Chapter 17
Biofiltration of Odorous Gases*

17.1 Introduction

Malodorous gas streams from pulping processes are frequent targets of public complaints (Chan 2006; Burgess et al. 2001). Owing to public health concerns and the personal comfort of neighboring residential communities, the industry is put under increasingly stringent regulations. Odors can also seriously lower real estate property values and there are indications that odor causing stress-induced illnesses can result in lower working productivity and lost workdays. People living in or near a kraft pulp mill complain of the bad smell associated with the mill's operations. These complaints are directly related to the production of odorous compounds during the cooking of wood chips with white liquor and subsequent points of gaseous release to the atmosphere. Even when pure sodium hydroxide is used to treat wood and straw, odors are produced. The cause of these odors is to be found in the residual sulfur-containing protoplasm, which reacts with the alkali to form mercaptans and organic sulfides during the digestion phase. It was found that the mercaptans are formed by the saponification of lignin methoxyl groups by sulfide ions.

17.2 Emissions from Pulping

17.2.1 Kraft Pulping

The foul smelling gases released from the kraft process include the following:

- H_2S
- Methyl mercaptan (CH_3SH)
- Organic sulfides (such as dimethyl sulfide ($CH_3–S–CH_3$) and dimethyl disulfide ($CH_3–S–S–CH_3$)), collectively referred to as total reduced sulfur (TRS). They are formed during kraft pulping by reaction of sulfides with methoxy groups of lignin via nucleophilic substitution reactions.

The major source of TRS emissions include:

- Digester blow and relief gases
- Multiple effect evaporator vent and condensates
- Recovery furnace with direct-contact evaporators
- Smelt dissolving tank and slacker vents
- Brown-stock washers
- Seal tank vents
- Lime kiln exit vents

Table 17.1 shows the typical characteristics of the gaseous emissions from kraft pulp mill. It is apparent that the source of largest volume of potential emissions is the recovery furnace, followed closely by the digester blow gases and the washer hood vents. However, the most concentrated emissions come from the digester blow and relief gases. Overall, the three most important source of odor production are

Table 17.1 Typical off-gas characteristics of kraft pulp mill

Emission source	Offgas flow rate (m³/ton pulp)	Concentration (ppm by volume)			
		H_2S	CH_3SH	CH_3SCH_3	CH_3SSCH_3
Batch digester					
Blow gases	3–6,000	0–1,000	0–10,000	100–45,000	10–10,000
Relief gases	0.3–100	0–2,000	10–5,000	100–60,000	100–60,000
Continuous digester	0.6–6	10–300	500–10,000	1,500–7,500	500–3,000
Washer hood vent	1,500–6,000	0–5	0–5	0–15	0–3
Washer seal tank	300–1,000	0–2	10–50	10–700	1–150
Evaporator hotwell	0.3–12	600–9,000	300–3,000	500–5,000	500–6,000
BLO tower exhaust	500–1,500	0–10	0–25	10–500	2–95
Recovery furnace	6,000–12,000	(After direct-contact evaporator)			
		0–1,500	0–200	0–100	2–95
Smelt dissolving tank	500–1,000	0–75	0–2	0–4	0–3
Lime kiln exhaust	1,000–1,600	0–250	0–100	0–50	0–20
Lime slacker vent	12–30	0–20	0–1	0–1	0–1

Based on data from Andersson et al. (1973) and Environmental Pollution Control Pulp and Paper Industry (1976)

Table 17.2 Odor threshold concentration of TRS pollutants

Reduced sulfur compound	Odor threshold concentration (ppb)
Hydrogen sulfide (H_2S)	8–20
Methyl mercaptan (CH_3–SH)	2.4
Dimethyl sulfide (CH_3–S–CH_3)	1.2
Dimethyl disulfide (CH_3–S–S–CH_3)	15.5

Based on data from Springer and Courtney (1993)

Table 17.3 Typical emissions of SO_x and NO_x from kraft pulp mill combustion sources

Emission source	Concentration (ppm by volume)			Emission rate (kg/ton[a])		
	SO_2	SO_3	NO_x (as NO_2)	SO_2	SO_3	NO_x (as NO_2)
Recovery furnace						
No auxiliary fuel	0–1,200	0–100	10–70	0–40	0–4	0.7–5
Auxiliary fuel added	0–1,500	0–150	50–400	0–50	0–6	1.2–10
Lime kiln exhaust	0–200		100–260	0–1.4		10–25
Smelt-dissolving tank	0–100	–	–	0–0.2		
Power boiler	–	–	161–232	–	–	5–10[b]

Based on data from Environmental Pollution Control Pulp and Paper Industry (1976) and Someshwar (1989)
[a]kg/ton of air dried pulp
[b]kg/ton of oil

black liquor combustion, weak black liquor concentration and the digestion process. About 0.1–0.4 kg of TRS is emitted per ton of pulp at 5 ppm in the recovery boiler flue gases. The principal difficulty with TRS emission is their nauseous odor, which are detected by the human nose at very low concentrations. Table 17.2 presents the odor threshold (odor detectable by 50% of the subjects) concentrations of the principal TRS compounds emitted by kraft mills which are only few parts per billion by volume (Springer and Courtney 1993). At low concentrations, TRS is more of a nuisance than a serious health hazard. Thus, odor control is one of the main air pollution problems in a kraft mill.

Oxides of both sulfur and nitrogen are also emitted in varying quantities from few points in the kraft system. The main source of SO_2 emission is the recovery furnace due to the presence of sulfur in the spent liquor used as a fuel. SO_3 is sometimes emitted when fuel oil is used as an auxiliary fuel. The lime kiln and smelt dissolving tank also emit some SO_2. The emission of nitrogen oxides is more general because nitric oxide is formed whenever oxygen and nitrogen, which are both present in air, are exposed to high temperatures. A small part of the nitric oxide formed may further oxidize to nitrogen dioxide. These two compounds, nitric oxide and nitrogen dioxide, are termed as total oxide of nitrogen. Under normal operating conditions, the temperature in the recovery furnace is not high enough to form large quantities of oxides of nitrogen (NO_x). The main source of NO_x emissions is the lime kiln. Table 17.3 presents SO_x and NO_x emission rates from various kraft mill sources. Large variations in the emission rates are due to the variations in operating conditions at different mills. Large amounts of NO_x are produced if the flame temperature is above 1,300°C

and oxygen concentration greater than 2%. Modern recovery boilers should have So_x emissions below 100 ppm when properly operated. Sulfur emissions from power boilers are controlled by using fuels of low sulfur content.

Another type of odorous emissions of nonsulfur compounds is produced by the hydrocarbons associated with the extractive components of wood, such as terpenes and fatty and resin acids, as well as those from materials used in processing and converting operations, such as defoamers, pitch control agents, bleach plant chemicals, etc. These hydrocarbon emissions are small compared to TRS emissions, but they may be odorous, or act as liquid aerosol carriers contaminated with TRS, or undergo photochemical reactions.

17.2.2   Emissions from Neutral Sulfite Semichemical (NSSC) Pulping

In general, the emissions from neutral sulfite semichemical (NSSC) are much less than those from the kraft process. Because no Na_2S is present in the pulping liquor, both methyl mercaptan and dimethyl sulfide (DMS) are absent from the gaseous emissions, a very low amount of reduced sulfur is emitted (Dallons 1979). The sulfur emissions from the Na_2CO_3 (sulfur free) process has been traced to sulfur in the fuel oil and process water streams used. The emissions of SO_2 and NO_x are similar to those of a kraft mill.

17.2.3   Emissions from Sulfite Pulping

The sulfite process mainly operates with acidic SO_2 solutions and as a consequence SO_2 is the principal emission. Organic reduced sulfur (RS) compounds are not produced if proper conditions are maintained in the process. Because the odor threshold is about 1,000 times higher for SO_2 than for RS compounds, sulfite mills generally do not experience the odor problem of a kraft mill. The method of attack on lignin by sulfite liquor is quite different than that by kraft liquor. The sulfite process involves sulfonation, acid hydrolysis, and acid condensation reactions (Rydholm 1965). Volatile compounds such as methyl mercaptan and DMS are not produced in sulfite pulping.

