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REVIEWS

Biological systems for waste gas elimination

Simon P. P. Ottengraf

Since the early sixties biological processes have been introduced as a technique for odour abatement of waste gases. Nowadays there is a clear trend to use these systems more broadly. In the last four years these processes have been developed into a technique of increasing importance for air pollution control. These reliable and cheap techniques have proved to be very appropriate for the prevention of air contamination with undesirable components in general.

The continuing use of water, soil and air for the disposal of liquid, solid and/or gaseous wastes is partly based on the principle of dilution: if wastes are sufficiently diluted, their presence is not noticeable, sometimes even not detectable. This is not a good starting point for a trustworthy and correct environmental control. 'Dilution is no solution for pollution'. The trend is, therefore, towards controlled processing of wastes, and in these biological processes are playing increasingly an important part. In the environment, it is biological processes which play an important role in the final elimination of compounds by mineralization.

Microbial purification processes are based on the ability of many micro-organisms (generally bacteria, and to a small extent filamentous fungi and yeasts) to degrade a variety of organic compounds (Fig. 1). Under aerobic conditions, these organisms can oxidize compounds into mineral end-products (e.g. H_2O , CO_2 etc.). Part of the organic compounds is transformed into new cell material (Fig. 1).

The biodegradability of organic compounds generally reflects their source: they can be classified as

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biogenic (of natural origin) or anthropogenic (man-made) (Fig. 2).

During millions of years' evolution micro-organisms have developed enzymatic systems to degrade biogenic compounds very well. Of the anthropogenic compounds, the xenobiotic compounds include those sufficiently resembling biogenics to be rather well degraded (weak xenobiotics) and those with such unnatural structures that their biodegradation is very low (recalcitrant compounds) or even nil (persistent compounds).

Gaseous waste

Discharged industrial waste gases contain volatile organics and sometimes oxidizable inorganic compounds. Many of these discharged compounds can be smelled by

humans at very low concentrations (ppm or ppb levels) and even small emissions cause a nuisance even if they do not directly endanger health.

Biological methods are increasingly being applied in the purification of waste gases. Biological processes generally have the advantage that pollutants are not transferred to another phase and therefore, new environmental problems are not created or are only minimal. Moreover, these processes are cheap and reliable and do not usually require complex process facilities.

Biological processes

Volatile organic compounds in waste gases can serve as energy sources and/or carbon sources for microbial metabolism. In addition, oxidizable inorganic compounds in odorous waste gas (e.g. H_2S , NH_3) may be treated directly by biological methods as the micro-organisms concerned are autotrophic (CO_2 in the waste gas serves as a carbon source for anabolism). As micro-organisms need a relatively high water activity, the oxidation reactions take place in the aqueous phase: both the waste compounds to be degraded and the oxygen required for their oxidation have to enter the liquid phase. Therefore, mass transfer processes are important.

There are three groups of biological waste gas purification systems which can provide appropriate conditions: bioscrubbers, trickling filters and biofilters. They can be distinguished (Table 1) by the behaviour of the liquid phase (which is either continuously moving or stationary in the contact apparatus)

Fig. 2

and of the micro-organisms (which are either freely dispersed in the aqueous phase or immobilized on a carrier or packing material). In compost production plants, sewage plants and in agriculture there is a preference for biofilters and trickling columns, while biofilters and bioscrubbers are preferred in industry¹.

Bioscrubbers

A bioscrubber (Fig. 3a) generally consists of a scrubber compartment and a regeneration compartment². In the scrubber compartment which may be a spray column in which finely distributed water droplets flow countercurrently with the waste gas, there is a continuous mass transfer of pollutants and oxygen from the waste gas to the liquid phase.

The rate of mass transfer of a given compound is determined by the product of the overall mass transfer coefficient, the total contact area in the column, and the average driving force (the difference between the equilibrium concentration and the actual concentration in the water-phase of the compound). Hence the absorption of a compound will be higher if its concentration in the wastewater is low and its solubility in water higher. Substances absorbed in the water will be oxidized through microbial activity and eliminated from the liquid phase by an activated sludge suspension in a regeneration compartment.

Mixing either by stirring or by aeration may be necessary to prevent sedimentation of the microbial sludge suspension. Physical and chemical conditions (e.g. temperature, pH value, carbon to nitrogen to phosphorous ratio) will need to be adjusted to assure optimal microbial oxidation.

Bioscrubbing processes have already been successfully employed

in several branches of industry; e.g. waste gases from enamelling ovens, containing alcohols, glycols, ketones, glycolether, aromats, resins etc. have been treated. Waste gases from incinerators, foundries (containing amines, phenol, formaldehyde, ammonia etc.) and fat smelteries have been deodorized³⁻⁵.

Trickling filters

In contrast with bioscrubbers, in trickling filters the processes of gas absorption and liquid phase regeneration occur simultaneously in one process apparatus. Trickling filters

oxygen are transferred to the liquid phase, then to the biolayer where they are eliminated by aerobic biological reactions. In this way, a continuous driving force for mass transfer of further gaseous compounds into the liquid phase is established.

Slime caused by microbial growth and mineralization of the biofilm may be sloughed off onto the liquid phase but this can, if necessary, be withdrawn from the water before recirculation. As a result of evaporation, some fresh water has to be continuously supplied to the system.

