17
Process Engineering of Biological Waste Gas Purification

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17.1
Introduction

Process engineering of biological waste gas purification aims at the selection and operation of biological waste gas purification technologies with the ultimate aim of assuring mass transfer and biodegradation of one or more pollutants in a waste gas stream. Biodegradation of the pollutants occurs when microorganisms use the pollutants as a carbon source or an electron donor. In some special situations, microorganisms using a particular substrate such as glucose, ethanol, etc., can also oxidize another pollutant. This is due to unspecific metabolism by the enzymes of organisms and is called cometabolism (Alexander, 1981). The extent to which biological waste gas purification can occur is determined mainly by the physicochemical characteristics of the pollutant(s), the intrinsic capabilities of the microbial physiology and ecology, and the operating and environmental conditions.

When selecting the bioreactor technology, focus is placed on the operational and control requirements needed to ensure an optimal chemical and physical environment for mass transfer and biodegradation so as to achieve a high and constant removal efficiency of the pollutant.

17.2
Biological Waste Gas Purification Technology

17.2.1
General Characteristics

Biological waste gas purification technology currently includes bioreactors known as biofilters, biotrickling filters, bioscrubbers, and membrane bioreactors. The mode of operation of all these reactors is similar. Air containing volatile compounds is passed through the bioreactor, where the volatile compounds are transferred from the gas phase into the liquid phase. Microorganisms, such as bacteria or fungi, grow

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in this liquid phase and are involved in removing the compounds acquired from the air. The microorganisms responsible for the biodegradation usually grow as a mixture of organisms. Such a mixture of different bacteria, fungi and protozoa depends on a number of interactions and is often referred to as a microbial community. Microorganisms are generally organized in thin layers called biofilms. The pollutants in the air (such as toluene, methane, dichloromethane, ethanol, carboxylic acids, esters, aldehydes, etc.; Tolvanen et al., 1998) usually act as a source of carbon and energy for growth and maintenance of the microorganisms. Some waste gases, such as those produced during composting, are composed of many (often up to several hundred) different chemicals, such as alcohols, carbonyl compounds, terpenes, esters, organosulfur compounds, ethers, ammonia, hydrogen sulfide, etc. (Tolvanen et al., 1998; Smet et al., 1999). The remarkable aspect of the microbial community is that it generally develops to a composition so that all these different chemicals are removed and metabolized simultaneously. Microorganisms also require essential nutrients and growth factors to function and produce new cells. These include nitrogen, phosphorous, sulfur, vitamins and trace elements. Most often these nutrients and growth factors are not present in the waste gas and have to be supplied externally.

There are fundamental differences between the four types of reactors mentioned above. They range from whether the microorganisms are immobilized or dispersed to the state of the aqueous phase in the reactor (mobile or stationary). The aqueous phase significantly influences the mass transfer characteristics of the system. A short description of each of the four types of bioreactors for biological waste gas purification currently in use is given below (also see Figure 17.1).

17.2.2 Technology Types

17.2.2.1 Biofilter

In a biofilter, the air is passed through a bed packed with organic carrier materials, e.g., compost, soil or wood bark. The compounds in the air are transferred to a biofilm that grows on the filter materials. The nutrients necessary for growth of the microorganisms are supplied by the organic matter. On top of the biofilm is a thin liquid layer. An important control parameter is the moisture content of the overall carrier matrix, which must be between 40% and 60% (w/w). To avoid dehydration, the air is generally humidified before entering the biofilter. If the waste gas contains high levels of solid particles (i.e., the waste gas is an aerosol), an aerosol removal filter can be installed before the humidification chamber. This prevents clogging of the biofilter by the particles.

17.2.2.2 Biotrickling Filter

A biotrickling filter is similar to a biofilter. Here, pollutants are also transferred from the gas phase to a biofilm that grows on a packing material. However, the packing materials are made of chemically inert materials, such as plastic rings. Because nu-

trients are not available in these materials, they have to be supplied to the microorganisms by recirculating a liquid phase through the reactor in co- or countercurrent flow.

17.2.2.3 **Bioscrubber**

A bioscrubber consists of two reactors. The first part is an absorption tower, where pollutants are absorbed by a liquid phase. This liquid phase goes to a second reactor, which is a kind of activated sludge unit, where microorganisms growing in suspended flocs in the water degrade the pollutants. The effluent of this unit is recirculated over the absorption tower in a co- or countercurrent direction to the flow of the waste gas.

17.2.2.4 **Membrane Bioreactor**

In a membrane bioreactor, the waste gas stream is separated from the biofilm by a membrane that is selectively permeable to the pollutants. One side of the membrane is in contact with a liquid phase supplemented with nutrients, and the other side is in contact with the waste gas stream. The nutrient-rich liquid phase is inoculated with microorganisms capable of degrading the pollutant. These microorganisms organize themselves and form a biofilm attached onto the membrane. As the pollutants migrate through the selectively permeable membrane, they enter the nutrient-rich liquid phase and are degraded. The liquid phase is maintained in a reservoir where the nutrients are refreshed, oxygen is supplied and the pH and temperature are controlled. Different types of membranes can be used, such as polar or hydrophobic membranes. They can be installed as tubular or flat sheets. Figure 17.1 shows a close-up of the site of biological activity in the four types of bioreactors. Note that in a bioscrubber the microorganisms are in the second reactor and are fully suspended as flocs or granules in the liquid.

