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Elimination of mass transfer and kinetic limited organic pollutants in biofilters: A review

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ABSTRACT

Mass transfer and kinetic limitations are two obstacles to the removal of a pollutant from the gas phase in a biofilter (BF) or a biotrickling filter (BTF). The issue becomes more challenging when mass transfer and kinetic limitations are present especially for treatment of pollutants in mixtures. In the present study, the most common organic pollutants which may have mass transfer or kinetic limitations in BFs and BTFs are described. Accordingly, the recent studies of mass transfer limited and kinetic limited organic pollutants elimination in BFs and BTFs are reviewed. Subsequently, the most effective operating parameters for each sort of limitations are discussed. Finally, some improved bioprocesses like two liquid phase biotrickling filters, step feeding and hybrid biofilters to overcome the limitations of mass transfer and kinetic limited organic pollutants are discussed.

1. Introduction

Gaseous emissions like volatile organic components (VOCs) (e.g., benzene, styrene) or volatile inorganic components (VICs) (e.g., hydrogen sulfide (H_2S), ammonia (NH_3)) from chemical, petrochemical, pulp and paper industries contribute to air pollution (Delhoménie and Heitz, 2005). In addition, greenhouse gas emissions (GHGs) like methane (CH_4) from landfill, livestock, coal mine and wastewater treatment plants with drastic influence on climate change and global warming are also considered as air pollutants (Limbri et al., 2013; Ménard et al., 2012). In some cases, odorous components like acetic acid or ammonia (NH_3) are necessary to be removed since they have unpleasant smells (Rene et al., 2013). Pollutant's removal from gas phase is mainly based on two techniques: 1) physico-chemical and 2) biological techniques. Adsorption, absorption, condensation, incineration and plasma are some examples of physico-chemical techniques (Delhoménie and Heitz, 2005; Devinny et al., 1999; Ralebitso-Senior et al., 2012). Biological techniques are based on pollutant biodegradation by a microbial transformation into carbon dioxide (CO_2), water (H_2O), biomass, etc. (Rene et al., 2013). The initial interest in biological methods for waste gas treatment arose from their promising potential of contaminants mineralization with low secondary pollutions and disposals unlike what usually happens with other physico-chemical methods (Rene et al., 2013). Biofilter (BF), biotrickling filter (BTF) and bioscrubber are the main types of bioreactors which have been used for bioxidation of VOCs, VICs, GHGs and odor components (Iranpour et al., 2005; Veillette et al., 2012). Lab scale BFs and BTFs have been focused in several studies for pollutant inlet concentrations usually lower than 1% (v/v) and gas flow rates usually less than 1 m^3 h^{-1} (Detchanamurthy and Gostomski, 2012; Kennes et al., 2009; Kennes and Veiga, 2004). An aqueous phase (biofilm phase) and a gas phase are in contact with each other in BFs and BTFs. Therefore, the mass transfer of a target pollutant from gas to the biofilm phase as well as the pollutant's solubility in the biofilm phase are among the concerns which may affect the BF's performance (Devinny and Ramesh, 2005). For example, mass transfer limitations from gas to the biofilm phase in BFs and BTFs for pollutants like CH_4, ethylene (C_2H_4), n-hexane, toluene, styrene, xylene and α-pinene could be as a result of poor pollutant solubility in the biofilm phase (<500 g m^{-3}_{Liq} at 25 °C and 1 atm), high dimensionless Henry's law constant (>0.1 at 25 °C and 1 atm) or high vapor pressure (>5000 kPa at

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25 °C) (Kraakman et al., 2011). In contrast, components with less mass transfer limitations like alcohols, volatile fatty acids (VFAs) and ketones can be limited by the kinetics of biodegradation. In this regard, the high concentration of pollutants in the biofilm phase may increase the risk of toxicity for the biocatalysts or cause excess biomass growth and pressure drop (Rene et al., 2013). A number of studies including review articles discussed the performances of BFs and BTFs as well as operating parameters (filter bed, temperature, moisture content, etc) while paying less attention to the nature of the limitations in terms of mass transfer or kinetics (Detchanamurthy and Gostomski, 2012; Iranpour et al., 2005; Schiavon et al., 2016).

In this study, two groups of organic pollutants described as mass transfer limited and kinetic limited were selected. Subsequently, a literature review was made discussing about BFs and BTFs performance implemented for each group of pollutants usually in the last 10 years. In addition, the operating parameters that could cause problems for each group of pollutants were analyzed. Finally, the applications and limitations of BFs and BTFs for a mixture of both groups of pollutants were investigated. In this regard, some improved designs and configurations of BFs for treating simultaneously both types of the pollutants were reviewed.

