C temperature increase, from 12 to 29˚C [31]. Therefore, heating the wastewater by this amount before treatment would reduce the stripping air requirement by half.

Fig. 2 also demonstrates that the percentage removal of BTX at higher temperatures and high G/L ratios will approach an equilibrium condition. This is due to the combined effect of high temperature and G/L ratio which result in accelerated BTX removal. This is similar to the results obtained by Chuang et al. and Lin et al. [18,19]. Furthermore, the effect of increase in temperature on BTX removal efficiency is observed to be more significant at low temperature conditions (30–35˚C) than at higher temperature conditions (45–50˚C) as shown in Fig. 3(a)–(c). This non-linear trend in the effect of temperature on VOC removal has been reported by Lin et al. in the research on chlorobenzene removal efficiency using air stripper [19]. They concluded that temperature change at higher temperature range in the stripping of chlorobenzene does not significantly influence the stripping efficiency. Also, this situation occurred because the optimum removal efficiency is reached due to the combined effect of high temperature and high air-water ratio [18].

3.3. Effect of air-water ratio on BTX removal efficiency

Air flow rate is the most important operating parameter in air stripping. The entire principle is based on maximizing the contact surface area between the water and air [17]. Air flow rate also affects the overall mass transfer coefficient and the removal efficiency increases with increase in overall mass transfer coefficient. Lin et al. reported that the air flow rate is directly proportional to the overall mass transfer coefficient [19]. Obviously the total air-water interface surface area is proportional to the number and size of the air bubbles. An increase in air flow rate will result in an increase in the overall mass transfer coefficient values.

The effects of air-water on percentage removal efficiency were studied at air-water ratio range of

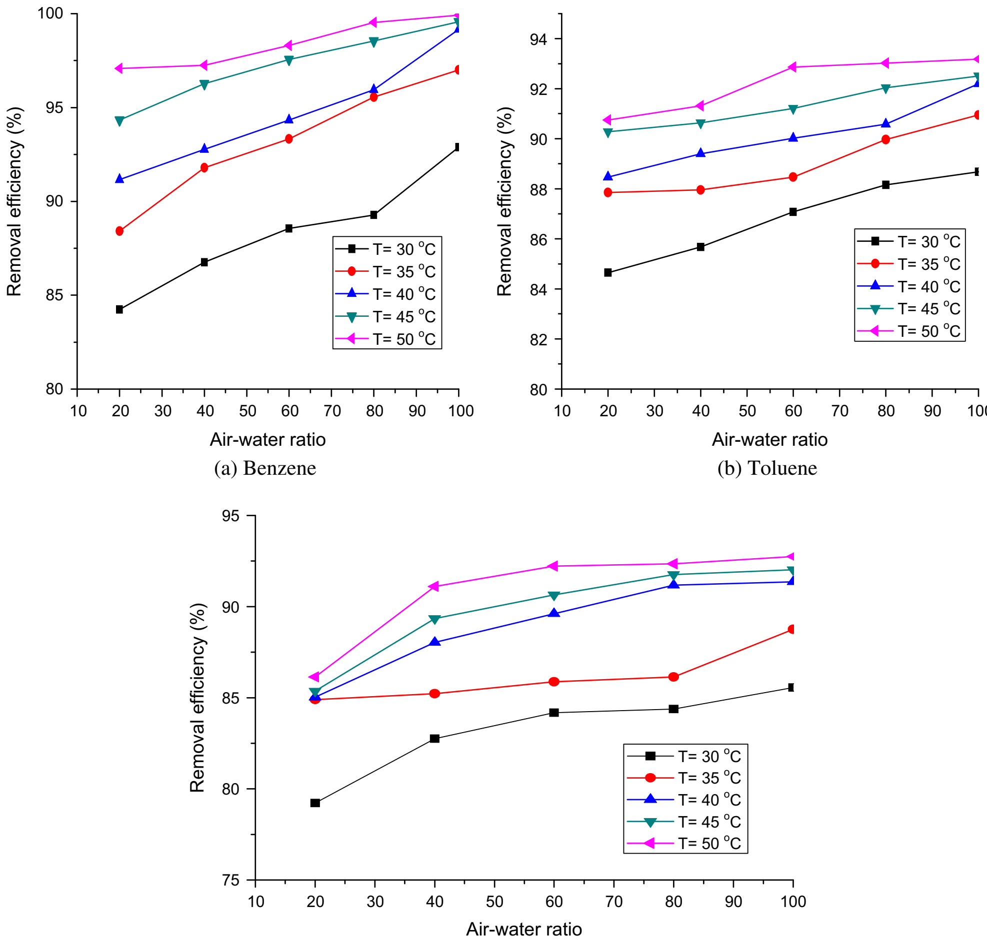


(a) Benzene

(b) Toluene

(c) Xylene

Fig. 3. Changes in percentage removal efficiency with temperature.



(a) Benzene (b) Toluene

(c) Xylene

Fig. 4. Effect of air-water ratio on the percentage removal efficiency.