17.3 Performance Parameters

Different biological waste gas purification technologies can be compared based on performance by using a set of parameters. These parameters include

- empty bed contact time (s)
- surface loading rate ($m^3\ m^{-2}\ h^{-1}$)
- mass loading rate ($g\ m^{-3}\ h^{-1}$)
- volumetric loading rate ($m^3\ m^{-3}\ h^{-1}$)
- elimination capacity ($g\ m^{-3}\ h^{-1}$)
- removal efficiency (%)

The discussion below particularly relates to the biofilter type of reactor.

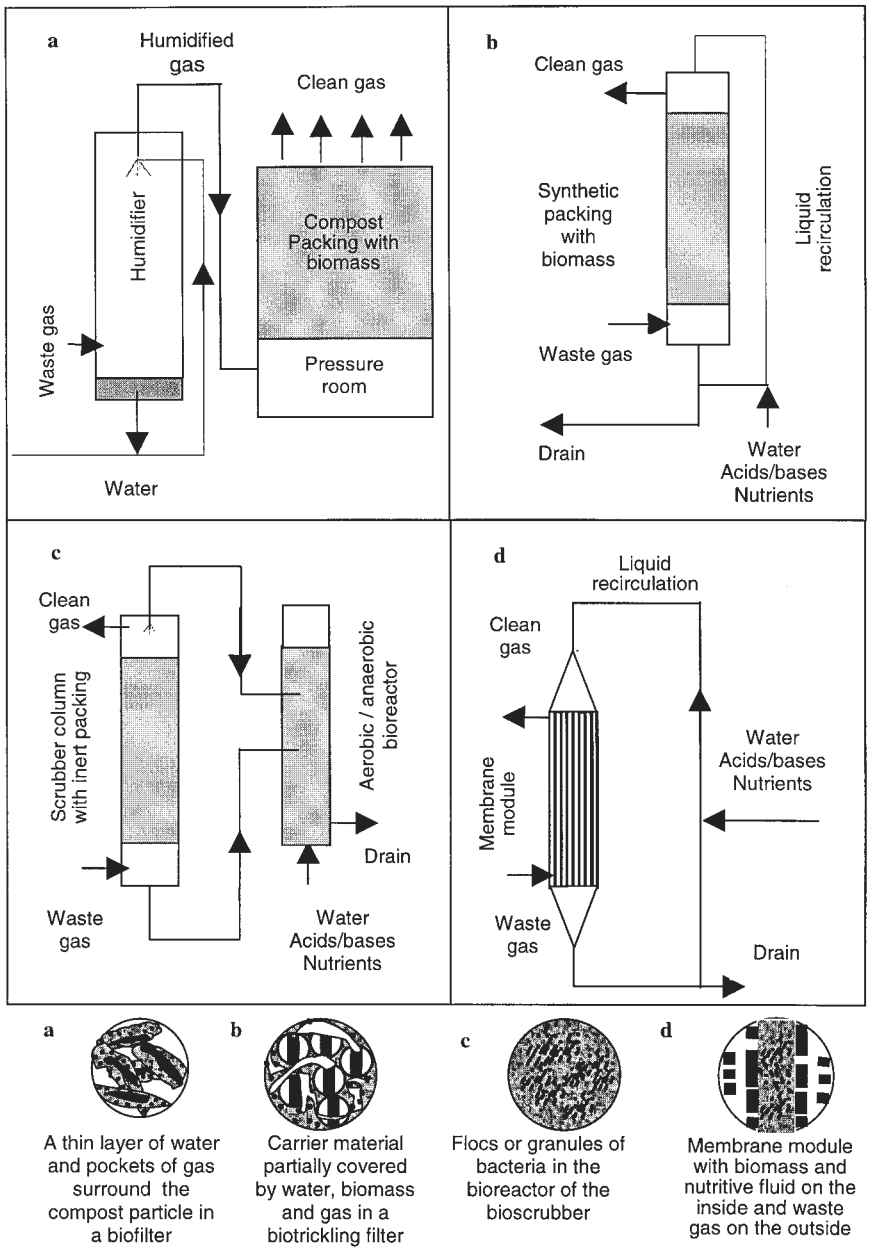

Fig. 17.1 Schematic representation of four types of bioreactors used in biological waste gas purification and close-up view of their respective microbial configurations: (a) biofilter, (b) biotrickling filter, (c) bioscrubber, (d) membrane bioreactor.