Typical emissions in the sulfite process are SO_2 with special oxides of nitrogen (problems arising in the ammonium-base process). SO_2 is also emitted during sulfite liquor preparation and recovery. Very little SO_2 emission occurs with continuous digesters. However, batch digesters have the potential for releasing large quantities of SO_2, depending on how the digester is emptied. Digester and blow-pit emissions in the sulfite process vary depending on the type of system in operation. These areas have the potential for being a major source of SO_2 emission. Pulp washer and multiple-effect evaporator also emit SO_2.

17.3   Methods for the Elimination of Odorous Compounds

Following methods are available to remove odors components from gaseous emissions (Ottengraf 1986):

- Gas-phase methods
- Liquid-phase methods
- Solid-phase methods
- Combustion
- Biological methods

The most important one is biological methods. These methods generally have the specific advantage that the pollutants are converted to harmless or much less harmful oxidation products (e.g., CO_2, H_2O, etc.). These processes do not generally give rise to new environmental problems, or if they do these problems are minimal. An exhaust air problem should preferably not become a solid waste or waste-water problem. Another advantage of biological treatment is the possibility of carrying out the process at normal temperature and pressure. Moreover, the process is reliable and relatively cheap, while the process equipment is simple and generally easy to operate. The elimination of volatile compounds present in waste gases by microbial activity is due to the fact that these compounds can serve as an energy source and/or a carbon source for microbial metabolism. Hence, a broad range of compounds of organic as well as of inorganic origin can be eliminated by microbiological processes.

As microorganisms need a relatively high water activity, these reactions generally take place in the aqueous phase and as a consequence the compounds to be degraded as well as the oxygen required for their oxidation first have to be transferred from the gas phase to the liquid phase. Therefore, mass transfer processes play an important role in this methodology. The microbial population can either be freely dispersed in the water phase or is immobilized on a packing or carrier material. The first-mentioned operation is carried out in bioscrubbers, the second one in trickling filters and biofilters. Bioscrubbers and tricking filters are more energy intensive than biofilters, as water circulation in these two systems requires relatively much more energy than gas transport through a biofilter. Also, the reliability of operation of bioscrubbers is relatively low due to possible washing away of active microorganisms. On the contrary, the presence of a large amount of packing material with a buffering capacity diminishes the sensitivity of biofilters to different kinds of fluctuations. Therefore, biofiltration technology is receiving a significant attention (Singhal et al. 1996).

17.3.1   Biofiltration Technology

Biofiltration technology is a promising method of odor, volatile organic compounds (VOCs) and air toxic removal from waste-gas streams because of low capital and

operating costs, low energy requirements, and an absence of residual products requiring further treatment or disposal (Bajpai et al. 1999; Cáceres et al. 2010; McNevin and Barford 2000; Burgess et al. 2001; Wani et al. 1997; Govind and Bishop 1996; Swanson and Loehr 1997). Biofiltration utilizes microorganisms that are capable of oxidizing many compounds and thus having potential for being used for the abatement of odors, VOCs, and air toxics (Kennes et al. 2007; Ottengraf 1987). The concept of biofiltration is actually not new; it is an adaptation of the process by which the atmosphere is cleaned naturally (Bohn 1992).

Biofiltration is similar to the biological treatment of wastewater or in situ bioremediation of contaminated soils and hazardous sludge (Rozich 1995). It is becoming more popular as stringent emission regulations are implemented. The acceptance of biofiltration has followed from biotechnological advances that provide an increasingly thorough knowledge of the system and how the process can be optimized not only to achieve high removal efficiencies with low energy consumption but importantly, to achieve these elimination efficiencies over long periods of time with minimal operator intervention and/or need for maintenance (Marsh 1994). VOC emissions have become a substantive issue for industrial operators as a result of the implementation of the US 1990 Clean Air Act Amendments and similar regulations in Europe, and thus a major driving force for the exploration of cost effective control options. Biofiltration is a promising control technology for processes that emit large off-gas volumes with relatively low concentrations of contaminants. With respect to the purification of polluted air, biofiltration is a commonly applied technique to odor abatement, where it is an established control method. It has also demonstrated limited success in controlling VOCs.

Biofiltration uses naturally occurring microorganisms immobilized in the form of a biofilm on a porous substrate such as soil, compost, peat, bark, synthetic substances, or their combination. The substrate provides the microorganisms with both a hospitable environment in terms of oxygen, temperature, moisture, nutrients, pH, and a carbon source of energy for their growth and development. As the contaminated air stream passes through the filter bed, contaminants are transferred from the vapor phase to a thin water layer (biofilm) covering the microorganisms held over the surface of the packing particles. The microorganisms utilize these favorable conditions to metabolize carbon-based compounds to their primary components – carbon dioxide and water, plus additional biomass and innocuous metabolic products (Ottengraf 1987; Rozich 1995; Marsh 1994). The absorption and/or adsorption capacity of the filter media is thus continuously renewed by the biological oxidation of the sorbed contaminants (Bohn and Bohn 1988; Hodge et al. 1991).

Biofiltration has the advantage that the pollutants are not transferred to another phase and therefore, new environmental problems are not created or are only minimal (Ottengraf 1986, 1987; Bohn 1992, 1993). Moreover, the process is said to be cheap and reliable and does not usually require complex process facilities (Ottengraf 1987).

Biofilters do extremely well in two main domains; in the removal of odoriferous compounds and in the elimination of volatile organic chemicals (Ottengraf 1986; Hirai et al. 1990; Deshusses and Hammer 1993; Leson and Wikener 1991), primarily solvents, from air. Under optimum conditions, the pollutants are fully biodegraded

without the formation of aqueous effluents. As gases pass through a biofilter, odorous compounds are removed by processes thought to include sorption (absorption/adsorption) and biooxidation (Williams and Miller 1992). The odorous gases adsorb onto the surface of the biofilter medium and/or are absorbed into the moisture film on the biofilter particles. Given a sufficient rate of biological activity in the filter, the sorbed compounds are then oxidized (degraded) by microorganisms. End products from the complete biooxidation of the air contaminants are CO_2, water, mineral salts, and microbial biomass. The elimination of a gaseous pollutant in a biofilter is the result of a complex combination of different physicochemical and biological phenomena.

Biofilters are commonly constructed in a vessel packed with loose beds of solid material, soil, or compressed cakes with microbes attached to their surface. Waste gases are passed through these units via induced or forced draft. Biofilters are capable of handling rapid air flow rates and VOC concentrations in excess of 1,000 ppm. These units are gaining importance in bioremediation also and are timely in that they are a cost-effective means by which to deal with the more stringent regulations on VOC emission levels.

There are essentially two types of biofilters. The first and simplest is the soil filter. Contaminated air from a small waste stream or other treatment process is passed through a soil–compost type design, so-called open system (Ottengraf 1986). Sometimes, nutrients are preblended into the compost pile to provide conditions for microbial growth and biodegradation of the waste by indigenous microorganisms. Being usually installed in the open air and partly underground, these systems are exposed to many weather conditions: rain, frost, temperature fluctuations, etc. These filters are usually over designed; they require a very large area. To increase the reliability of these filters, a number of another type (closed type) of systems have been developed which house the treatment beds or disks of different packing materials/media. In the treatment bed, the waste air stream and the filter are humidified as the waste is passed through one, two, or more beds. In this approach, a series of humidified disks or beds are placed inside a reactor shell (Shareefdeen et al. 1993). These layered disks contain packing material/media, nutrients, microbial cultures, and/or compost material. The waste air stream organics undergo biodegradation as they pass through the system. Any collected water condensate from the process is returned to the humidification system for reuse. Biofilters have reportedly been built to handle up to 3,000 m^3/min of air flow using filters up to 6,500 m in wetted area (Anon 1991). The filters can be customized with specific carriers, nutrients blends, or microbial cultures. Some biofilters can endure up to 5 years before replacement is necessary (Holusha 1991). Spent filters can be utilized as fertilizer since they present no hazard.