20–100 and at temperatures of 20–50˚C as shown in Fig. 4(a)–(c). The figures show an increase in the removal efficiencies of the three compounds with an increase in the air-water ratio at all temperatures. Another effect of increased air-water ratio is it causes a decrease in partial pressure of the solute in the gas phase, decreases its solubility and improves its removal efficiency [14,18,30].

The differences in percentage removal efficiency become smaller with increasing of air-water ratio, particularly at 40–50˚C. Hence, the effect of an increase in G/L ratio on the percentage removal of BTX is more significant at low G/L ratios (20–60) than at higher water-air ratios (80–100), thus revealing a non-linear trend in the effect of temperature and air-water ratio on BTX removal. According to Lin et al., this could be attributed to the non-linear increasing of interfacial area as the air flow rate increases [19]. Frequent bubble collision at higher air flow rate condition will increase the diameter of air bubbles during the air stripping; as a result, the interfacial area does not linearly increase with an increase in air flow rate.

Fig. 4 also indicates that a high removal of BTX can be achieved by operating the air stripper at high temperature condition even at a relatively lower G/L ratio. Similarly, high percentage removal can also be achieved by stripping at high G/L ratio at relatively lower temperature. These observations are fundamental for the design and operation of air stripping system to minimize operation cost. It is possible to save the cost of heating the system by operating at a higher air flow rate to obtain high percentage removal efficiency. However, excessive air flow rate prevents water from flowing down the packed column resulting in accumulation of the water at the top of the packing. This phenomenon is called "flooding" and the air flow rate at this point is called "flooding velocity". The pressure drop in the tower should be between 200 and 400 N/m^2 per metre of the tower to height to avoid flooding [32].

4. Conclusions

The effects of temperature and air-water ratio on the on the removal efficiency of BTX from wastewater using packed column air stripper was studied at a temperature range of 30–50˚C and air-water ratios of 20–100. It can be concluded that high percentage removal of BTX can be achieved by stripping at high temperature condition even at relatively lower G/L ratio. Also, high percentage removal of BTX can be achieved by stripping at high G/L ratio even at relatively lower temperature. This relationship is important for both design and operation of an air stripper in order to minimize the operation cost. The physical properties of each contaminant also determine its ease of removal from wastewater using air stripper. The physical parameters can explain the size of removal efficiency, where benzene > toluene > xylene. The effect of increase in temperature on the percentage removal of BTX is more significant at low temperatures (30–35˚C) than at higher temperatures (45–50˚C). Also, the effect of an increase in G/L ratio on BTX removal is less significant at higher G/L ratios (80–100) than at low G/L ratios (20–60) particularly at high temperatures. This reveals a non-linear trend in the effect of temperature and air-water ratio on BTX removal.

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References

[1] M.P. Abdullahi, S.S. Chian, Chlorinated and non-chlorinated volatile organic compounds (VOCs) in drinking water of Peninsular Malaysia, Sains Malaysiana 40 (2011) 1255–1261.

[2] J.S. Zorgoski, J.M. Carter, T. Ivahnenko, W.W. Laphan, M.J. Moran, B.L. Rowe, P.L. Squillace, P.L. Toccalino, The quality of nation's water—Volatile organic compounds in the nation's ground water and drinking water supply wells, US Geol. Surv. Circular 139 (2006) 101–102.

[3] M. Sanchez, S. Karnae, K. John, Source characterization of volatile organic compounds affecting the air quality in a coastal urban area of South Texas, Int. J. Environ. Res. Public Health 5 (2008) 130–138.

[4] S. Navaladian, C.M. Janet, B. Viswanathan, R.P. Viswanath, On the possible treatment procedure for organic contaminants, Res. Signpost 37/661 (2007) 1–51.

[5] X. Font, A. Artola, A. Sanchez, Composition and treatment of volatile organic compounds from waste treatment plants, Sensors 11 (2011) 4043–4059.

[6] K. Mourad, R. Berndtsson, W. Abu-El-Sha'r, M.A. Qudah, Modeling tool for air stripping and carbon adsorbers to remove trace organic contaminants, Int. J. Therm. Environ. Eng. 4 (2012) 99–106.

[7] Y.C. Kuo, S.F. Cheng, P.W.G. Liu, H.Y. Chiou, C.M. Kao, Application of enhanced bioremediation for TCE-contaminated groundwater: A pilot-scale study, Desalin. Water Treat. 41 (2012) 364–371.

[8] S.M. Yakout, A.A.M. Daifullah, Removal of selected polycyclic aromatic hydrocarbons from aqueous solution onto various adsorbent materials, Desalin. Water Treat. 51 (2013) 6663–6675.

[9] V. Naddeo, M. Landi, D. Scannapieco, V. Belgiorno, Sonochemical degradation of twenty-three emerging contaminants in urban wastewater, Desalin. Water Treat. 51 (2013) 6601–6608.