17.3.1
Empty Bed Contact Time or True Contact Time

The residence time of the gas in a bioreactor can be calculated in two different ways;

- Superficial residence time or empty bed residence time, based on the total volume of the reactor and referred to as empty bed contact time (EBCT):

$$\mathrm{EBCT} = \frac{V3600}{Q} \tag{1}$$

  where V = volume of filter material in the reactor (m^3), and Q = waste gas flow rate ($m^3\ h^{-1}$).
- True residence time τ, which is based on the free space in the reactor and defined as

$$\tau = \frac{\varepsilon V\,3600}{Q} \tag{2}$$

  where ε = porosity of the packing materials (dimensionless).

Often the exact porosity needed to calculate the true residence time is not known. Hence, most often the empty bed contact time is used. The EBCT is typically used for comparison of gas residence times in different reactor technologies or under different loading conditions. However, one has to remember that this gives an overestimation of the true residence time. Due to preferential currents through the larger voids in the packing, the actual residence time can differ considerably from the calculated residence time.

The residence time in the reactor is useful as an indicator of the time available for mass transfer of the pollutant from the gas phase to the liquid phase through the biofilm, which is often the factor limiting microbial degradation.

17.3.2
Surface Loading Rate (B_A)

The surface loading rate indicates the amount of air that is passed through the bioreactor per unit surface area per unit time:

$$B_A = \frac{Q}{A} \tag{3}$$

where A = total surface area of the packing or filter material in the bioreactor (m^2).

One can also express the velocity of the gas ($m\ h^{-1}$) through the empty reactor. However, the reactor is normally filled with packing materials, which results in a velocity of gas higher than the surface loading rate.

17.3.3 Mass Loading Rate (B_V)

The mass loading rate gives the amount of pollutant that is introduced into the bioreactor per unit volume and per unit time:

$$B_V = \frac{QC_{g-in}}{V} \tag{4}$$

where C_{g-in} = concentration of the pollutant in the inlet waste gas stream (g m^{-3}).

17.3.4 Volumetric Loading Rate (v_S)

The volumetric loading rate is the amount of waste gas passed through the reactor per unit reactor volume:

$$v_S = \frac{Q}{V} \tag{5}$$

17.3.5 Elimination Capacity (EC)

The elimination capacity EC gives the amount of pollutant removed per volume bioreactor per unit time. The overall elimination capacity is defined by Eq. (6):

$$EC = \frac{Q(C_{g-in} - C_{g-out})}{V} \tag{6}$$

where C_{g-out} = concentration of the pollutant in the effluent waste gas (g m^{-3}).

17.3.6 Removal Efficiency (RE)

Removal efficiency is the fraction of the pollutant removed in the bioreactor expressed as a percentage. It is defined as

$$RE = \frac{(C_{g-in} - C_{g-out})}{C_{g-in}}\ 100 \tag{7}$$

We should note that the various parameters are interdependent. There are only four independent design parameters: reactor height, volumetric loading rate, and gas phase concentrations at the inlet (C_{g-in}) and outlet (C_{g-out}).

17.4 Characteristics of the Waste Gas Stream

Several characteristics of the waste gas stream have to be known when considering the implementation of biological waste gas purification technologies. Table 17.1 lists the characteristics of the waste gas stream that are essential for correctly designing a biological purification system.

Physical parameters such as relative humidity and temperature are important, because they have considerable influence on microbial degradation of the pollutant. Different microorganisms have different optimal ranges of temperature and relative humidity for growth. Temperature also affects the partitioning of the pollutant between the gas and liquid phases. The waste gas flow rate influences the volumetric loading rate of pollutant on the biologically active phase and, hence, the elimination capacity. Equally important are the identity and concentration of the pollutant and/or odor units in the waste gas stream, because they influence the overall efficiency of the biological waste gas system.

It is also important to establish the chemical composition of the waste gas stream before starting to design the treatment system. The microbial degradability of the pollutant in the waste gas stream is largely dependent on its chemical identity. The pollutant can be organic or inorganic. Typical organic pollutants that are often encountered in waste gas streams are ethers, ketones, fatty acids, alcohols, hydrocarbons, amines, and organosulfur compounds. Valuable information about the biodegradability of chemicals can be obtained, e.g., from Van Agteren et al. (1998). Waste gases can also contain inorganic compounds such as NH_3, NO_2, NO, H_2S, and SO_2. Some of these compounds may be present at toxic levels or they may reduce the degradation capacity by, e.g., acidifying the biofilter material. Therefore, either these compounds have to be eliminated before the waste gas stream enters the bioreactor, or a means of controlling the pH has to be installed. Different compounds can also

Table 17.1 Important characteristics of a waste gas stream.

