1 Biotechnology for Air Pollution Control – an Overview

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1.1 Introduction

Biotechnology offers the most economical and environmentally benign method for air pollution control when dealing with the removal of odorous and toxic contaminants from industrial and municipal airstreams. When emitted in large amounts, volatile organic compounds (VOCs) and inorganic odorous compounds create hazards to the ecosystem and health effects to humans. Substances such as ammonia, amines, hydrogen sulfide, methyl mercaptan, dimethyl sulfide, and dimethyl disulfide cause odor nuisance in the environment. Increase in population density, new development of housing and industrial facilities create a growing need for air pollution control systems that provide nuisance-free, breathable air. This chapter provides an overview of various biotechnological methods used in odor and air pollution control.

The need for the removal of odors and VOCs is driven by regulatory issues, generally enforced as a result of public complaints about poor local air quality and through emission monitoring by the enforcement agencies. In the early 1990s, it was not an easy task for an industry to select a biotechnology system to reduce odor or VOC air emissions as a means of compliance. In Chapter 2, the details on odor and VOC control laws, regulatory measures to handle citizens' complaints, performance standards required for biological treatment systems, and review of regulations in several countries are discussed.

1.2 Methods of Odor and VOC Control

The treatment of off-gases has been practiced for years and is primarily based on non-biological methods such as condensation, activated carbon adsorption, absorption/scrubbing, and incineration. In the condensation process, cooling and compression condense contaminant vapors from air. This process is economical for higher boiling point compounds and more concentrated airstreams. In the adsorption process, pollutants are adsorbed onto adsorbents (i.e., activated carbon). This process is effective when the concentration in the airstreams is low. Regeneration of the adsorbents is done using steam or hot air. However, recovery of compounds is costly, and spent adsorbents such as

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solid waste need to be land-filled or incinerated. In absorption or scrubbing, pollutants from the air are absorbed into a scrubbing solution such as water or solvents. Often, chemical costs are high and liquid waste needs further treatment. Nozzle maintenance, complex chemical feed and control systems and high operating costs are a few problems associated with this method (Devinny et al. 1999). The incineration technology has been widely used due to its high efficiency. To increase the efficiency of incineration and reduce fuel requirement for combustion, several forms of this technology, such as recuperative, regenerative and catalytic oxidation, are practiced. Regardless, incineration is an expensive method due to high energy requirements, and it is not economical if concentration levels are low and large airflow volumes need treatment. This process also produces the highest amount of greenhouse gases (i.e., carbon dioxide, or NO_x gases).

Biological methods are effective and economical for biodegradable odorants and VOC contaminants. Air-phase bioreactors used in industries for odor and VOC removal include *biofilters*, *biotrickling filters*, and *bioscrubbers*. In general, highly soluble and low molecular weight VOCs (i.e., methanol, ethanol, aldehydes, acetates, ketones, and some aromatic hydrocarbons) and inorganic compounds (i.e., hydrogen sulfide, ammonia) are easily biodegradable in these bioreactors. Low molecular weight aliphatic hydrocarbons such as methane, pentane and some chlorinated compounds are difficult to biodegrade (Devinny et al. 1999). Novel bioreactors for VOC and odor control include rotating drum biofilters, horizontal flow biofilters, foamed emulsion bioreactors, short contact time biotrickling filters (Gabriel et al. 2002), higher plant-based biofilters (Guilbault 2002), and microwave concentrator/biofilter integrated systems (Webster et al. 2002). However, these bioreactors are in the early stages of development, and several pilot-scale demonstration studies are in progress. Chapter 3 gives a detailed review on all physicochemical methods (i.e., condensation, membranes, UV oxidation, plasma, masking, and ozone oxidation) and biological methods for odor and VOC control.

