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Start-up, performance and optimization of a compost biofilter treating gas-phase mixture of benzene and toluene

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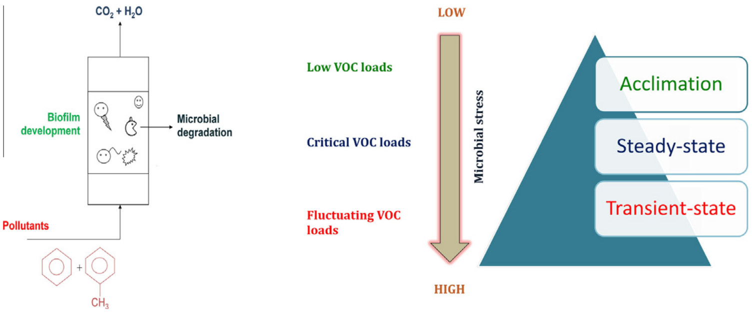
HIGHLIGHTS

- Compost biofilter was exposed to steady and transient state operations.
- Maximum elimination capacity was 91.2 g/m^3 h at a total inlet load of 150.2 g/m^3 h.
- The presence of toluene inhibited benzene removal strongly at higher loading rates.
- Main effects of process variables were statistically significant with low *P* values.
- After prolonged periods of starvation, the biofilter was able to convalesce.

GRAPHICAL ABSTRACT



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ABSTRACT

The performance of a compost biofilter inoculated with mixed microbial consortium was optimized for treating a gas-phase mixture of benzene and toluene. The biofilter was acclimated to these VOCs for a period of ~18 d. The effects of concentration and flow rate on the removal efficiency (RE) and elimination capacity (EC) were investigated by varying the inlet concentration of benzene (0.12–0.95 g/m^3), toluene (0.14–1.48 g/m^3) and gas-flow rate (0.024–0.072 m^3/h). At comparable loading rates, benzene removal in the mixture was reduced in the range of 6.6–41% in comparison with the individual benzene degradation. Toluene removal in mixture was even more affected as observed from the reductions in REs, ranging from 18.4% to 76%. The results were statistically interpreted by performing an analysis of variance (ANOVA) to elucidate the main and interaction effects.

1. Introduction

Benzene and toluene constitutes among the major volatile organic compound (VOC) fraction that gets released into the atmosphere from various industrial activities leading to ozone depletion and global warming (Balasubramanian et al., 2012). The overall European Union continental air emission rate of benzene and toluene are 79 and 976 Kt per year which constitutes roughly ~0.02% and 3%, respectively, of the total non-methane VOCs emitted annually (EURAR, 2007, 2003). Although they constitute less percentage of total non-methyl emissions, they are significant from a health and environmental viewpoint. World Health Organization recommends the air quality guidelines with permissible limit of

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260 μg/m^3 for toluene (WHO, 2000), while the European Union legislation stipulates 5 μg/m^3 in air as the permissible limit for benzene (EURAR, 2008). These VOCs are not only toxic to human health but they can also be a potent carcinogen and/or exhibit mutagenic properties (Gallastegui et al., 2011).

The removal of individual VOCs from contaminated air streams has been a subject of many research studies, wherein either chemical or biological or a combination of both the techniques have been proposed (Chang et al., 2011; Chan and Lai, 2008; Li et al., 2012; Singh et al., 2006). Chemical based techniques for treating VOCs have proven to be expensive due to its high maintenance, energy and operational costs (Mudliar et al., 2010). Biological techniques are not only economically efficient and environment friendly for treating VOCs at low concentrations and high flow rates, but they also produce innocuous end-products. Although different bioreactor configurations have been proposed so far, biofilter is the most commonly used and successful reactor for industrial applications (Devinny et al., 1999; Rene et al., 2012). They generally use filter bed matrices which are either readily available or considered as secondary product of other industries (Saravanan and Rajamohan, 2009). Concerning the efficacy of the biomass used in a biofilter to mineralize the VOCs, a recent study has proved that bacteria based biofilters are more efficient than fungi inoculated biofilters due to the presence of a highly diversified population of microorganisms (Estrade et al., 2013). The success and longevity of biofiltration primarily depends on the kinetics of micro processes such as absorption, adsorption, diffusion and biodegradation.