Parameter	*Unit*
Relative humidity	%
Temperature	°C
Waste gas flow rate	$m^3\ h^{-1}$
Pollutant identity (chemistry)	
Pollutant concentration	$g\ m^{-3}$
Odor concentration	$ou\ m^{-3}$

Odor unit (ou) is the amount of (a mixture of) odorous compounds present in 1 m^3 of odorless gas (under standard conditions) at the panel threshold (CEN, 1998).

affect each other's degradation without being toxic to the microorganisms. Smet et al. (1997) reported that isobutyraldehyde (IB) had to be removed by a first layer of the biofilter before a *Hypohomicrobium*-based microbial community in a subsequent layer could develop and metabolize the dimethyl sulfide (DMS) present in the waste gas. In separate batch experiments they showed that the same *Hypohomicrobium* sp. switched its metabolism from using IB to consuming DMS when the IB concentrations decreased.

When bioreactors are used for odor abatement, the concentration of odiferous compounds in the waste gas has to be determined as well. The odor concentration in odor units per cubic meter (ou m^{-3}) corresponds to the number of times a waste gas sample has to be diluted with reference air before the odor of the diluted sample can be distinguished from the reference air by 50% of the members of a standard panel. In this respect, the European Committee for Standardisation (CEN) is currently involved in standardizing the determination of odor compounds by dynamic olfactometry. This will improve the reproducibility of olfactometric measurements, basically by using panels standardized with respect to 1-butanol (detection threshold of 40 ppbv) (CEN, 1998). Although the evaluation of bioreactor performance aimed at odor reduction has to be based on olfactometric measurements, design and optimization always require chemical characterization of the overall process.

The concentration of the pollutants and/or odor units largely depends on the source of the waste gas stream. Waste gas streams from, e.g., hexane oil extraction processes have a pollutant concentration in the range of a few g m^{-3}. On the other hand, for waste gas streams polluted with offensive odors, concentrations of the odorous compounds can be in the range of mg m^{-3} or less (Smet et al., 1998).

The characteristics of the waste gas stream determine to a large extent the type of bioreactor system that can be used. Table 17.2 gives a first indication of the suitability of bioreactors for waste gas purification in relation to the characteristics of the waste gas stream. Note the preponderant importance of the Henry coefficient. Chemicals that dissolve easily in water (hydrophilic substances) can be retained efficiently by scrubbing with water. Chemicals that are poorly water soluble (high Henry coefficient) are better dealt with by means of a biofilter. In Table 17.2, the mem-

Table 17.2 Pollutant concentrations, Henry coefficients, and concomitant operating parameters of biofilters, biotrickling filters, and bioscrubbers (after van Groenestijn and Hesselink, 1993).

	Biofilter	***Biotrickling Filter***	***Bioscrubber***
Pollutant concentration (g m^{-3})	<1	<0.5	<5
Henry coefficient (dimensionless)	<10	<1	<0.01
Surface loading rate (m^3 m^{-3} h^{-1})	50–200	100–1000	100–1000
Mass loading rate (g m^{-3} h^{-1})	10–160	<500	<500
Empty bed contact time (s)	15– 60	30–60	30– 60
Volumetric loading rate (m^3 m^{-3} h^{-1})	100–200		250–580
Elimination capacity (g m^{-3} h^{-1})	10–160		
Removal efficiency (%)	95– 99		85– 95

brane reactor is not mentioned – depending on the nature of the membranes, it can be suited to handle a range of compounds (Stern, 1994).

17.5
Process Principles

Several processes take place in biological waste gas cleaning systems. They include partitioning of the pollutant from the gaseous to the liquid phase, followed by its diffusion from the bulk liquid to the biofilm. Microbial degradation of the pollutant takes place in the biofilm, and the end products diffuse back into the bulk liquid. Mass transfer is the combined migration of compounds from the gaseous to the liquid phase and from the bulk liquid to the biofilm (Fig. 17.2).

17.5.1
Equilibrium Partitioning of the Pollutant

The first step toward microbial degradation of the pollutant is partitioning of the gaseous pollutants to the liquid phase. In a bioscrubber and biotrickling filter this is obvious, but also in a biofilter a small water layer is normally present on top of the microbial biofilm.

In describing gas–liquid mass transfer, the interfacial resistance between the liquid and the gas is often neglected. For practical reasons, it is usually assumed that straightforward partitioning of the pollutant between the two phases occurs, and the resulting concentration in both the gas and the liquid phase is at equilibrium. Equilibrium partitioning largely depends on the Henry constant of the pollutant.

The concentrations of the pollutant in the gas and liquid phases are related by Eq. (8) (Sander, 1999).

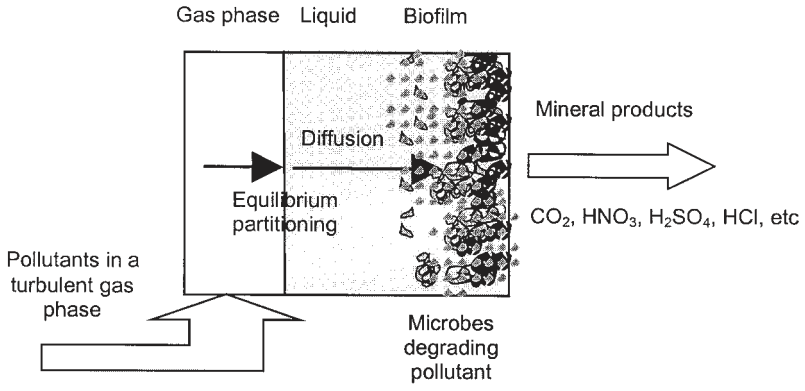

Fig. 17.2 Schematic view of the sequence of processes leading to microbial degradation of pollutants in a biofilter.

$$K_H = \frac{C_g}{C_l} \tag{8}$$

where: K_H = dimensionless Henry constant, C_g = gas phase concentration (mol m^{-3} or g m^{-3}), and C_l = liquid phase concentration (mol m^{-3} or g m^{-3}).