17.3.2   Microorganisms in Biofilter

Several microorganisms are involved in the degradation of air pollutants in biofilters including bacteria, actinomycetes, and fungi (Ottengraf 1987). The microbial population is generally made up of autotrophic microorganisms (feed directly

Table 17.4 Microbial cultures used for degradation of pollutants

Culture	Pollutant(s)
Soil (indigenous microbes)	Sewage odors-H_2S
Compost (indigenous microbes)	Various VOCs
Aerobically digested sludge of night soil	Sulfur compounds (H_2S, DMS, methanethiol)
Peat (indigenous microbes)	H_2S
Sludge from sewage treatment	H_2S, C_2H_5SH, $(C_2H_5)_2NH$, C_4H_9CHO
Thiobacillus sp. strain MS_1	Methyl sulfides (DMS, DMDS)
Thiobacillus thioparus TK-m	H_2S, DMS, DMDS, methanethiol
Thiobacillus thioparus strain E_6	DMDS
Hyphomicrobium sp. strain S	DMS, DMSO
Hyphomicrobium sp. strain EG	Methylated sulfur compounds
Pseudomonas fluorescens	Methanol, isopropanol, butanol, etc.
Bacterial consortium consisting of *Pseudomonas*, *Methylomonas*, *Aeromonas*, *Achromobacter*, *Flavobacterium*, *Alcaligenes*	Methanol

Based on data from Leson and Wikener (1991), van Lith et al. (1997), Bohn (1975), Pomeroy (1982), Hirai et al. (1990), Lee and Shoda (1989), Furusawa et al. (1984), Ottengraph et al. (1983), Sivela and Sundman (1975), Kanagawa and Kelly (1986), Kanagawa and Mikami (1989), Smith and Kelly (1988a, b), DeBont et al. (1981), Suylen et al. (1986, 1987), Kirchner et al. (1987), and Shareefdeen et al. (1993)

from inorganic compounds) and heterotrophic microorganisms (utilize organic compounds as source of energy and carbon) (Marsh 1994). The composition and survival of microorganisms on the filter bed are the main process parameters. Their growth and activity depends on the physical and chemical conditions in the packing material. The diversity of the active microorganisms is a function of the inlet gas stream composition. Some packing materials of natural origin, such as compost, contain a sufficient number of different microorganisms to initiate the reactions for the elimination of simple contaminants. The efficiency of the purification process is generally increased following the growth of active strains during the adaptation time after the start up of the biofilter. For easily biodegradable organic compounds acclimatization can typically take about 10 days (Ottengraf 1986), and for less biodegradable and those contaminants for which the microorganisms are less likely to be initially present in the biofilter material, the period can be longer (Leson and Wikener 1991).

Different types of representative microorganisms/cultures used by various investigators have been given in Table 17.4.

Soil and compost contain a large variety of indigenous microorganisms which degrade the odorous compounds in air. The common soil bacteria, *Bacillus cereus* var. *mycoides* and strains of *Streptomyces* are most frequently identified in the soil samples. Autotrophic bacteria such as *Thiobacillus*, which grow on thiosulfate medium, are also present in the soil. But the counts of heterotrophic bacteria are much higher. They have been demonstrated to reduce the sewage odors, especially by eliminating the hydrogen sulfide present in the waste air stream (Carlson and Leiser 1966; van Lith et al. 1997; Bohn and Bohn 1988). Following bacteria and microfungi: *Actinomyces globisporus*, *Penicillium* sp., *Cephalosporium* sp., *Mucor* sp., *Micromonospora albus*, *Micrococcus albus*, *Ovularia* sp., etc. are the most frequently occurring microorganisms in the compost cultures. Compost has been a

common choice of microbial source in biofiltration (Leson and Wikener 1991; van Lith et al. 1997; Bohn 1975; Pomeroy 1982). In addition to the source of microorganisms, the soil and compost provide a physical support for the microorganisms; these materials also provide water holding capacity and some amount of minor and trace nutrients. Aerobically digested sludge of night soil has also been used as a source of microbial cultures in the biofilters for the removal of H_2S, DMS and methanethiol (Hirai et al. 1990; Lee and Shoda 1989). The digested sludge of night soil is supposed to contain several types of microorganisms, useful in biooxidation of air pollutants. The indigenous microorganisms in the peat have been tried for biooxidation of H_2S in a biofilter (Furusawa et al. 1984). In few cases, sludge from sewage treatment works is used as the source of microorganisms (Ottengraph and Van Denoever 1983). Classical microbiological techniques have revealed the presence of mixed populations of bacteria, yeast, fungi, and higher organisms in the biofilters. Bacterial species of *Thiobacillus* and *Hyphomicrobium* degrade many sulfur compounds such as H_2S, methyl sulfide, DMS, DMDS, DMSO, methanethiol, etc. (Sivela and Sundman 1975; Kanagawa and Kelly 1986; Kanagawa and Mikami 1989; Smith and Kelly 1988a, b; DeBont et al. 1981; Suylen et al. 1986, 1987). For methanol biooxidation, *Pseudomonas fluorescens* (Kirchner et al. 1987) and a bacterial consortium (Shareefdeen et al. 1993) consisting of *Methylomonas*, *Aeromonas*, *Achromobacter*, *Flavobacterium*, *Alcaligenes*, and *Pseudomonas* have been used.

17.3.3   Packing Materials for Biofilters

The conventional packing material for biofilter have been soil, compost, peat moss, bark, or other material that contain a large variety of indigenous microorganisms (Carlson and Leiser 1966; van Lith et al. 1997 ; Bohn and Bohn 1988; Bohn 1975; Furusawa et al. 1984; Ottengraph and Van Denoever 1983; Sivela and Sundman 1975; Van Langenhove et al. 1986; Luo and van Oostrom 1997; Qiao et al. 2008). These materials provide water holding capacity and some amount of minor and trace nutrients in addition to providing a physical support for the microorganisms. Soil, peat, and compost materials exhibit low biodegradation rates, have limited supply of nitrogen and phosphorus, eventually begin to plug due to growth of microorganisms, and have limited capacity to neutralize acidic products of degradation. Hence, compost biofilters are capable of treating low concentration contaminants and are not ideally suited for treating air contaminated with high concentration organics. Sometimes, the bed material is amended with bulking agents such as wood chips, saw dust, bark, sand, bagasse, etc. to improve air flow or with other additives such as limestone for pH control in systems removing sulfur based odors (Ottengraf 1986; Deshusses and Hammer 1993; Sivela and Sundman 1975; Luo and van Oostrom 1997; Chou and Chen 1997; Campbell and Connor 1997; Deshusses et al. 1995; Ottengraf et al. 1986). Peat has the advantages over soil or compost of broadness of the maximum permeable value of the moisture content and a lower pressure drop due to its fibrous structure (Hirai et al. 1990; Furusawa et al. 1984). The peat has been reported to possess a unique combination of chemical and physical properties, such as adsorbency, which could be employed in environmental protection applications (Martin 1992).

Other types of support media used in biofilters are synthetic media, such as ceramic, plastic, etc., with active bacteria immobilized on the surface in the form of biofilms. These synthetic media biofilters are known as biotrickling filters. Synthetic support media are used in trickling filters for wastewater treatment, gas absorption towers, catalytic reactors, etc. However, the design of support media in biotrickling filters is different than in any other application, the major difference being the growth of biomass. In trickling filters, used for waste water treatment, the water flows as a liquid film on the biofilm surface, and sufficient distance between the support media is designed to accommodate biomass growth and air, which provides oxygen for the biodegradation reaction. The contaminants, present in the waste water, diffuse into the biofilm as the water flows over the biofilms and biodegrades. In a biotrickling filter, the contaminants, present in air, diffuse perpendicular to the direction of flow, and biodegrade in the supported biofilms. Since the process is diffusion controlled, designing a large distance between the supported biofilms reduces the overall degradation rate in the filter. Further, unlike the submerged biofilms in the case of the wastewater trickling filter, the biofilms in a biotrickling filter have to be kept moist to maintain bioactivity. Air flowing through the biotrickling filter draws moisture away from the biofilms, and a trickling flow of aqueous nutrients has to be maintained to provide nutrients and water to the active bacteria in the biofilms.