In previous studies, two compost biofilters were studied for the long-term removal (~8 months) of gas-phase benzene and toluene as an individual pollutant, wherein a maximum elimination capacity (EC) of 128 and 65 g/m^3 h was observed at inlet loading rates (ILR) of 263 and 125 g/m^3 h, respectively (Rene et al., 2005, 2010). However, while treating mixtures, interaction effects between pollutants can play an important role in both mass transfer and biodegradation steps of the biofiltration process leading to somewhat reduced removal efficiencies of the target pollutants (Gallastegui et al., 2013; McNevin and Barford, 2000). With the advent of various statistical and computational modeling procedures, biofilters can be optimized for their performances when mixture of VOCs is present in the contaminated air stream (Saravanan et al., 2013). Computational Fluid Dynamics (CFD) based techniques have been also been successfully tested to predict complex interactions between benzene concentration profile along the bed height and biological reactions in a biofilter (Rahul et al., 2012).

The main objective of this research was to evaluate the steady-state removal efficiency (RE) of gas-phase benzene and toluene mixture at different inlet concentrations and gas-flow rates in a lab scale compost biofilter that was previously used to treat benzene (Rene et al., 2010). The inlet concentration of benzene (0.12–0.95 g/m^3), toluene (0.14–1.48 g/m^3) and gas-flow rate (0.024–0.072 m^3/h) were varied from low to high levels according to 2^3 full-factorial design of experiment. The resilience capacity of the biofilter was tested by subjecting the biofilter to prolonged periods of non-use (30 d). The results were statistically analyzed using Analysis of Variance (ANOVA) and the main and interaction effects between the different process parameters were identified.

2. Methods

2.1. Chemicals used

All the chemicals used in this study were of laboratory grade, purchased from Ranbaxy Fine Chemicals Limited, India.

2.2. Microorganism and medium composition

Mixed microbial consortium obtained from a sewage treatment plant was used to inoculate the biofilter that was tested previously for removing benzene vapors (Rene et al., 2010). The nutrient solution (pH – 6.85) had the following composition (in g/L); K_2HPO_4 – 0.8, KH_2PO_4 – 0.2, $CaSO_4 \cdot 2H_2O$ – 0.05, $MgSO_4 \cdot 7K_2O$ – 0.5, $(NH_4)_2SO_4$ – 1.0 and $FeSO_4$ – 0.01 in distilled water.

2.3. Experimental setup

Fig. 1 illustrates the schematic of the experimental setup. The biofilter was made of poly acrylic tubes (5 × 70 cm) having sampling ports that were placed equidistantly along the biofilter height and sealed with a rubber septa. The packing material consisted of sieved compost (3–6 mm) and ceramic beads (4–6 mm) mixed in a 6:4 volume ratio. The filter material, containing the mixed consortia, was loosely packed into the biofilter. The filter material, supported on a perforated plate, was packed to a height of 50 cm (bed volume – 0.98 L). 150 mL of nutrient medium was sprinkled manually, once every 3 d, from the top of the biofilter. Mixture of benzene and toluene were generated by passing a major stream of air through a humidification unit, while two minor streams of air were passed through tanks containing liquid phase benzene or toluene. The generated benzene and toluene vapors were mixed with the humidified air in a mixing chamber. Samples were collected at regular time intervals using a gas tight syringe and analyzed for residual benzene and toluene concentrations. A U-tube manometer (in cm of H_2O) was attached to the biofilter to monitor the pressure drop variations along the filter bed.

2.4. Experimental conditions for steady-state experiments

The ranges of process parameters tested in this study according to the statistically significant 2^3 full factorial design is shown in Table 1. The initial values of benzene and toluene concentration and flow rate were chosen, such that their loading rates were near equal to the critical ILR noticed previously (Rene et al., 2005, 2010). The entire design of experiments (runs 1–10) along with their corresponding RE and EC profiles of benzene and toluene is shown in Table 1. Statistical analysis in the form of ANOVA for the RE and EC of benzene and toluene was done and the RE values were compared with those observed in individual study in absence of a co-substrate. An introduction of replication of biofiltration runs (runs 9 and 10) at the center point of the experimental conditions determined the error in performing experiments (Pakshirajan et al., 2009; Rene et al., 2006). The main effects plots indicate the effect of co-substrate on the removal of the primary substrate, whereas, interaction effect plots (data not shown) reveal information about the possible interactions among the VOCs and their effect on the performance variables, namely RE and EC.

2.5. Analytical methods

Benzene and toluene concentrations in gas-phase were measured using a gas chromatograph (Model 5765, Nucon gas chromatograph, Nucon Eng. India) fitted with a poropak column (1/8″ ID, liquid – 10% FFAP, solid – Ch-WIHP, 80/100 mesh) and flame ionization detector. Nitrogen was used as the carrier gas at a flow rate of 20 mL/min. The temperatures of the injection port, oven and detection port were 150, 120 and 250 °C, respectively. The elution times were 1.1 min for benzene and 1.7 min for toluene, respectively.