2. Biofilter (BF) and biotrickling filter (BTF)

In recent years, conventional BFs have been used as the primary bioreactor configuration for waste gas biotreatment, odor removal or even as a secondary treatment stage after physical-chemical oxidation (Detchanamurthy and Gostomski, 2012; Kennes et al., 2009). In lab scale BFs, a contaminated and humidified air stream is passed through a packed bed column which has been enriched by appropriate biocatalysts (Rene et al., 2013). In the presence of oxygen, an organic pollutant, as a substrate, is biodegraded. Thus, the pollutant is converted to less hazardous materials such as CO_2, H_2O and biomass (Rene et al., 2013). The gas flow direction in a BF or BTF can be upward or downward. A solution is frequently supplied to BFs in order to provide sufficient macro and micro nutrients like nitrogen, phosphorous and potassium for the biocatalysts. Fig. 1 shows the main phenomena which occur during biofiltration. The pollutant biodegradation happens in an aqueous phase (biofilm phase). Therefore, mass transfer of pollutants from gas to liquid phase (biofilm phase) and biodegradation of the pollutant in the biofilm phase by the biocatalysts are the two main limitations for the elimination of gaseous pollutants in biofiltration (Devinny and Ramesh, 2005). The main difference between BFs and BTFs is the presence of a recirculating liquid phase in BTFs. The thickness of the biofilm phase in BFs is small enough to enhance the mass transfer of pollutants from gas into the biofilm phase (Devinny and Ramesh, 2005). The main drawback of BFs is the accumulation of biomass due to the lack of a mobile liquid phase. The mobile aqueous phase in BTFs provides an extra layer of liquid around the biofilm and represents a barrier to contaminant's mass transfer (Devinny and Ramesh, 2005). However, the mobile liquid phase in BTFs makes the control of operating parameters like pH, temperature, water content and nutrient solution easier. For instance, for treatment of H_2S with the potential of acidification, the mobile liquid phase ensures the neutral condition by the addition of buffering materials to the storage tank of recirculation liquid (Iranpour et al., 2005).

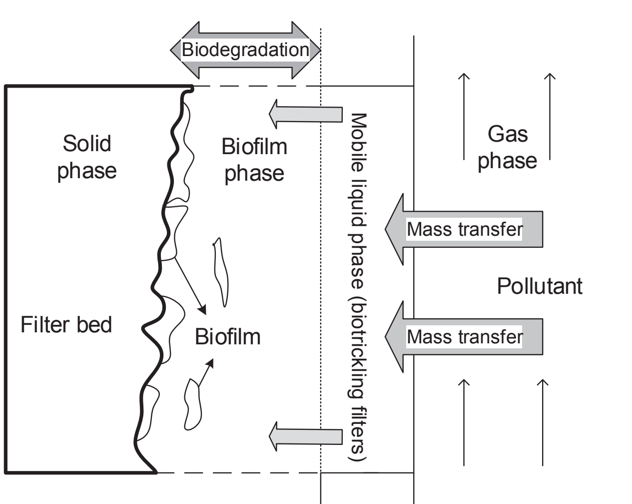

Fig. 1. The main phenomena and limitations in biofiltration and biotrickling filtration.

2.1. Performance parameters

The performance of BFs and BTFs can be illustrated by different parameters (Detchanamurthy and Gostomski, 2012):

Removal efficiency (RE)	$\frac{(C_{Gi}-C_{Go})}{C_{Gi}} \times 100$	(%)
Inlet load (IL)	$\frac{Q \times C_{Gi}}{V_f}$	(g m^{-3} h^{-1})
Elimination capacity (EC)	$\frac{(C_{Gi}-C_{Go}) \times Q}{V_f}$	(g m^{-3} h^{-1})

C_{Gi} and C_{Go} are the inlet and outlet pollutant concentrations (g m^{-3}) respectively. Q is the gas flow rate (m^3 h^{-1}) and V_f (m^3) is the volume of the biofilter.

3. Classification of organic pollutants based on their mass transfer and kinetic limitations

Different categorizations of organic pollutants have been suggested based on chemical structures of the components in order to be removed in BFs and BTFs (Kennes and Thalasso, 1998). However, classification of pollutants due to different resistances they meet in their biodegradation in a BF or BTF gives a better understanding of the limitations (Kennes and Thalasso, 1998; Muñoz et al., 2012). According to Fig. 1, pollutant's mass transfer from gas phase to the biofilm phase and kinetics of biodegradation are the two most important sorts of limitations in a biofilter. Therefore, a typical organic pollutant in a biofilter with limitations of elimination in terms of mass transfer from gas to the liquid phase is a mass transfer limited pollutant. On the other hand, a typical organic pollutant which is a potential candidate to cause kinetic limitations (e.g., inhibition, toxicity) in a biofilter is a kinetic limited pollutant. Mass transfer and kinetic limited pollutants are defined by the pollutants bioavailability in the biofilm phase in a pseudo gas-liquid equilibrium in a biofilter (Cheng et al., 2016a; Devinny and Ramesh, 2005). In this regard, mass transfer limitation results in a limited bioavailability of a typical mass transfer limited pollutant in the biofilm phase. However, excess bioavailability of a kinetic limited pollutant in the biofilm phase ends up to kinetic limitations in terms of inhibition or toxicity. The bioavailability of a typical organic pollutant can be determined by a gas-liquid equilibrium equation (Henry's law constant), chemical structure of a pollutant (solubility and miscibility with water) and the state of the pollutant (gaseous or liquid). Table 1 shows a classification on the contaminants bioavailability (in the biofilm phase) basis. Physical-chemical properties of the pollutants in terms of water solubility, dimensionless Henry's law constant and vapor pressure at 25 °C and 1 atm are listed. According to Table 1, gaseous alkanes and alkenes like CH_4 and C_2H_4, liquid alkanes like n-hexane and n-pentane, liquid