Synthetic support media can be in the form of high surface area pellets, with either a porous or nonporous surface. In some cases, the support media may be coated with activated carbon, to enhance adsorption of contaminant(s). The synthetic support media can be synthesized from plastic, ceramic, metallic, or any other composite material. The desired features of a good support media are as follows: High void fraction, High surface area per unit volume of the biofilter bed, Low gas-phase pressure drop, Hydrophilic surface, to allow good water wettability, and Low cost.

17.3.4   Mechanisms in Biofilter Operation

There are many mechanisms which operate simultaneously or in sequence in a biotrickling filter. These mechanisms include:

- Diffusion of the contaminant(s) from the bulk gas flow to the active biofilm surface
- Sorption of the contaminants directly on the biofilm surface
- Solubilization of the contaminant(s) into the water content of the biofilms
- Direct adsorption of the contaminant(s) on the surface of the support media
- Diffusion and biodegradation of the contaminant(s) in the active biofilm
- Surface diffusion of the contaminant(s) in the support media surface
- Back diffusion of the adsorbed contaminant(s) from the support media surface into the active biofilms. The effect of adsorption of contaminant(s) on support media surface, surface diffusion, and back diffusion of the adsorbed contaminant(s) from the support media surface into the active biofilms, predominantly occurs in activated carbon-coated support media and contaminant(s), which have affinity for the support media surface

In the case of compost biofilters, the contaminant(s) diffuse into the porous compost particles, dissolve into the sorbed water films, adsorb on the organic and inorganic fraction of the compost, and biodegrade by the attached active compost bacteria, entrapped within the compost particles.

17.3.5   Development of Biofiltration Technology

Biofiltration has been used to control odors for several years in many countries (Germany, The Netherlands, UK, Japan, and to a limited extent in the USA) but the use of biofilter to degrade more complex air emissions from chemical plants has occurred within the last 2 decades. This vapor-phase biological treatment is rapidly gaining acceptance as an abatement technology for use in the treatment of VOCs, including odorous chemicals and air toxics because of its technical and economic advantages (Tonga and Skladany 1994). The process was initially applied to odor abatement in composting works, waste water treatment plants and similar situations. It is known that in 1953 a soil biofilter system was used for the treatment of odorous air in Long Beach, California (Pomeroy 1982). In Europe the first attempt with a soil bed was made in Geneva for deodorization at a composting facility (Ottengraf 1986). Around 1959 a soil bed system was used at municipal sewage treatment in Nuremberg, Germany (Leson and Wikener 1991; Shimko et al. 1988). In early 1960s Carlson and Leiser (1966) started systematic research on biofiltration in the USA and used biofilters to treat hydrogen sulfide emissions from sewage. After that, biological gas cleaning has made considerable progress, but is still in its developing stages for application to the control of VOCs and air toxics in industrial use.

During the last 3 decades research activities, especially on the soil bed systems, have intensified in USA with the installation of some full scale operations (Bohn 1975; Prokop and Bohn 1985). Excellent reviews of the historical development of biofiltration have been presented by Ottengraf (1986), Leson and Wikener (1991), and Shimko et al. (1988). Having proven its success in deodorization, current research and application of biofiltration has been focused on the removal of VOCs and air toxics from the chemical and other process industrial exhausts. Current research activities are aiming at understanding the practical behavior of the biofiltration process, optimizing its operational parameters and modeling the system on the basis of reaction kinetics for single as well as multiple contaminant gas streams (Ottengraf 1986; Ottengraph and Van Denoever 1983; Deshusses et al. 1995).

Furusawa et al. (1984) used a packed bed of fibrous peat for the removal of hydrogen sulfide from air. H_2S was almost completely removed irrespective of its inlet concentration when the loading was less than 0.44 g sulfur per day per kg of dry peat. The removal rate of hydrogen sulfide by the acclimatized peat was fairly constant under a constant inlet concentration but the reaction rate constant was proportional to the influent concentration of H_2S. In another study, the elimination of H_2S from odorous air using a wood bark filter to improve the low permeability of soil beds has been reported (Van Langenhove et al. 1986). Lee and Shoda (1989) reported the biological deodorization of methyl mercaptan using an activated carbon

fabric as a carrier of microorganisms for the biofilters. The activated carbon fabric seeded with digested night soil was found to be best packing material amongst the five materials evaluated. The critical load of methyl mercaptan, in which the gas can be completely removed, was determined as 0.48 g S/kg activated carbon fabric/day. About 80% of methyl mercaptan removed in the biofilter was converted into the sulfate ion. Effluent gas concentrations of methyl mercaptan and dimethyl disulfide were not detected below 50 ppm inlet concentration at a space velocity of 50/h. Fibrous materials that are flexible, light, and less microbially degradable may become significant as carriers of microorganisms.

The kinetics of removal of three kinds of odorous sulfur compounds – H_2S, methanethiol (MT), and DMS – in acclimatized peat were compared by Hirai et al. (1990) by supplying single or mixed odorous gases. H_2S and MT were found to be degraded on peat irrespective of the acclimatizing gas, and their maximum removal rates were unaffected by the presence of DMS. On the contrary, DMS was degraded only in DMS acclimatized peat. It has been reported that the peat has the advantages over soil or compost of broadness of the maximum permeability of the moisture content and a lower pressure drop due to its fibrous structure. The same laboratory has reported earlier about the characteristics of the peat as a packing material in deodorization device with the following results: zero-order kinetics in complete H_2S removal by peat biofilters (Furusawa et al. 1984), characteristics of isolated H_2S oxidizing bacteria inhabiting a peat biofilter (Wada et al. 1986), and biological removal of organosulfur compounds by peat biofilters (Hirai et al. 1988). Gradual increase of load was better for obtaining a high removal rate than the high load at the start of the experiment. Acclimation periods for H_2S, MT, and DMS were 19, 17, and 24 days, respectively. During this period, the pH of the peat gradually decreased due to accumulation of sulfate ions.

The maximum removal rate of H_2S in its acclimatized peat was one order larger than those in MT and DMS acclimatized peat. The removability of DMS was affected by the mixed gasses. Although the removal of DMS decreased when present with MT, the existence of H_2S will weaken the effect of MT on DMS removal to a certain extent. Thus, it would be better to maintain the space velocity (SV) value lower to guarantee DMS removal (Hirai et al. 1990). At a high SV, two stage columns in series are recommended. In the first column, most of the H_2S and MT can be removed, while the second column will be exclusively for DMS removal. This method is also appropriate for the maintenance of operation including the washing of accumulated ions and the exchange of packing material.

Shareefdeen et al. (1993) used an eight-membered bacterial consortium, obtained from methanol-exposed soil, and a peat–perlite column for the biofiltration of methanol vapors. The biofilter was found to be effective in removing methanol at rates up to 112.8 g/h/m³ packing. They also derived a mathematical model and validated it. Both experimental data and model predictions suggested that the methanol biofiltration process was limited by oxygen diffusion and methanol degradation kinetics. Bench scale experiments and a numerical model were used by Hodge and Devinny (1994) to test the effectiveness of biofiltration in treating air contaminated with ethanol vapors. Out of the three different packing materials used viz., granulated

activated carbon (GAC), compost, and a mixture of compost and diatomaceous earth, the GAC supported the highest elimination rates, ranging from 53 to 219 g/ m²/h for a range of loading rates. Partitioning coefficients for the contaminant on the biofilter packing material had a strong effect on the efficiency of the biofilters. Several studies on removal of volatile solvents such as ketone mixtures, toluene, ethyl acetate by biofiltration have also been reported (Kirchner et al. 1987; Campbell and Connor 1997; Bibeau et al. 1997; Deshusses et al. 1997).