For pollutants with high Henry constants, partitioning of the pollutant to the liquid phase is very poor. In Table 17.3 some Henry constants are compared for different kinds of pollutants. The Henry constant varies with temperature and with salinity of the water. Dewulf et al. (1995) carried out several measurements of Henry constants and found that, in general, the Henry constant increases with a decrease in temperature and increases with an increase in salinity, as expressed by Eq. (9):

$$\ln K_H = a\,\frac{1}{T} + bZ + c \tag{9}$$

where: K_H = dimensionless Henry constant, a, b, c = constants, T = absolute temperature (K), and Z = salt concentration (g L^{-1}).

In a biofilter, there is a low water content (40%–60%), and therefore the gas–liquid mass transfer takes place with less interfacial resistance than in a biotrickling filter or a bioscrubber, where the water content is higher. In a membrane bioreactor there is no gas–liquid interface. Therefore, this reactor can be very suitable for treating pollutants with high Henry coefficients, provided the membrane is quite apolar such as are, e.g., silicone membranes (De Smul and Verstraete, 1999). However, we should note that in a membrane bioreactor, two mass transfers have to be dealt with: gas–membrane and membrane–biofilm. For the gas–membrane mass transfer, an equation similar to the Henry equation can be used:

$$S = \frac{C_m}{C_g} \tag{10}$$

where: S = solubility ratio (dimensionless), C_g = gas phase concentration (mol m^{-3} or g m^{-3}), and C_m = pollutant concentration in the membrane (mol m^{-3} or g m^{-3}).

Methods to enhance gas–liquid mass transfer have been explored. Addition of a surface-active reagent, as, e.g., silicone oil, to the liquid phase gives good results in laboratory-scale biofilters (Budwill and Coleman, 1997). In a biotrickling filter, intermittent circulation can be used to enhance the transfer of poorly water soluble pollutants into the biofilm. De Heyder et al. (1994) used this approach to remove ethene from air and obtained an increase in removal of ethene by a factor of 2.25.

Table 17.3 Henry constants (dimensionless) for pollutants treatable with a biotechnological waste gas treatment system (Howard and Meylan, 1997).

Compound:	*Ethanol*	*Butanone*	*Isobuteral-dehyde*	*Dimethyl-sulfide*	*Trichloro-ethene*	*Limonene*	*Hexane*
K_H (25 °C)	0.00021	0.0023	0.0074	0.0658	0.403	0.82	74

17.5.2 Diffusion

Migration of the pollutant from the bulk liquid to the biologically active phase (biofilm) occurs by diffusion, which can be described by Fick's law:

$$J = - D \frac{dC_1}{dx} \tag{11}$$

where: J = mass flux (mol m^{-2} s^{-1} or g m^{-2} s^{-1}), D = diffusion coefficient (m^2 s^{-1}), C_l = liquid concentration (mol m^{-3} or g m^{-3}), and x = distance within the biofilm (m).

The value of the effective diffusion coefficient D varies over some orders of magnitude, depending on the medium (Table 17.4).

Diffusion is much slower in water than in air and even slower in a membrane than in water. In porous membranes, diffusion occurs through the fluid in the pores, and in dense membranes it occurs through the membrane material itself. When choosing a membrane, a study should be made to determine an appropriate material with high diffusion characteristics for the given pollutant.

In bioreactors without membranes, the pollutant has to pass through the water phase before it reaches the biofilm. The limit between the water phase and the biofilm is as yet vaguely defined. The diffusion coefficient varies between its value in water and in the biofilm (Devinny et al., 1999). Roughly, diffusion in a biofilm is about 0.5–0.7 of that in water. Most important in the whole concept is that the concentration gradient needed for diffusion flux is maintained by a constant input from the gas phase and removal of pollutants by the microbial degradation in the biologically active phase. Figure 17.3 illustrates the concentration gradient that exists between the gas phase, through the liquid phase, to the biofilm. Although microorganisms have high affinity for most biodegradable substrates, they can have difficulty in consuming substances at concentrations below 1 µg L^{-1} of water (Verstraete and Top, 1992). This so-called lower microbial threshold means that, for substances with high Henry constants, the corresponding levels (C_{thr} H) remain in the gas phase. Various approaches have been described to derive appropriate kinetic parameters from such performance curves (De Heyder et al., 1997b).