1.3 Biological Reactors

1.3.1 Bioreactor Media

Media selection for a bioreactor is, in general, based on the ability to support bacterial growth. However, criteria vary depending on the reactor types. The performance of a bioreactor for odor or VOC control depends on the nature of the carrier or support media where the adhesion of microorganisms takes place, resulting in the development of a biofilm due to contaminant degradation. Large surface area, pressure drop, cost, chemical reactivity, and void space are important factors considered in selecting a bioreactor medium. For biofilters, in addition to biological properties, media must provide good absorption capacity, adsorption property, pH buffering capacity, good pore structure, and very low compaction over time (Leson and Winer 1991; Williams and Miller 1992). Although the selection of biofilter media should be based on all these parameters, frequently only media with good biodegradation properties (i.e., peat, compost, soil, chicken manure) are selected, without giving consideration to structural, mass transfer and adsorption properties. Some of these issues have been resolved with the introduction of vendor-supplied manufactured media that are produced with definitive specifications. For example, Biorem's manufactured medium consists of hydrophilic mineral cores coated with hydrophobic sorption material to give a high specific surface area. The coating of the media includes nutrient-rich organic material for microbe hosting, and suitable binders to provide product strength, buffer capacity and stability. Through research and experience in field-scale demonstrations, bioreactor vendors have now put emphasis on media development and selection for more efficient odor and VOC removal performance that meets compliance. In Chapter 4, medium selection criteria, engineering specifications and limitations are discussed in detail.

1.3.2 Microbiology

Several groups of microorganisms, primarily bacterial species, are responsible for the degradation of the air pollutants in bioreactors. Naturally occurring biofilter media such as peat and compost contain about 1 billion microorganisms per gram, capable of degrading odor and VOC contaminants present in the air. Activated sludge suspensions from sewage treatment plants serve as inoculum for many compounds (Ottengraf and Diks 1990), but poorly biodegradable compounds such as chlorinated hydrocarbons and aromatics require inoculation with specially cultivated organisms (Ottengraf et al. 1986; Ottengraf and Diks 1990). In manufactured media supplied by some vendors, inoculum is added during the media-production stage. During treatment, the introduction of odorants or VOC contaminants into a bioreactor shifts the distribution of the existing microbial populations toward a strain that can metabolize the target odor or VOC pollutants.

Compared to pure cultures, the use of microbial consortia or mixed cultures is common in large-scale applications for odor or VOC contaminants. Wastewater sludge or a filter bed containing a diverse natural community are the most frequently used, non-defined inoculums for the startup of bioreactors. However, some studies with single strain or defined consortium inoculation at startup have reported high contaminant removal efficiencies (Cox et al. 1997; Veiga et al. 1999; Veiga and Kennes 2001). Biofilters using natural organic carriers are expected to contain a wide range of organisms including bacteria, fungi, yeasts, algae, and protozoa, as compared to synthetic or inert carriers. However, biofilter inoculation may speed up the startup period.

Various species of bacteria have been identified from the bioreactors treating waste gases. Some of the common species belong to the genera *Pseudomonas*, *Alcaligenes*, *Bacillus*, *Corynebacterium*, *Sphingomonas*, *Xanthomonas*, *Nocardia*, *Mycobacterium*, *Rhodococcus*, and *Xanthobacter*. Anaerobic bacterial species of *Clostridium* and *Enterobacter* have also been identified in biofilters (Arnold et al. 1997; Juneson et al. 2001; Kennes and Veiga 2001). Use of white-rot fungi such as *Phanerochaete chrysosporium*, *Tramtes versicolor*, *Pleurotus ostreatus* and *Bjerkandera adusta* has been reported in biofiltration studies for the elimination of compounds such as α-pinene, styrene and alcohols (Braun-Lüllemann et al. 1997). A fungal species of *Exophiala jeanselmei* has been reported to utilize pollutants as a sole carbon and energy source, and high styrene removal rates in biofilters containing this fungus as the main styrene-degrader have been reported (Cox et al. 1996, 1997). The aerial hyphae of fungi represent a large surface area for direct contact with pollutants in contaminated air, facilitating transfer of compounds to the cell surface without any phase transition issues. Fungi are generally resistant to extreme environmental conditions, but a potential problem is the accumulation of intermediate products. Fungi are suitable for removal of hydrophobic compounds, such as alkyl benzenes and styrene.

Although microbes can be isolated and identified by classical microbiological methods, only a limited number (approximately 20%) of the contaminant-degrading strains present in a bioreactor are cultivable, and can therefore be isolated and identified by classical microbiological methods. Advanced molecular tools have been recently developed for identifying "hard to culture" microorganisms to obtain useful information on microbial populations present in a particular ecosystem (van Elsas et al. 1998; Theron and Cloete 2000). Phospholipid fatty acid analysis (PLFA), fluorescent in-situ hybridization (FISH) and 16S rRNA characterization are some of the techniques used in such ecological studies. However, such investigations have not been popular in characterizing biofilter populations (Sakano and Kerkhof 1998).

