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Review

Recent progress and perspectives in biotrickling filters for VOCs and odorous gases treatment

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ABSTRACT

Pollution caused by volatile organic compounds (VOCs) and odorous pollutants in the air can produce severe environmental problems. In recent years, the emission control of VOCs and odorous pollutants has become a crucial issue owing to the adverse effect on humans and the environment. For treating these compounds, biotrickling filter (BTF) technology acts as an environment friendly and cost-effective alternative to conventional air pollution control technologies. Besides, low concentration of VOCs and odorous pollutants can also be effectively removed using BTF systems. However, the VOCs and odorants removal performance by BTF may be limited by the hydrophobicity, toxicity, and low bioavailability of these pollutants. To solve these problems, this review summarizes the design, mechanism, and common analytical methods of recent BTF advances. In addition, the operating conditions, mass transfer, packing materials and microorganisms (which are the critical parameters in a BTF system) were evaluated and discussed in view of improving the removal performance of BTFs. Further research on these specific topics, together with the combination of BTF technology with other technologies, should improve the removal performance of BTFs.

1. Introduction

Air pollution and health are closely related and a series of adverse health effects especially mortality and morbidity owing to cardiovascular and respiratory diseases are closely associated with the current-day concentrations of ambient air pollutants (Hoek et al., 2013). It has been reported that outdoor air pollution leads to 3.3 million (95% confidence interval [1.61, 4.81]) premature deaths per year worldwide, predominantly in Asia (Jerrett, 2015). Odorous pollutants and volatile organic compounds (VOCs) are common and typical outdoor air pollutants. They have adverse effects on the social and physical environment, and create disproportionate disease burdens in less affluent segments of the society (Garcia et al., 2015). Thus, air pollution problems caused by the emission of odorous pollutants and VOCs not only threaten public health, but also deteriorate personal welfare (Balasubramanian et al., 2012). VOCs can adversely affect both short- and long-term health of humans and animals. They are involved in the formation of photochemical smog, ozone and respirable suspended particulates in the atmosphere, and contribute to sharp declines in crop yields and destruction of forests and ecosystems (Yang et al., 2010b). VOCs are organic compounds, including alkanes, aromatics, olefins, halocarbons, esters, aldehydes, ketones, etc., with a boiling point ranging from 50 °C to 260 °C (Kim, 2011; Zhang et al., 2018). Furthermore, as a common environmental problem, emission of odorous pollutants is not only a public health concern, but also a threat to personal comfort (Leuch et al., 2008). The main components of odorous pollutants are (1) nitrogen-containing compounds (including inorganic compounds such as NH_3 and NO_X, and amines such as methylamine, dimethylamine, and trimethylamine) (Han et al., 2016; Wan et al., 2011b); (2) sulfur-containing compounds (including inorganic compounds such as H_2S and SO_2, and organosulfur compounds such as methyl mercaptan, ethyl mercaptan, dimethyl sulfide, and dimethyl disulfide) (Chung et al., 2010; Lebrero et al., 2012b; Montebello et al., 2013; Shammay et al., 2016); and (3)VOCs (including aromatic, aliphatic and chlorinated hydrocarbons, fatty acids, aldehydes, terpenes and ketones) (Munoz et al., 2010; Xue et al., 2013). In addition to their potent offensive smell, VOCs and odorous gases also result in acute toxic and chronic long-term health effects (Kim, 2011; Zhang and Tay, 2015). Therefore, air pollution caused by VOCs and odorous gas need to be immediately solved.

In recent years, to improve air quality and reduce or eliminate air pollution caused by VOCs and odorous gases, various technologies have

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been developed. Among them, the common methods used can be grouped into three categories: physical technologies, which usually include condensation, adsorption, water scrubbers; chemical technologies, which mainly include chemical scrubbers, thermal oxidation, catalytic oxidation, and ozonation; and biological technologies such as biofilters (BF), bioscrubbers, and biotrickling filters (BTFs) (Wan et al., 2011a). Despite the effectiveness of physical–chemical methods in destroying VOCs and odorous gases, the disadvantages of high cost and secondary pollution are characteristic of these techniques. For some applications of physical–chemical methods, the concentration of waste gas should be relatively high, otherwise economic benefits are unachievable (Khan and Kr. Ghoshal, 2000). However, the concentration of waste air contaminated by VOCs and odorous gases is usually from low to moderate, but the volumes are high. Furthermore, owing to the limitation of technology and production process, the use of VOCs and other odorous volatile compounds cannot be completely prohibited. Thus, VOCs and odorous gas pollution cannot be eliminated soon, and the use of conventional methods such as adsorption, condensation, and incineration for the treatment of low concentrations of VOCs and odorous gases may not be economical (Singh et al., 2010b).

Biotechnologies are currently recognized as the best available methods for the treatment of low and moderate concentrations of waste gases containing odorous pollutants and VOCs because they are cost-effective and environment-friendly, when compared with other physical and chemical technologies (Ryu et al., 2011). These processes usually use bioreactors that play a very important role in the control of VOCs and odorous gases. Bioreactors have been found to be cost-effective for treating off-gases with low concentrations of VOCs (usually $< 3\,g/m^3$) and can achieve 99% odor reduction for some pollutants (Groenestijn and Kraakman, 2005).