Table 17.4 Diffusion coefficients of some compounds in air, water, and membrane materials (after Reid et al., 1987).

Compound	D_{air} (m^2 s^{-1})	D_{water} (m^2 s^{-1})	*Membrane Material*	$D_{membrane}$ (m^2 s^{-1})
Oxygen			natural rubber	2.5×10^{-10}
Oxygen (25 °C)	1.40×10^{-5}	2.50×10^{-9}	polydimethyl siloxane (35 °C)	4.0×10^{-9}
Ethanol	1.24×10^{-5}	1.13×10^{-9}	poly(vinyl acetate)	1.5×10^{-13}
CO_2	1.64×10^{-5}	2.00×10^{-9}	PMDA-MDA (20 °C)	9.0×10^{-13}
Benzene	1.20×10^{-5}	1.30×10^{-9}	poly(vinyl acetate)	4.8×10^{-17}

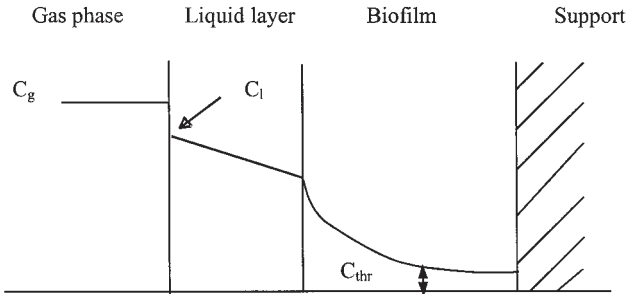

Fig. 17.3 Concentration gradient of a pollutant between the gas phase, through the liquid phase, to the biofilm. C_g: concentration in the gas phase; C_l: concentration in the liquid phase; C_{thr}: lower threshold level.

17.5.3
Microbial Degradation of the Pollutant

Microbial metabolism of pollutants readily occurs when the pollutants are used as a source of energy. For instance, toluene is used as an electron and carbon donor by several organotrophic bacteria; they use oxygen as an electron acceptor. Ammonium is used as an electron donor by lithotrophic nitrifying bacteria; they use oxygen as an electron acceptor and carbon dioxide as a carbon source to build cell biomass (Focht and Verstraete, 1977). Sometimes the pollutant can be a cosubstrate. For instance, trichloroethene can be metabolized together with toluene (Mu and Scow, 1994).

Sufficient availability of nutrients such as minerals, vitamins and growth factors is essential for proper growth of the microbial community. Hence, the microbial biomass acts as a kind of biocatalyst that constantly maintains itself (e.g., by dying off and regrowing).

The energy released during degradation of the pollutants is used for maintenance metabolism and for growth of the microorganisms, according to the modified Monod equation:

$$\frac{dC_1}{dt} = \left(\frac{\mu}{Y_{XS}}\right) X \tag{12}$$

where: C_l = concentration of the substrate dissolved in the liquid (g m^{-3}), μ = growth rate (g g^{-1} h^{-1}), Y_{XS} = yield of dry cell weight per mass of substrate metabolized (g g^{-1}), m = maintenance energy consumption [g substrate (g cell dry weight)$^{-1}$ h^{-1}], and X = dry weight of biomass in the biofilm or suspension (g m^{-3}).

In practice, however, it is difficult to obtain values for these parameters. Therefore, the design of reactor performance should be based on pilot experiments.

In a waste gas treatment reactor, growth of the bacteria is often minimal. This means that all the released energy serves mainly for maintenance metabolism of the bacteria. The advantage is that there is little or no waste sludge, in contrast to, e.g., wastewater treatment systems. Often one deliberately tries to minimize the growth of excess biomass, e.g., by limiting the supply of mineral nutrients such as phos-

phate (Wubker and Friedrich, 1996) or by seeding the reactor with protozoa that graze on the bacteria (Cox and Deshusses, 1999). Microbial degradation of the pollutant depends on a multitude of factors. The most important external factors are temperature, nutrient availability and toxicity of the gaseous components. There are also a series of internal factors directly related to the way microorganisms develop and work. For instance, different species, each with different capabilities, can cooperate and achieve very effective pollutant removal. De Heyder et al. (1997a) described the stimulation of ethene removal by *Mycobacterium* sp. in the presence of an active nitrifying population. Veiga et al. (1999) identified two different bacterial species (*Bacillus* and *Pseudomonas*) and a fungus (*Trichosporon*) functioning as cooperative agents in a biofilter treating alkylbenzene gases.

The microorganisms (biomass) can be introduced into the bioreactor in several ways. In some situations, natural sources such as manure, aquatic sediments or sludge from wastewater treatment plants are used as the inoculum. Moreover, in a biofilter, the carrier material (compost, wood bark, etc.) itself has a naturally occurring microbial community. In other instances, specific bacteria or mixtures of isolated strains of naturally occurring bacteria that can metabolize the pollutant in the waste gas stream are introduced into the bioreactor (Kennes and Thalasso, 1998). Such seeding is referred to as bioaugmentation. To accelerate the removal of a particular recalcitrant pollutant, one could make use of genetically modified microorganisms having improved degradation capacities. For bioscrubbers in which the removal occurs in an activated sludge reactor system, bioaugmentation as described for wastewater systems by Van Limbergen et al. (1998) could be applied.