The performance of biofiltration to remove odors (about 40 compounds) from animal rendering plant's gaseous emissions was investigated by Luo and Oostrom (1997) using pilot-scale biofilters containing different media (sand, sawdust, bark, bark–soil mixture). Biofilter odor removal efficiencies of 75–99% were obtained at various air loading rates (0.074–0.057 m³/m³ medium/min) and medium moisture contents. Bio-Reaction Industries Inc., Tualatin, OR, the USA has reported to develop a modular vapor-phase biofilter that is capable of treating extremely high concentrations of VOC in low air volumes (Stewart and Thom 1997). These systems are more suitable for point source industrial process air streams, storage tanks and other vent emissions.

Biofiltration of NO_x is reported to be enhanced by the addition of an exogenous carbon and energy source (Apel et al. 1995). pH control is found to be an important operating parameter due to acidic nature of the gas. Addition of calcite to the biofilter bed provided an effective internal buffer and the optimum temperature was found to be 50–60°C. The biofilter using activated carbon or anthracite as the packing material was reported to be most acceptable process for the removal of malodorous compounds containing nitrogen or sulfur (Hwang et al. 1995), since it produced no oxidized organics noticed with ozonation, and it had an equally high removal efficiency of both sulfur and nitrogen containing odorous compounds.

Biofiltration has been successfully applied to remove α-pinene, a very hydrophobic VOC discharged in pulp and paper and wood products emissions, from a contaminated air stream (Mohseni and Grant 1997). Two identical bench scale biofilters were utilized for more than 4 months of experiment. The biofilter medium consisted of a mixture of wood chips and spent mushroom compost that was amended with higher perlite, for the first filter and with GAC, for the second biofilter, the experiment was conducted at loading rates between 5 and 40 g α-pinene/m³ bed medium/h. Under steady state operating conditions, both biofilters, amended with perlite and GAC, performed similarly and provided removal rates of up to 30–35 g α-pinene/ m³ bed medium/h with gas retention times as low as 30 s. The adsorption characteristics of GAC were significant only during the start-up period where the GAC biofilter had a significantly better performance than perlite biofilter. When the biofilters were subjected to a sudden increase in the loading rate, the performance of the biofilters decreased significantly. The reacclimation period, however, was not long and biofilters reached more than 99% removal within less than 48 h of the spike load.

Studies on the transient behavior of a laboratory-scale compost based biofilters have been reported (Deshusses 1997). This included start-up, carbon balances, and interactions between pollutants in the aerobic biodegradation of VOC mixtures from effluent air streams. The study of transient behavior offers a genuine basis for the

development of a conceptual explanation of the complex phenomena that occur in biofilters during pollutant elimination, thereby providing an opportunity for further progress in establishing fundamental understanding of such reactors (Shareefdeen and Baltzis 1994; Tang et al. 1995; Deshusses et al. 1995). During long-term operation of a biofilter, the mandatory absence of net cell growth forces the cells into maintenance metabolism, which is of relatively low rate compared to substrate consumption during the active growth of the acclimation phase. Postacclimation nutrient addition increases activity primarily by allowing a return to the high substrate consumption rate of active growth, and only secondarily helps raise bed activity because of the ultimately higher amount of biomass in the bed (Cherry and Thompson 1997). The biomass content of a biofilter during the acclimation phase can be estimated using two approximate methods. The first follows the cumulative amount of substrate converted and uses the yield of cells from substrate during active growth to estimate the total biomass created. The second method follows a rate constant for conversion of substrate in the bed. This number is proportional to the amount of biomass as long as the conditions in the bed (e.g., temperature, pH, substrate concentration) are relatively constant (Cherry and Thompson 1997).

Generally, the empirical knowledge dictates the design and scale-up of biofiltration plants, even though substantial performance improvement could be expected from a more comprehensive knowledge of the individual processes involved in pollutant elimination. For improved design and performance, an appropriate model for the whole process is required. Deshusses (1997) and Deshusses et al. (1995) have developed a novel diffusion reaction model for the determination of both the steady-state and transient-state behavior of biofilters for waste air treatment, and experimentally evaluated/verified the same. Although this model deals with the aerobic biodegradation of methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK) vapors from air, similar mathematical treatment can be given to other biofilters degrading H_2S, organosulfur compounds, and other volatile organics. Most of the mathematical models have been developed mainly to correlate a particular set of experimental data, to explain the influence of selected parameters on the efficiency of the process, and sometimes to seek a better fundamental understanding of the phenomena occurring in a biofilter (Shareefdeen et al. 1993; Hodge and Devinny 1994; Deshusses et al. 1995). More promising quantitative structure–activity relationships for biofiltration have been presented by Choi et al. (1996).

Qiao et al. (2008) studied the removal characteristics of hydrogen sulfide experimentally in the biofilters with fibrous peat and resin as the packed materials. The biofilter with 100% of the peat showed higher removal capacity than the resin biofilter, but the gas flow resistance was lower in the latter. The mixture of the peat and resin as the packed material of the biofilter was proved to be an advisable method to keep the high removal capacity and reduce the gas flow resistance for a long-term operation. The flow resistance can decrease by 50% when 50% of the resin mixed with the peat, but the removal capacity was still considerable high.

Goncalves and Govind (2010) treated H_2S polluted airstreams in two biotrickling filter columns packed with polyurethane (PU) foam cubes, one with cubes coated with a solution of 25 mg/L of polyethyleneimine (PEI, coated reactor) and the other

containing just plain PU cubes (uncoated reactor) at empty bed residence times (EBRT) ranging from 6 to 60 s. and inlet H_2S concentrations ranging from 30 to 235 ppm_v (overall loads of up to 44 g H_2S/m^3 bed/h), with overall removal efficiencies (RE) in the range of 90–100% over 125 days. The acclimatization characteristics of the coated reactor outperformed those of the uncoated one, and both the observed elimination capacity (EC) of 77 g H_2S/m^3 bed/h and retention of volatile solids (VS) of 42 mg VS/cube were maxima in the coated reactor. Insights into the controlling removal mechanisms were also provided by means of dimensionless analysis of the experimental data. Denaturing gradient gel electrophoresis (DGGE) showed that the dominant surviving species in both units belonged to the genus *Acidithiobacillus.*

Wani et al. (2001) studied biofiltration using compost and hog and a mixture of two to remove reduced sulfur (RS) gases emitted from pulp mills. The hog fuel showed more resistance to microbially induced bed degradation than compost or mixtures of both and was found to be effective at RS gas removal as compost, with the advantage of costing less.

Biological Filtration Oxygenated Reactor (Biofor) is a new generation of modern apparatus, an aerobic biological reactor from Degremont, with fixed biomass on a support material (Brenna 2000). The principal advantages of biofiltration are a high concentration of biomass that brings the reactor to operation without the problems of bulking with the elimination of pollutants difficult to degrade biologically. Biofor gives these results as a result of an ideal support material, an efficient aeration system, a process of ascending equal currents of air and water, and optimized washing processes. The support material, Biolite, presents optimal qualities of density, hardness friction, and porosity. As well as working without odors and noise, Biofor is adapted for plants to limit environmental impact.

