International Biodeterioration & Biodegradation 109 (2016) 96–103

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

journal homepage: www.elsevier.com/locate/ibiod

Benzene control from waste gas streams with a sponge-medium based rotating biological contactor

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ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form
13 January 2016
Accepted 14 January 2016
Available online 1 February 2016

Keywords:
Rotating biological contactor
Gaseous benzene
Biodegradation
Sponge medium
Enterobacter sp.
Kinetics

ABSTRACT

Rotating biological contactors (RBCs) are low-cost, efficient and an eco-friendly volatile organics control technique. In this study, a state-of-art disk-based RBC has been modified to a drum-based with sponge supporting medium and its performance at different inlet loading rates (ILR) of gaseous benzene, and its effect on elimination capacity (EC) and removal efficiency (RE) have been investigated. The results showed that the RE remained over 90% up to the ILR of about 8 g m^{-3} h^{-1}, and decreased to about 80% with the further increase in ILR. The EC reached maximum to about 45 g m^{-3} h^{-1} at a benzene load of about 69 g m^{-3} h^{-1}. The EC of benzene increased with the increase in loading rate, but the RE showed an opposite trend. The production of carbon dioxide, which determines the degree of pollutant degradability, also increased with the increase in EC. Along with benzene the nutrients (NH_3–N and PO_4–P) from liquid phase also got removed in RBC, which shows its potential application in industries. Furthermore, a potential benzene degrader was tentatively identified as genera *Enterobacter*. The maximum biodegradation rate (r_{max}) and half saturation constant (K_s) were determined as 21.46 g m^{-3} h^{-1} and 1.71 g m^{-3}, respectively.

1. Introduction

Gaseous volatile organic compounds (VOCs) are released in large quantity from industries. VOCs participate in atmospheric photochemical reactions and contribute to ozone, which is harmful to the ecosystem (Padhi and Gokhale, 2014). Benzene, toluene, ethylbenzene, and xylene (BTEX) are widely found VOCs. Benzene is more carcinogenic and classified as a hazardous compound by United States Environmental Protection Agency (USEPA) (Singh and Fulekar, 2010). Exposure to benzene is a global environmental problem due to its several short-term and long-term health effects, which include from dizziness, eye irritation to asthma, cancer, liver and kidney damages (MDH, 2010).

VOCs are conventionally treated with several physico-chemical methods. Most of which have direct or indirect environmental consequences as these methods consume more raw materials and produce a large amount of wastes, which degrade the environment (Padhi and Gokhale, 2014). The application of biodegradation techniques for industrial VOCs treatment has become popular because they overcome the drawbacks of physico-chemical methods, are economical and environment friendly (Rene et al., 2015). A few researchers applied biodegradation methods to control VOCs from industries (Datta and Philip, 2012), which included various bioreactors such as biofilter (Mathur and Majumder, 2008; Swissa et al., 2015), biotrickling filter (Cox and Deshusses, 2002), bioscrubber (Lo and Hwang, 2004), membrane bioreactor (Fitch et al., 2003), and suspended cell bioreactor (Ensley and Kurisko, 1994). These methods are simple, eco-friendly and have limitations of poor oxygen mass transfer due to restriction of forced aeration and of mixing due to the volatility of compounds, which make treatment difficult (Mudliar et al., 2008). Novel bioreactors overcome some of the drawbacks and limitations of the conventional methods (Mudliar et al., 2010). RBC is one of such bioreactors, which offers scope for modification in its design, materials and operating parameters to provide higher removal efficiency (Padhi and Gokhale, 2014). Mixed microbial consortium from activated sludge was used in RBC to biodegrade VOCs such as dichloromethane (Ravi et al., 2015). The activated sludge from wastewater treatment plant contains a wide variety of organisms, which biodegrade a range of pollutants (Wagner et al., 2002). Microorganisms play major role in mineralization, transformation and immobilization of pollutants (Díaz, 2004). Microorganisms are

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http://dx.doi.org/10.1016/j.ibiod.2016.01.007
0964-8305/

inhibited at high substrate concentrations and are starved at low substrate concentrations (Singh and Fulekar, 2010). Therefore, optimization of the underlying biodegradation process is of interest to researchers.

RBC was originally developed for treating wastewaters. Gai et al. (2001) used a rotary trickle-bed reactor for waste gas treatment. Due to rotation, RBCs prevent excess biomass accumulation occurring in traditional biofilters (Ravi et al., 2010). Yang et al. (2004) used a bioreactor containing activated sludge with a rotating drum process for treating toluene. Later, Yang et al. (2008) developed a multilayer rotating drum biofilter (RDB) for treating diethyl ether, which showed high removal efficiency even at higher organic loading rate by utilizing nutrients from a liquid phase. RBCs, due to the advantage of continuous removal of biomass, can be operated longer without increasing the pressure drop (Datta and Philip, 2014). Literature is scarce on the use of RBC for gaseous VOCs control (Vinage and von Rohr, 2003). Moreover, no study is found on the treatment of gaseous benzene using RBC.

In this study, an RBC has been developed, which unlike the existing RBCs uses open-pore reticulated polyurethane sponge mounted over a perforated drum to support the uniform growth of biofilm layer. The main goal has been to investigate its performance for treating gaseous benzene at different inlet loading rates (ILR), study its effect on elimination capacity (EC) and removal efficiency (RE). Further, the effect of production of carbon dioxide (Pco_2) on EC, and removal of the nutrients (ammonical nitrogen (NH_3–N) and phosphorus (PO_4–P)) has also been examined in RBC to prove its potential in removing gaseous benzene and nutrients simultaneously.