Microorganisms require a range of nutrients for growth and activity to carry out biodegradation of pollutants. Nutrients may be naturally present in organic filter beds, but are added to the synthetic or inert beds. Microbial cells consist of carbon, nitrogen, oxygen and hydrogen, with typical cell compositions of $C_5H_{8.3}NO_{1.35}$ for bacteria and $C_4H_7N_{0.6}O_2$ for fungi. Trace elements such as P, K, Mg, Ca, S, Fe, and Mn may be required by some species. Yield of biomass depends on the nature of the nutrients. Oxygen is required for the aerobic degradation of pollutants, and could be limiting in thick biofilms or at high substrate loads. Microbial activity slows down considerably in a dry environment. Optimum water content (moisture) in polluted air treatment is crucial, as an excessively high water content may result in mass transfer limitation of contaminants and possible anaerobic conditions.

Although bacteria grow in a pH range of 5–9, while fungi can grow under the more acidic to neutral pH range of 2–7 for appreciable growth and biodegradation, microbial activity slows down below pH 4 or above pH 8. Most microorganisms do not tolerate pH fluctuations of more that 2–3 pH units. Although most waste gas treatment studies are made under mesophilic (15–40 °C) conditions, bioreactors operating efficiently under psychrophilic (< 10 °C) and thermophilic (> 45 °C) conditions have been described. The temperatures of contaminated air and waste gases are often higher than the mesophilic range.

Pressure drop and clogging are a well-known phenomenon in biofilters, due to the nature of the carrier, particle size and shape, moisture content, superficial gas velocity, and excessive microbial growth. Clogging due to extensive biomass formation is more common with inert material where a nutrient solution is fed at regular interval. Limiting the supply of some nutrients such as phosphate and potassium ion or nitrogen is a possible means to reduce biomass growth (Wübker and Friedrich 1996). In Chapter 5, the microbiology of bioreactors for waste gas treatment is discussed in detail.

1.3.3 Types of Bioreactors

In recent years, biofiltration has received increased acceptance for odor removal in the wastewater treatment industry. Industrial sectors including rendering, food processing, flavor manufacturers, and composting facilities are selecting biofilter systems for odor and VOC removal in their facilities. In biofilters, as the contaminated air is passed through a bed of media, the contaminants and oxygen are first transferred to the biofilms formed on the surface of the media particles, and then metabolized by bacteria. In order to sustain microbial growth on the media particles, moisture is provided by saturating the process air before it enters the biofilter unit. The moisture is also provided by intermittent, occasional spray irrigation of the media. The media within a biofilter are normally composed of material such as peat, wood bark, soil, compost, coated ceramic particles, synthetically manufactured media, or a combination of these products. If properly designed, biofilters can provide complete removal of the odor and VOC contaminants present in waste air. Chapter 6 covers the historical development, fundamental theory, process mechanisms, and important parameters of the biofiltration process.

The major difference between biotrickling filters and biofilters is the presence of continuous water flow in the reactor. The water phase carries nutrients for the microorganisms, and is usually neutralized before recirculation, for pH-control purposes. Microbial oxidation takes place in the water phase as well as in the immobilized biofilms attached on the media particles. Microorganisms in the biofilms degrade absorbed contaminants into harmless and odorless products. Excessive biomass growth and clogging are major problems encountered in biotrickling filters. Biotrickling biofilters are more complex to construct and operate than classical biofilters. For chlorinated VOCs and compounds that produce intermediate acidic by-products, however, biotrickling filters are very effective (Devinny et al. 1999). Chapter 7 covers recent advances in biotrickling filter technology.

While biofilters and biotrickling employ immobilized organisms, bioscrubbers utilize dispersed (suspended) cultures. Bioscrubbers consist of two units: the usual scrubber in which VOCs and odorous compounds are transported from the air to a water phase, and a liquid-phase bioreactor where the water exiting the scrubber is subjected to biological treatment in a liquid phase. The bioreactor, which contains suspended cultures, requires sufficient oxygen through aeration to maintain a high level of biodegradation. However, due

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