Domtar's kraft mill, Cornwall, Ontario, Canada carried out research to find a way of reducing the odors from the plant (Lau et al. 2006). Three types of biofiltration technology were researched: biofilters, bioscrubbers, and biotrickling reactors. This last option seemed the most favorable for treating the gas leaving the brownstock reactor. With a biotrickling reactor conditions such as temperature, pH, and growth of the biomass can be controlled. Four types of packing material were tried. The packing material should have a high void fraction, have a high specific surface area, be made from an acid-resistant material; have a low bulk density, and the microorganisms should stick to the packing. Lantec's HD Q-PAC gave the optimum results

17.3.6   Present Status

Biofiltration is now a well established air pollution control technology. In Europe several chemical process industries are using biofilters for deodorization and treatment of VOCs from the waste gas. In Netherlands and Germany, biofiltration has developed since the early 1960s into a widely used APC technology which is now considered "best available control technology" in a variety of VOC and odor

control applications. Successful biofilter applications in Europe include the following: chemical manufacture, chemical storage, adhesive production, coating operations, iron foundries, waste oil recycling, flavors and fragrances, tobacco processing, industrial waste treatment plants, composting facilities, other food processing industries, oil mills, beer yeast drying, etc. (Singhal et al. 1996) with odor control efficiency of 91–99% and organic removal efficiency of 71–95%. Compounds that are typically well degraded include alcohols, ethers, aldehydes, ketones, amines, sulfides, and inorganic compounds such as ammonia and hydrogen sulfide. Higher chlorinated organics show relatively lower ratio of biodegradation. More than 40% of New Zealand animal rendering plants now use biofilters which are usually effective (Luo and Oostrom 1997). Commercial use of biofilters has been less extensive in the United States, although the need for cost-effective air emission technology is clearly acute (Shareefdeen et al. 1993). But lately biofiltration technology has started picking up in the US also. Although very little information is available in the literature about the application of biofilters, in pulp and paper industry for odor removal, substantial information is available for the removal of various compounds similar to those generated in pulp and paper industry. This information could be very useful in installing biofiltration systems in pulp and paper mills.

17.3.7   Parameters Affecting the Performance of Biofilter

In addition to the microbial culture and packing materials, several other parameters are also important which affect the performance of a biofilter. In order to avoid deposits in the filter layer, dusts and aerosols are to be removed to a great extent from the waste gas by means of appropriate separators. Before it enters the filter, the waste gas should be humidified to saturation. The raw gas is humidified in a spray humidifier or by adding steam to it. The dust separation and humidification can be combined in wet scrubbers wherein scrubbing is done by water. Sometimes, the biofilters can be poisoned by the presence of off-gas constituents that are toxic to the microorganisms. Elimination of these substances or changing the vent system can make the off-gas suitable for biofiltration. High particulate loads in the raw gas can adversely affect the operation of a filter in different ways. Clogging of the air distribution system and the filter material itself by grease and resin can also occur. The deposition of dust in the humidifier will generate sludge and can result in the improper humidification. In such cases, the installation of particulate filter is required (Leson and Wikener 1991). Pollutant concentration and pollutant loading rates affect the performance. For example, in cases of H_2S removal by compost biofilter, the efficiency does not change as long as the H_2S loading rate is less than the maximum acceptable value for the compost. The concentration of H_2S as high as 4,000–4,500 ppm can be treated with an efficiency of 99%, but if the concentration increases drastically, say more than 100,000 ppm, then fresh air can be introduced to reduce the H_2S concentration and increase the oxygen concentration (Yang and Allen 1994). The maximum elimination capacity is a function of the biofilter material and the operating conditions. The pollutant loading should be applied accordingly.

To ensure the maximum pollutant elimination capacity of the biofilter system, the gas should stay on the bed for sufficient time. It is 30–40 s for H_2S elimination in compost bed (Yang and Allen 1994). There is no significant increase in the efficiency if the time is greater than 25 s. but when it is decreased to say 10 s, the efficiency decreases by about 80%. The reduction of H_2S removal efficiency at shorter residence time is not necessarily due to the insufficient reaction time between the H_2S molecule and the biomass, but may be due to the slow step involved in the overall process. This slow step comprises of H_2S diffusion from the gas phase into the liquid phase where the microorganisms exist (Yang and Allen 1994).

The moisture content and pH of the packing bed are other important parameters. For the compost, moisture level should be held between 40 and 60%. If the moisture content is reduced below 30%, the H_2S removal efficiency decreases proportionately. Proper moistening equipment such as sprinklers should be installed and operated in such a way that moisture content stays in the prescribed limits. Since the dominant active species present in this biofilter are primarily acidophiles, which prefer an optimum pH value near 3, maximum H_2S removal occurs at a compost pH of 3.2. Sulfur-oxidizing bacteria can live in environments having a wide range of pH (1–8). At the pH below 3, the efficiency decreases drastically. At the higher pH range, chemical reaction between H_2S and the compost material or reaction products can significantly enhance its removal, in addition to biological oxidation (Yang and Allen 1994).

For high pollutant removal efficiency, the temperature of the filter bed should be in the optimum range. The optimum range is 35–50°C for H_2S removal. The efficiency drops rapidly with decreases in temperature. For example, if the temperature reduces to, say 7°C, the H_2S removal efficiency decreases by about 80%. The decrease in H_2S removal at the higher temperature is less significant than that at lower temperature. The removal of H_2S at higher temperatures is probably due to increased chemical oxidation reactions in addition to biological oxidation. Normally, the temperature of biofilter is 10–15°C higher than the ambient temperature. This is due to the biological respiration of the microbes and the exothermic reactions in the filter. Thus, the biofilter can function properly even if the ambient temperature is low.

Since sulfate is the final product of the biofiltration, involving sulfur compounds, it may accumulate in the filter bed if not removed. Accumulation of sulfate can easily reach a level that can significantly reduce the biological function of the biofilter. Therefore, sulfate should be washed off periodically before it reaches the toxic level. A sulfate content of 25 mg/g is a critical level for the microbial environment.

The pressure drop increases approximately linearly with packing height. It increases in significantly larger increments with packing height for smaller particles than that for larger ones. It also depends on the water content of the packing. If the water content is increased, the coagulation of small viscous particles is enhanced and the pressure drop increases sharply. However, the rapid buildup of pressure can be suddenly released by channeling, i.e., a breakdown of filter bulk with much less resistance caused by a separation of packing materials. This situation is undesirable because it allows pollutants to exit the system without treatment. To prevent the high back pressure build up, the surface load of up to 300 m^3 off-gases/h/m^2 of filter should be maintained for proper functioning of the compost filter. Mineralization

and compaction of the compost packing during extended operation may eventually increase the bed pressure drop. Practically, the bed needs to be repacked or the compost replaced when the overall pressure drop is greater than 25 kPa (Yang and Allen 1994).

17.3.8   *Advantages, Limitations and Future Prospects*

Since biofilters compete with incineration and carbon adsorption in many situations, they are attractive in terms of not having to deal with landfilling costs or regeneration headaches. This has already been recognized in Europe, and some biofilter technology has found its way to the US (Anon 1991). Also, the thought of not simply transferring contaminants from one medium to another is particularly appealing. The biofilter creates a truly destructive process.

The use of microbial filter techniques in the treatment of air effluents containing organic pollutants can offer a number of advantages. They are inexpensive, work efficiently at ambient temperature, self-generating, maintenance free with low running cost, long life, environment safety, and oxidize most common VOCs to carbon dioxide and water producing virtually no by-products. The microbial flora survive a fairly long period during which the filter bed is not loaded (periods of a fortnight are easily spanned with hardly any loss of microbial activity). This is important in view of the dynamic behavior of filter bed at discontinuous operation, and means a very short starting time after longer periods of not operating the filter bed (Ottengraph and Van Denoever 1983). Moreover, the presence of a large amount of packing material with a buffering capacity diminishes the sensitivity of biofilters to different kinds of fluctuations.

Although such methods have long been known to be cost-effective, they have not found general acceptance in practice, even when the exhaust gas components to be removed are biodegradable. Long adaptation periods of the biomass (in particular with large exhaust gas flow discontinuities) or low space velocities i.e., low specific purification capacities, are the reasons often cited. Bed compaction problems, specially with soil and compost biofilters, have also been noticed. This results in high pressure drop across the filter. However, with the help of GAC and other synthetic packing materials, individually or in combination with soil–peat–compost materials, have solved these problems to a great extent.