Generally, inoculation of the reactor with appropriate bacteria significantly decreases the startup period for these reactors (Smet et al., 1996). However, the operating conditions and the prevailing environmental factors generally exert selective pressure on the microorganisms present in the bioreactor, resulting in the development of a specific microbial community. This community can be quite different from the enrichment culture that was introduced into the reactor (Bendinger, 1992). The development of the structure and function of the microbial community in the bioreactor affects the microbial degradation rate and, hence, the extent of pollutant removal. The microorganisms are surrounded by an extracellular organic layer, which normally has a negative charge and serves many functions, including adhesion, protection, carbon storage, and ion exchange (Bishop and Kinner, 1986).

Most often, biological waste gas treatment results in non-reusable end products. For SO_2 scrubbing, however, a special approach has been developed (De Vegt and Buisman, 1995; Verstraete et al., 1997). As schematized in Figure 17.4, a sequence of biotechnological reactors enables SO_2 to be recovered as sulfur powder.

17.6 Reactor Performance

The overall performance of a bioreactor is mainly determined by mass transfer, as governed by equilibrium partitioning at the gas–liquid phase and diffusion from the

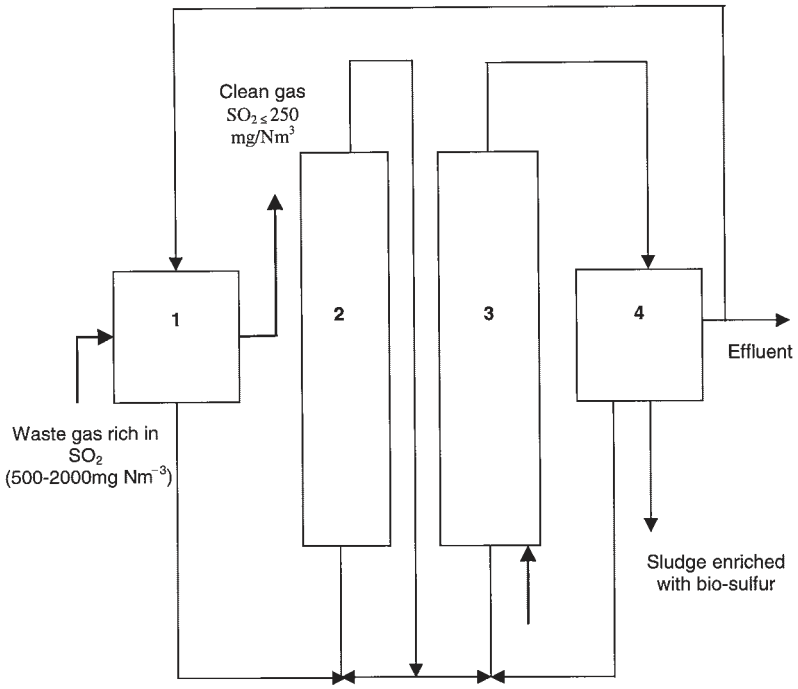

Fig. 17.4 Conversion of SO_2 by means of sulfate reduction and subsequent sulfide oxidation reactors to biologically formed elemental sulfur (after Grootaerd et al., 1977). 1: absorption of SO_2 gas; 2: sulfate reduction; 3: partial oxidation of hydrogen sulfide; 4: separation of sludge enriched with biosulfur.

bulk liquid to the bioactive phase (biofilm), combined with microbial degradation of the pollutant. As mentioned before, this is expressed in removal efficiency (%) or elimination capacity (g m^{-3} h^{-1}). Figure 17.5 shows a typical elimination capacity as a function of the mass loading rate. Such a performance diagram can be experimentally determined by changing the concentration in the influent gas flow and measuring the resulting elimination capacity. In most studies these curves are determined in short-term experiments. This means that no significant growth of biomass is allowed to occur during the experiment. In Figure 17.5, two main regions can be distinguished. At the lower mass loading rate the elimination capacity is equal to the mass loading, and the removal efficiency is 100%. In this range the reactor kinetics are first-order; the microbial metabolism normally represented by the Monod equation follows a simple equation:

$$-\frac{dC_1}{dt} = \frac{KC_1}{K_S + C_1} \tag{13}$$

where: C_l = concentration in the liquid (mol m^{-3} or g m^{-3}) substrate, K = maximum conversion rate (g substrate (g cell dry weight)$^{-1}$ h^{-1}), and K_S = substrate level at which the biomass works at half-maximum velocity (mol m^{-3} or g m^{-3}).