The work involved the design and installation and operation of RBC, measurement and analysis of gaseous benzene, CO_2, biomass, and nutrients, and then performance evaluation of the RBC followed by isolation of benzene degrading microorganisms and determination of the kinetic constants for benzene.

2. Materials and methods

2.1. Design and installation of RBC

The RBC built was a closed chamber with a rotating contactor consists of perforated drum supported by a sponge medium. The chamber was made of 6 mm perspex sheet of length of 410 mm, width 400 mm and height 400 mm with a working volume of 0.0656 m^3 (65.6 L). For the convenience of cleaning, one side of the chamber could be opened was bolted with the remaining part by placing butyl rubber gaskets in between them to ensure it airtight. The sponge medium of volume 0.008 m^3 was mounted concentrically over the drum to support the biofilm growth. The drum was closed by disks at both ends, and was placed horizontally in the center of the chamber with the help of stainless steel hollow shaft. The shaft at its one side was coupled with a geared motor having a speed controller and the other side was connected to the air outlet chamber. The shaft rotates the drum at 2 rpm along with the supporting medium during operation. The inlet and outlet ports were provided for feeding and discharge of mineral salt medium (MSM) by a peristaltic pump. Similar inlet and outlet ports were provided for sampling of gaseous benzene. Fig. 1 shows the schematic of the laboratory scale RBC with important components.

2.2. Operation of RBC

The MSM was continuously supplied to the RBC at a flow rate of 5.1 L d^{-1} and discharged with the same flow rate at the outlet. The 26% of the sponge medium was kept submerged in the nutrient solution. The air stream was divided into major and minor air streams to connect to the mixing chamber and to the impinger, respectively. The waste gas containing benzene was generated from the impinger at NTP and connected to the mixing chamber. Two rotameters, each for the major and minor streams, were used to control the total flow rate of air between 0.121 m^3 h^{-1} and 0.545 m^3 h^{-1} to get an empty bed contact time (EBCT) of 12.44–2.75 min, respectively. The waste gas containing benzene entered the reactor through the air inlet port and released at the bottom of RBC through air diffusers. The gaseous benzene was absorbed partly into the nutrient medium, and suspended cell biodegradation (SCB) occurred. The unabsorbed benzene passed through the supporting medium, wherein the biofilm grew, to exit through the hollow shaft into the outlet chamber. The samples from the air inlet and outlet ports were collected every 24 h by scrubbing in methanol (10 ml methanol for 1 min) at different loading rates and concentrations were analyzed by using gas chromatography (GC) with flame ionization detector (FID) as described by Pandey et al. (2007). Magnetic stirrer was used to provide uniform mixing of biomass in the liquid medium of RBC and a U-tube manometer (in cm of H_2O) was attached to measure the pressure drop.

2.3. Seeding and medium

The source of mixed biomass was activated sludge obtained from a wastewater treatment plant of Indian oil corporation, Guwahati, which was used as an inoculum in RBC for treatment of benzene in the waste gas stream. Table 1 shows the characteristics of the activated sludge with the presence of macro and micro nutrients such as carbon, nitrogen, phosphorus, sulfate, and specific benzene degraders as well. The MSM was prepared with the constituent (g l^{-1} of water):- K_2HPO_4 (0.8), KH_2PO_4 (0.4), $(NH_4)_2SO_4$ (1), $MgSO_4 \cdot 7H_2O$ (0.5), $CaCl_2$ (0.125), $FeSO_4$ (0.01), $NaHCO_3$ (0.048), H_3BO_3 (0.0225), $ZnSO_4 \cdot 7H_2O$ (0.06), $NiCl_2$ (0.018), $CuSO_4 \cdot 5H_2O$ (0.0025), $MnSO_4$ (0.0375), and $COCl_2$ (0.014). These chemicals were of the analytical grades of 99.5–99.8% purity and the pH of the MSM was 6.95 ± 0.05.

2.4. Measurements and analysis

2.4.1. Benzene and CO_2

Benzene concentration was determined by gas chromatography (Model – GC Dhruva, Chromatography and Instruments Company, Vadodara, India), equipped with a capillary column BPX 70 (30 m × 0.32 mm × 0.25 μm) and a flame ionization detector. The temperature of the injector, oven, and detector was maintained at 210 °C, 60 °C, and 230 °C, respectively (Mathur et al., 2007). The hydrogen gas was used as the fuel and nitrogen gas as the carrier at a flow rate of 30 ml min^{-1}. A calibration curve was prepared by injecting a known amount of benzene in methanol at different concentrations into a sealed bottle with Teflon septum and was analyzed by gas chromatography. This curve was used to determine benzene concentrations in samples. The CO_2 concentrations were measured by an automatic CO_2 analyzer (TSI, IAQM-7545) at air inlet and outlet ports of the RBC. The concentrations reported were the average of two replicates (n = 2).

2.4.2. Nutrients

The $(NH_4)_2SO_4$, and K_2HPO_4 and KH_2PO_4 were the sources of nitrogen and phosphorus, respectively. The concentrations of ammonical nitrogen (NH_3–N), nitrite (NO_2–N), nitrate (NO_3–N), and phosphorus (PO_4–P) of effluent liquid were determined at steady state. The effluent liquid sample was centrifuged at 10,000 rpm for 5 min, and the supernatant was used for the analysis. The analyses of these nutrients were carried out as per