[10] Y.A. Mustafa, A.H. Shihab, Removal of 4-chlorophenol from wastewater using a pilot-scale advanced oxidation process, Desalin. Water Treat. 51 (2013) 6663–6675.

[11] O.Y. Garba, Separation of volatile organic compounds (BTEX) from aqueous solutions by a composite organophilic hollow fiber membrane-based pervaporation process, J. Membr. Sci. 319 (2008) 82–90.

[12] A.M. Vandenbroucke, R. Morent, N.D. Geyter, C. Leys, Non-thermal plasmas for non-catalytic and catalytic VOC abatement, J. Hazard. Mat. 195 (2011) 30–54, doi:10.1016/j.jhazmat.2011.08.060.

[13] D.M. Foster, A.J. Rachwal, S.L. White, New treatment processes for pesticides and chlorinated organics control in drinking water, Water Environ. J. 5 (1991) 466–476.

[14] R. Alam, M.D. Hossain, Effect of packing materials and other parameters on the air stripping process for the removal of ammonia from the wastewater of natural gas fertilizer factory, J. Water Res. Prot. 1 (2009) 210–215.

[15] M.A. El-Behlil, S.A. Adma, Volatile organic chemicals removal from contaminated water using low profile sieve tray air stripping towers, Int. Water Tech. J. 2 (2012) 164–176.

[16] M.A. El-Behlil, S.M. El-Gezawi, S.A. Adma, Simplified packed tower calculation for the removal of VOCs from contaminated water, IWTC, Istanbul, Turkey, Seventeenth International Water Technology Conference (2012) 1–18.

[17] S. Kutzer, H. Wintrich, A. Mersmann, Air stripping—A method for treatment of wastewater, Chem. Eng. Tech. 18 (1995) 149–155.

[18] K.T. Chuang, S. Cheng, S. Tong, Removal and destruction of benzene, toluene, and xylene from wastewater by air stripping and catalytic oxidation, Ind. Eng. Chem. Res. 31 (1992) 2466–2472.

[19] M. Lin, Z. Zhao, F. Cui, Y. Wang, S. Xia, Effects of initial chlorobenzene concentration, air flowrate and temperature on mass transfer of chlorobenzene by air stripping, Desalin. Water Treat. 40 (2012) 215–223.

[20] A.J. Tóth, F. Gergely, P. Mizsey, Physicochemical treatment of pharmaceutical process wastewater: Distillation and membrane processes, Periodica Polytechnica 55/2 (2011) 59–67.
[21] M.T. Samadi, S. Nasseri, A.R. Mesdaghinia, M.R. Alizadefard, Removal of chloroform ($CHCl_3$) from Tehran drinking water by GAC and air stripping columns, Iranian, J. Environ. Health Sci. Eng. 1 (2004) 5–12.
[22] D.P. Harrison, K.T. Valsaraj, D.M. Wetzel, Air stripping of organics from ground water, Waste Manage. 13 (1993) 417–429.
[23] N. Nirmalakhandan, R.E. Speece, J.L. Peace, W. Jang, Operation of counter-current air-stripping towers at higher loading rates, Water Res. 27 (1993) 807–813.
[24] W.D. Byers, C.M. Morton, Removing VOC from groundwater; pilot, scale-up, and operating experience, Environ. Progr. 4 (1985) 112–118.
[25] D.R. Lide, CRC Handbook of chemistry and physics, 9th ed., CRC Press, Taylor and Francis group, New York, NY, 2010, pp. 586–589.
[26] J.M. Montgomery, Water Treatment Principles and Design, John Wiley and sons, New York, NY, 1985, pp. 237–261.
[27] D.W. Hand, D.R. Hokanson J.C. Crittenden, Gas-liquid Processes: Principles and Application in Water Quality and Treatment, A Handbook on Drinking Water, American Water Works Association, Mc Graw-Hill, New York, NY 2011, pp. 6.1–6.63.
[28] J. Lin, M. Chou, Henry's law constant variations of volatile organic compounds in wastewater and activated sludge, Aerosol Air Qual. Res. 6 (2004) 180–192.
[29] K. Sieg, E. Fries, W. Püttmann, Analysis of benzene, toluene, ethylbenzene, xylenes and n-aldehydes in melted snow water via solid-phase dynamic extraction combined with gas chromatography/mass spectrometry, J. Chromatogr. A 1178 (2008) 178–186.
[30] F. Zareei, A.A. Ghoreyshi, Modeling of air stripping-vapour permeation hybrid process for removal VOCs from wastewater and VOCs recovery, World App. Sci. J. 13 (2011) 2067–2074.
[31] D.H. Bass, T.E. Sylvia, Heated Air Stripping for the Removal of MTBE from Recovered Ground Water, Groundwater Technology Inc., 1992, pp. 17–26.
[32] A. Srinivasan, P. Chowdhudry, T. Viraraghavan, Air Stripping in Industrial Wastewater in Water and Wastewater Treatment Technologies, vol. 1, UNESCO and EOLSS, London, 2011, pp. 88–110.