Though a number of different configurations exist, the main types of conventional air-phase bioreactors include BF, BTF, and bioscrubber. The characteristics of these bioreactors are shown in Table 1 and Fig. 1. The basic differences among the reactors exist in the environment of the microorganisms (suspended or fixed), and the state of the liquid (flow or stationary). As indicated in Fig. 1A, in the BF system, the filter bed is usually made of organic material such as soil, peat, straw, compost, or other suitable substrate. The amount of nutrient supply is strongly correlated with the characteristics of the waste air. As the packing material used in BF systems usually contains microorganisms as well as lots of nutrients for the growth of microorganisms, additional supply of microorganisms and nutrients are not necessary for the treatment of odor problems. However, supply of some extra nutrients may enhance the biodegradation of VOCs (Wahman et al., 2007). Occasionally, water must be sprayed onto the packing bed to maintain high moisture content, and leachate can be recirculated to the BFs to avoid wastewater generation. Generally, the pollutant gases flow through the porous packing media, and are degraded by microorganisms. The BF systems have the advantages of cost effectiveness, and almost no secondary pollution. However, some disadvantages include difficulty in moisture and pH control, clogging of the medium due to particulate matter and abundant biomass, and medium deterioration.

As shown in Fig. 1B, bioscrubber systems consist of two subunits, one is an absorption unit and the other is a bioreactor unit. Gaseous and liquid phases flow counter-currently within the bioscrubber column. The waste gases are first cleaned by absorption and the clean gases are released at the top of the column. Pollutants in the aqueous solution are

Table 1
Characteristics of three types of bioreactors.

Bioreactor type	Microorganisms	Water phase
Biofilter	Fixed	Stationary
Biotrickling filter	Fixed	Dis- or continuously flowing
Bioscrubber	Suspended	Flowing

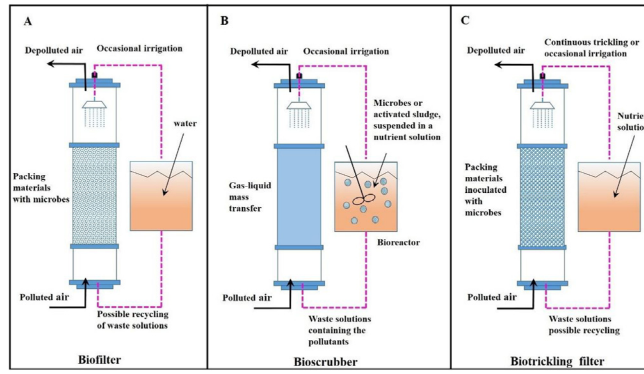

Fig. 1. Schematic view of conventional bioreactors. A: biofilter (BF); B: bioscrubber; C: biotrickling filter (BTF).

degraded by appropriate microbial strains suspended in the aqueous solution. The bioscrubber systems have the advantages of operational stability, adequate control of operation parameters (pH, nutrients), low pressure drop, and minimum space requirement. The disadvantages of bioscrubbers include the ability to treat only readily soluble VOCs and odorous pollutants having low Henry coefficient. Furthermore, bioscrubbers generate excess sludge and liquid waste that have to be treated.

In BTF systems (Fig. 1C), waste gas being treated is carried through a packed bed, which is continuously or intermittently irrigated with an aqueous solution containing essential nutrients required by the biological system. Microorganisms from an external source are inoculated on the surface of the packing material and form a biofilm. Pollutants are initially absorbed by an aqueous film that surrounds the biofilm and are then degraded by the biofilm. The BTF system has the advantages of low operating and capital costs, lower pressure drop during long-term operation, and capability to intensively treat acidic degradation products of VOCs and acidic odorous gases (Lebrero et al., 2012a). However, BTFs are relatively complex in construction and operation and accumulate excess biomass (Mudliar et al., 2010).

Comparison of BFs, BTFs, and bioscrubbers revealed that BTFs have better capacity in treating recalcitrant VOCs and acidic or alkaline compounds. Moreover, water management is the major advantage of BTFs, when compared with the BF systems, allowing defined control of pH, nutrient supply, and removal of toxic metabolites, thus achieving higher pollutants elimination rates (Seignez et al., 2004). Besides, when compared with bioscrubbers, BTFs exhibit rapid biodegradation of pollutants owing to enrichment of pollutants with extracellular polymeric substances acting as surfactants, resulting in large numbers of immobilized microorganisms coming into contact with the pollutants. Although the construction and operation of a BTF may be complex, as a typical form of biological treatment technology these systems have succeeded in treating many kinds of pollutants (Balasubramanian et al., 2012). Thus, when combining this benefit with its cost effectiveness, BTF technology is an attractive option for controlling VOCs and odor emissions from various industrial processes (Zehraoui et al., 2012). However, some limitations in BTF processes (such as excess biomass accumulation, low mass transfer rate, etc.) may affect the pollutant removal performance of BTFs. In a BTF system, the design, operating condition, mass transfer, packing materials and microorganisms are critical influences during BTF processes (Fig. 2) and can significantly affect the removal of gaseous pollutants.

Many methods have been investigated for enhancing the removal performance of BTFs, such as pollutant pretreatment, fungal BTF, surfactant addition, and other techniques. Essentially, these methods are designed to optimize the critical parameters of BTFs. Thus, examination of these critical parameters is necessary, because they are the foundation for utilizing BTFs and improving the pollutant removal performance.