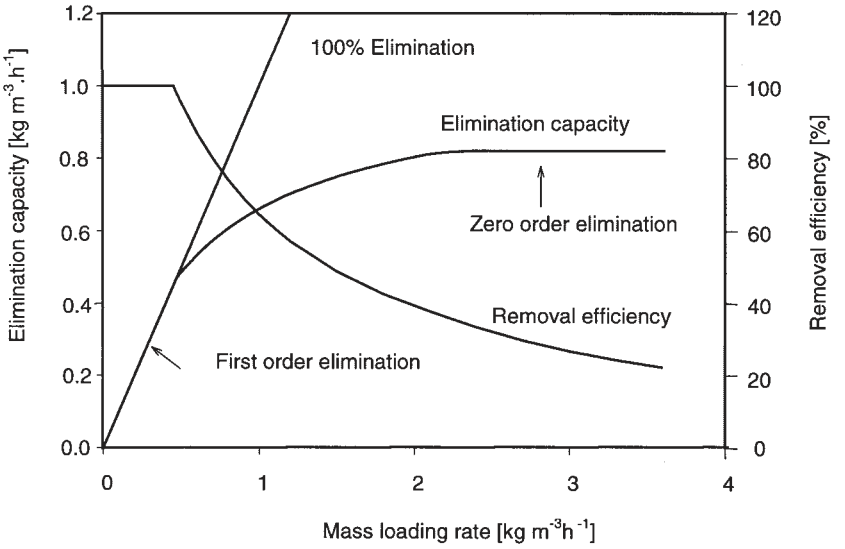

Fig. 17.5 Typical curve for the elimination capacity of a biofilter vs. its mass loading rate.

When $K_S \geq C_1$, Eq. (13) becomes

$$-\frac{dC_1}{dt} = kC_1 \tag{14}$$

All pollutants that are fed to the biofilter are removed from the air. Low mass loading can be achieved by a low concentration of the pollutants in the gas phase and by a low gas flow rate. When the mass loading increases, complete removal of the pollutants is no longer possible. At even higher mass loading, the elimination capacity does not increase further and remains at a steady value. This is the region of zero-order kinetics: the elimination capacity is independent of the mass loading rate. At this stage the removal efficiency (%) decreases as the mass loading rate is increased further. Two phenomena explain the incomplete removal of the pollutants: diffusion and reaction limitation. In diffusion limitation, not all the pollutants diffuse into the biofilm and not all microorganisms can take part in degradation of the pollutant. When the diffusion rate is slower than the degradation rate, e.g., for pollutants with a high Henry coefficient, the concentration in the liquid phase is lower than in the gas phase. In reaction limitation, the pollutants diffuse into the complete biofilm, but the pollutants are not removed rapidly and sufficiently enough by the biocatalyst. Indeed, microbial metabolism can be hampered by other limiting factors such as shortage of nutrients, presence of toxins, etc.

17.7 Reactor Control

The environmental factors prevailing in the bioreactor, such as pH, temperature, oxygen level and water content, affect the ability of the microorganism to metabolize the pollutant. Prevailing environmental factors largely determine the composition of the microbial community in the bioreactor. Most species of microorganisms exhibit optimal growth over a certain pH range (Devinny et al., 1999). A pH range of about 6–8 is suitable for most microorganisms, but some species can tolerate lower or higher pH values. Microbial activity is strongly influenced by temperature. Some microorganisms operate optimally in the mesophilic temperature range (15–40 °C), and others do so in the thermophilic temperature range (40–60 °C).

The microbial activity and the mass transfer of the pollutant from the gas phase to the biofilm are related to the water content in the bioreactor. This is especially true for biofilters that operate optimally at 40%–60% relative humidity (Devinny et al., 1999). Excess water in a biofilter may lead to loss of nutrient supplements (Smet et al., 1996). Moreover, wet pockets may be formed, in which diffusion of both pollutant and oxygen used as an electron acceptor for the microorganisms becomes limiting.

In practice, it is difficult to implement control and mitigation actions in biofilter systems. In contrast, because of the circulation of a liquid in the other reactor types, it generally is possible to optimize the latter reactor systems for temperature, pH, and nutrient supply. Eventually, if required, one can also supplement with a cosubstrate in accord with the needs of the bacteria.

17.8 Perspectives

Biological waste gas purification processes have strong competitors, such as activated carbon sorption and incineration. Also other physicochemical techniques, with a small footprint, are more frequently marketed for odor treatment of air, e.g., ozonization and UV treatment. The main advantages of biocatalytic removal of pollutants are the low investment and operation costs. The main disadvantages are the often slow startup and the limited reliability, e.g., as a result of changing environmental conditions and autointoxication.

The major efforts in the near future for bioprocess engineers should therefore be directed to the development of reactors with a controllable microbial biomass. Adequate natural or even possibly genetically modified organisms should be available as ready-to-use industrial biocatalysts. They should, as occurs for activated carbon, be immediately operational upon introduction in the reactor. Moreover, the overall environment and performance in the reactor should be monitored online and, if necessary, adjusted. These aspects, mass production of biocatalysts with a guaranteed quality and implementation of process control, are crucial for the future of biological waste gas treatment.

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