While biooxidizing H_2S and organic sulfur compounds in a filter, accumulation of sulfate can easily reach a level that can significantly reduce the biological activity of the biofilter. Therefore, sulfate should be periodically washed off before it reaches the toxic level. The removal of DMS decreases considerably if methanethiol (MT) is also present in the exhaust gas (Hirai et al. 1990). However, the existence of H_2S weakens the effect of MT on DMS removal rate to a certain extent. In this case, it would be desirable to maintain a low space velocity to ensure DMS removal. At high space velocity, two stage columns in series are recommended. So that, in the first column, most of the H_2S and MT can be removed, while the second column will

be exclusively for DMS removal. This method may also be appropriate for the maintenance of operation, including the washing of accumulated ions and the replacement of packing material. Multistage operation of biofilters may also be necessary when the waste gases contain components, which require different conditions for their microbial degradation. This way, optimal growth conditions for the different microbial population can be provided in separate stages. Also, more stages may be necessary when the waste gases include one component in a concentration so high that the capacity of one stage is inadequate for a sufficient degradation. Depending on the nature of the organic compounds present in the waste, the filter sometimes needs inoculation with appropriate microorganisms to start biological activity.

In recent years, there has been significant maturation of biological waste air treatment research. This has resulted in a large number of studies concerning the performance and operation of the biofilters. Biofilter technology has a high potential for exhaust gas clean up, but as with many biological processes, the design requirements have not been fully appreciated. Interestingly, the fundamental processes involved during the elimination of a pollutant in a gas-phase bioreactor are still very poorly understood.

Biofilter technology was utilized in the field well before there was a basic understanding of its fundamental principles. This has resulted in several cases of unsuccessful or suboptimum operation of large-scale bioreactors. Today, with recent advances in the understanding of the fundamental principles underlying biofiltration, promises exist for better reactor design with optimal operating conditions. However, a number of fundamental questions remain unanswered or require further clarification, e.g., the quantification of biomass turnover, biodegradation kinetic relationships and factors influencing these relationships ecology of biofilter microflora, the determination of the availability and cycles of pollutant, oxygen and essential nutrients. The above factors have been found to significantly influence the performance and long-term stability of biofilters, and thus require further investigation in quantitative term. The expanding use of modern tools of biotechnology should be able to make it easier. The largest problem to overcome will be the translation of recent and future basic advances into real process improvements for biofiltration technology to mature from the mysterious black box reactor to a well-engineered process based on solid science rather than on trial and error.

Biofiltration technology for purification of exhaust gases from pulp and paper industry has a great potential. Very little information directly related to the industry is available although reasonably good information is available on the biofiltration of organic compounds similar to those found in the exhaust gases of pulp and paper industry. More studies are needed to obtain a better understanding of the heat transfer, mass transfer and reaction processes occurring within the biofilter beds. Comprehensive long-term studies of full-scale biofilter systems would also be valuable in improving our understanding of biofilters used to remove VOCs from off-gases generated in the paper industry. Extended studies of transient behavior of biofilters are also needed to provide the basic empirical knowledge necessary for plant design, scale-up, and performance evaluation under real conditions.

References

Andersson B, Lovblod R, Grennbelt P (1973) Diffuse emissions of odorous sulfur compounds from kraft pulp mills, 1 VLB145. Swedish Water and Air Pollution Research Laboratory, Gutenberg

Anon (1991) Air pollution control may be reduced with biotechnology. RMT Network 6(1):5–8

Apel WA, Barnes JM, Barrett KB (1995) Biofiltration of nitrogen oxides from fuel combustion gas streams. In: Proceedings of the annual meet-air waste management association, San Antonio, Texas, 88th (vol 4A): 95-TP9C.04

Bajpai P, Bajpai PK, Kondo R (1999) Biotechnology for environmental protection in pulp and paper industry. Springer, Germany, pp 239–261

Bibeau L, Kiared K, Leroux A, Brzezinski VG, Heitz M (1997) Biological purification of exhaust air containing toluene vapor in a filter-bed reactor. Can J Chem Eng 75:921–929

Bohn HL (1975) Soil and compost filters for malodorant gases. J Air Waste Manage Assoc 25:953–955

Bohn HL (1992) Considering biofiltration for decontaminating gases. Chem Eng Prog 88:34–40

Bohn HL (1993) Biofiltration: Design principles and pitfalls. In: Proceedings of the 86th annual meeting of air & waste management association. Denver, Paper #93-TP-52A.01

Bohn H, Bohn R (1988) Soil beds weed out air pollutants. Chem Eng 95(4):73–76

Brenna V (2000) Biofor: biofiltration of paper mill effluents. Ind Carta 38(5):59–63

Burgess JE, Parsons SA, Stuetz RM (2001) Developments in odour control and waste gas treatment biotechnology: a review. Biotechnol Adv 19(1):35–63

Cáceres M, Morales M, San Martín R, Urrutia H, Aroca G (2010) Oxidation of volatile reduced sulphur compounds in biotrickling filter inoculated with *Thiobacillus thioparus*. Electron J Biotechnol 13(5). http://dx.doi.org/10.2225/vol13-issue5-fulltext-9. Accessed Sept 2010

Campbell HJ, Connor MA (1997) Practical experience with an industrial biofilter treating solvent vapor loads of varying magnitude and composition. Pure Appl Chem 69(11):2411–2424

Carlson DA, Leiser CP (1966) Soil bed for control of sewage odors. J Water Pollut Control Fed 38:829–833

Chan AA (2006) Attempted biofiltration of reduced sulphur compounds from a pulp and paper mill in Northern Sweden. Environ Prog 25(2):152–160

Cherry RS, Thompson DN (1997) Shift from growth to nutrient – limited maintenance kinetics during biofilter acclimation. Biotechnol Bioeng 56(3):330–339

Choi DS, Webster TS, Chankg AN, Devinny JS (1996) Quantitative structure – activity relationships for biofiltration of volatile organic compounds. In: Reynolds FE Jr (ed) Proceedings of the 1996 conference on biofiltration. The Reynolds Group, Tustin, pp 231–238

Chou MS, Chen WH (1997) Screening of biofiltering material for VOC treatment. Air Waste Manage Assoc 47(6):674–681

Dallons V (1979) Multimedia assessment of pollution potentials of non-sulfur chemical pulping technology. EPA-600/2-79-026, Jan 1979

DeBont JAM, vanDijken JP, Harder W (1981) Dimethyl sulfoxide and dimethyl sulfide as a carbon, sulfur and energy source for growth of *Hyphomicrobium* S. J Gen Microbiol 127:315–323

Deshusses MA (1997) Transient behavior of biofilters: start-up, carbon balance, and interactions between pollutants. J Environ Eng 123:563–568

Deshusses MA, Hammer G (1993) The removal of volatile ketone mixtures from air in biofilters. Bioprocess Eng 9:141–146

Deshusses MA, Hamer G, Dunn IJ (1995) Behavior of biofilters for waste air biotreatment. I: Dynamic model development. Environ Sci Technol 29(4):1048–1058

Deshusses MA, Johnson CT, Hohenstein GA, Leson G (1997) Treating high loads of ethyl acetate and toluene in a biofilter. In: Air and waste management association 90th annual meeting and exhibition, Toronto, Canada, 8–13 June 1997, p 13

Environmental Pollution Control Pulp and Paper Industry (1976) Part 1, air, U.S. EPA technology transfer series, EPA-625/7-76-001, Oct 1976

Furusawa N, Togashi I, Hirai M, Shoda M, Kubota H (1984) Removal of hydrogen sulfide by a biofilter with fibrous peat. J Ferment Technol 62(6):589–594

Goncalves JJ, Govind R (2010) Enhanced biofiltration using cell attachment promotors. Environ Sci Technol 43(4):1049–1054

Govind R, Bishop DF (1996) Overview of air biofiltration – basic technology, economics and integration with other control technologies for effective treatment of air toxics. In: Emerging solutions VOC air toxics control, Proceedings of the spec. conference, Pittsburgh, PA, pp 324–350

Hirai M, Terasawa M, Inamura I, Fujie K, Shoda M, Kubota H (1988) Biological removal of organosulfur compounds using peat biofilter. J Odor Res Eng 19:305–312

Hirai M, Ohtake M, Soda M (1990) Removal of kinetics of hydrogen sulfide, methanethiol and dimethyl sulfide by peat biofilters. J Ferment Bioeng 70:334–339

Hodge DS, Devinny JS (1994) Biofilter treatment of ethanol vapors. Environ Prog 13(3):167–173

Hodge DS, Medina VF, Islander RL, Devinny JS (1991) Treatment of hydrocarbonfuel vapors in biofilters. Environ Technol 12:655–662

Holusha J (1991) Using bacteria to control pollution. The New York Times, March 13:C6

Hwang Y, Matsuo T, Hanaki K, Suzuki N (1995) Identification and quantification of sulfur and nitrogen containing odorous compounds in wastewater. Water Res 29(2):711–718

Kanagawa T, Kelly DP (1986) Breakdown of dimethyl sulfide by mixed cultures and by *Thiobacillus thioparus*. FEMS Microbiol Lett 34:13–19

Kanagawa T, Mikami E (1989) Removal of methanethiol, dimethyl sulfide, dimethyl disulfide and hydrogen sulfide from contaminated air by *Thiobacillus thioparus* TK-m. Appl Environ Microbiol 55(3):555–558

Kennes C, Veiga MC, Yaomin J (2007) Co-treatment of hydrogen sulfide and methanol in a single-stage biotrickling filter under acidic conditions. Chemosphere 68(6):1186–1193

Kirchner K, Hauk G, Rehm HJ (1987) Exhaust gas purification using immobilized monocultures (biocatalyst). Appl Microbiol Biotechnol 26:579–587

Lau S, Groody K, Chan A (2006) Control of reduced sulphur and VOC emissions via biofiltration. Pulp Pap Canada 107(12):57–63

Lee S-K, Shoda M (1989) Biological deodorization using activated carbon fabric as a carrier of microorganisms. J Ferment Bioeng 68(6):437–442

Leson G, Wikener AM (1991) Biofiltration: an innovative air pollution control technology for VOC emissions. J Air Manage Assoc 41:1045–1054

Luo J, van Oostrom A (1997) Biofilters for controlling animal rendering odor – a pilot-scale study. Pure Appl Chem 69(11):2403–2410

Marsh A (1994) Biofiltration for emission abatement. Eur Coating J 7/8:528–536

Martin AM (1992) Peat as an agent in biological degradation: peat biofilters. In: Martin AM (ed) Biological degradation of waste. Elsevier, New York, pp 341–362

McNevin D, Barford J (2000) Biofiltration as an odour abatement strategy. Biochem Eng J 5(3):231–242

Mohseni M, Grant AD (1997) Biofiltration of α-pinene and its application to the treatment of pulp and paper air emissions. Tappi Environ Conf Exhib 2:587–592

Ottengraf SPP (1986) Exhaust gas purification. In: Schonborn W (vol ed) Biotechnology, vol 8, Rehm H-J, Reed G (series eds) Microbial degradations. VCH, Weinheim, Germany, Chap. 12, pp 425–452

Ottengraf SPP (1987) Biological system for waste gas elimination. Trends Biotechnol 5:132–136

Ottengraf SPP, Meesters JPP, van den Oever AHC, Rozema HR (1986) Biological elimination of volatile xenobiotic compounds in biofilters. Bioprocess Eng 1:61–69

Ottengraph SPP, Van Denoever AHC (1983) Kinetics of organic compound removal from waste gases with a biological filter. Biotechnol Bioeng 25:3089–3102

Pomeroy D (1982) Biological treatment of odorous air. J Water Pollut Control Fed 54:1541–1545

Prokop WH, Bohn HL (1985) Soil bed systems for control of rendering plant odors. J Air Waste Manage Assoc 35:1332–1338

Qiao S, Fu L, Chi Y, Yan N (2008) Removal characteristics of hydrogen sulfide in biofilters with fibrous peat and resin. Bioinform Biomed Eng 2008:3996–3999

Rozich A (1995) Tackle airborne organic vapors with biofiltration. Environ Eng World 1:32–34

Rydholm SA (1965) Pulping process. Wiley, New York, p 452

Shareefdeen Z, Baltzis BC (1994) Biofiltration of toluene vapor under steady-state and transient conditions-theory and experimental results. Chem Eng Sci 49:4347–4360

Shareefdeen Z, Baltzis BC, Oh YS, Bartha R (1993) Biofiltration of methanol vapor. Biotechnol Bioeng 41:512–524

Shimko IG, Spasov VA, Chinennaya SK, Zakirova RI, Tananina IN, Perchugor GY, Pavlova OI (1988) Biochemical methods of freeing gas-air mixture from sulfur containing compounds. Fiber Chem 19:373–378

Singhal V, Singla R, Walia AS, Jain SC (1996) Biofiltration – an innovative air pollution control technology for H_2S emissions. Chem Eng World 31(9):117–124

Sivela S, Sundman V (1975) Demonstration of *Thiobacillus* type bacteria which utilize methyl sulfides. Arch Microbiol 103:303–304

Smith NA, Kelly DP (1988a) Isolation and physiological characterization of autotrophic sulfur bacteria oxidizing dimethyl disulfide as sole source of energy. J Gen Microbiol 134:1407–1417

Smith NA, Kelly DP (1988b) Mechanism of oxidation of dimethyl disulfide by *Thiobacillus thioparus* strain E6. J Gen Microbiol 134:3031–3039

Someshwar AV (1989) Impact of burning oil as auxiliary fuel in kraft recovery furnaces upon SO_2 emissions. NCASI Technical Bulletin No. 578, Dec 1989

Springer AM, Courtney FE (1993) Air pollution: a problem without boundaries. In: Springer AM (ed) Industrial environmental control pulp and paper industry, 2nd edn. Tappi Press, Atlanta, pp 525–533

Stewart WC, Thom RC (1997) High VOC loading in biofilters industrial applications. In: Emerging solutions VOC air toxics control, Proceedings of the spec. conference, Pittsburgh, PA, pp 38–65

Suylen GM, Stefess GC, Kuenen JG (1986) Chemolithotropic potential of a *Hyphomicrobium* species capable of growth on methylated sulfur compounds. Arch Microbiol 146:192–198

Suylen GM, Large PJ, vanDijken JP, Kuenen JG (1987) Methyl mercaptan oxidase, a key enzyme in the metabolism of methylated sulfur compounds by *Hyphomicrobium* EG. J Gen Microbiol 133:2989–2997

Swanson W, Loehr R (1997) Biofiltration: fundamentals, design and operation principles, and applications. J Environ Eng 123:538–546

Tang HM, Hwang SJ, Hwang SC (1995) Dynamics of toluene degradation in biofilters. Hazard Waste Hazard Mat 2(3):207–219

Tonga AP, Skladany GJ (1994) Field pilot-scale vapor-phase treatment of styrene using biofiltration. In: Flathman PE, Jerger DE, Exner JH (eds) Bioremediation: field experience. Lewis Publishers, Ann Arbor, pp 507–521

Van Langenhove H, Wuyts E, Schamp N (1986) Elimination of hydrogen sulfide from odorous air by a wood bark biofilter. Water Res 20:1471–1476

Van Lith C, Leson G, Michelson R (1997) Evaluating design options for biofilters. J Air Waste Manage Assoc 47:37–48

Wada A, Shoda M, Kubota H, Kobayashi T, Katayama FY, Kuraishi H (1986) Characteristics of H_2S oxidizing bacteria inhabiting a peat biofilter. J Ferment Technol 64:161–167

Wani A, Branion R, Lau AK (1997) Biofiltration: a promising and cost-effective control technology for odors, VOCs and air toxics. J Environ Sci Health 32(7):2027–2055

Wani AH, Branion RMR, Lau AK (2001) Biofiltration using compost and hog fuel as a means of removing reduced sulphur gases from air emissions. Pulp Paper Can 102(5):27–32

Williams TQ, Miller FC (1992) Odor control using biofilters. BioCycle 33(10):72–77

Yang Y, Allen ER (1994) Biofiltration control of hydrogen sulfide design and operational parameters. J Air Waste Manage Assoc 44:863–868