Trickling filter columns have been used for many decades in sewage treatment⁶⁻⁸. The fundamental mode of operation is essentially the same as when applied to gas purification, but it is the water phase which has to be biologically purified.

Biofilters

To begin with, biofiltration was mainly used for odour abatement in

Table 1

Distinctions between biological waste gas purification systems

		Aqueous phase	
		Moving	Stationary
Microbial flora	Dispersed	Bioscrubbers	
	Immobilized	Trickling filters	Biofilters

(Fig. 3b) generally consist of columns filled with packing on whose surface a biofilm of microbial flora several millimeters thick develops. The specific area (the contact area per unit of column volume) of the packing is relatively low, 100–300 m² m⁻³. This creates a large void volume for gas passage, thus minimizing both the gas pressure drop in the column and the risk of the void space becoming obstructed by biological growth and loose films.

Water, containing dissolved inorganic nutrients, is continuously supplied at the upper side of the column and homogeneously distributed over the column cross section. This water flows down in a thin film, which surrounds the packing material and wets the biolayer. The waste gas is forced to rise through the void volume against the water flow. Water-soluble components and

waste water treatment plants, composting works and similar sites⁹⁻¹⁷.

The general design of such a conventional biofilter is shown in Fig. 4. The odorous waste gas is forced to rise through a layer of a biologically active packing of natural origin (compost, peat etc.) with a thickness of around 50–100 cm. Mixtures of these materials with chips of wood, heather-branches etc.

Table 2

Design parameters of conventional compost filters

gas velocity (superficial)	10–100 m ³ m ⁻² h ⁻¹
contact time	30–60 s
filter height	0.5–1.0 m
pressure drop	500–1000 Pa
water content	25–50% (w/w)
elimination capacity	6–16 g organic carbon m ⁻³ h ⁻¹

Fig. 3

and which create a loose structure for gas passage and prevent clogging have also frequently been used. The packing materials serve as a carrier for the microorganisms, mainly bacteria and fungi^{18,19}, which surround the constituting particles in a wet biolayer (Fig. 5a and 5b).

The packing material also supplies the inorganic nutrients necessary for microbial life. These nutrients are cycled but are eventually liberated by mineralization processes. Therefore,

the packing material will become exhausted and must generally be renewed usually after several years of operation. The packing particles of biological filters are usually of a size that provide both a reasonably adsorbing surface and an acceptable flow resistance: too small an adsorbing surface will necessitate an overly large and, consequently, uneconomical filter volume; too large a filter resistance will require an excessive energy consumption as the gas stream passes the filter.

and are usually greatly oversized to compensate for this (Table 2). They generally take up very large areas.

To meet the objections mentioned and to increase the reliability of compost filters, a number of closed systems have been developed^{20,21,26}. The composition and survival of the microbial flora on the packing are important process parameters. Some packing materials of natural origin, like compost, contain sufficient different genera to initiate the reactions for the elimination of simple (odorous) compounds. Following growth of the active strains, the efficiency of the purification process will be generally enhanced in the course of a certain adaption time (some few days or weeks) after the starting-up of a compost filter. The microbial flora can survive for fairly long periods when the filter bed is not loaded: periods of a fortnight are easily spanned, with hardly any loss

Fig. 4

Process considerations

For the optimal operation of the biological filter, the water content of the carrier material should be maintained at 30–60%: in open filters this is usually done by spraying water across the upper surface of the filter bed. Open systems such as that illustrated in Fig. 4 are exposed to a variety of weather conditions (rain, frost, temperature fluctuations etc.)

of microbial activity²². This is important in view of the dynamic behaviour of the filter bed during discontinuous operation, and means that reactivation times after the filter bed has lain idle (e.g., during holidays) will be relatively short.

The composition of packing materials has been very much improved in recent years²: 'ageing' of the filter packing can be retarded assuring an extended period (years) of relatively high biological activity; the pressure drop of the filter bed can also be decreased considerably and gas velocities of around 400 m h⁻¹ and elimination capacities of 100–200 g organic carbon m⁻³ h⁻¹ may be obtained for easily biodegradable compounds^{27–29}.

The macrokinetics of the degradation processes of a great number of volatile organic pollutants like alcohols, ketones, esters, aromatics etc. have been thoroughly studied in biofilter beds^{22,23}. Experimental results may be summarized as follows:

- the macrokinetics of the elimination processes in a biological filter bed can be modelled as an absorption process in a wet biolayer surrounding the constituent packing particles, accompanied by a biological degradation reaction;
- the elimination of these compounds within the bed follows zero order reaction kinetics down to very low concentrations of substrate. This has been confirmed by batch investigations of the degradation process in aqueous solutions of the compounds concerned;
- at low gas phase concentration levels or low water solubility of the compounds concerned, the elimination rate in the filterbed may become diffusion-controlled in the biolayer;
- the zero order kinetics of the elimination process means that any biodegradable compound may be removed completely during a finite residence time of the gas phase in the filter bed.

The cost of the biofilter process depends on the total volume rate of the waste gas to be treated, on the concentration and the nature of the pollutants concerned and on the cost of servicing the filter with piping, dustfilters, heat exchangers, humidifiers, etc. For a large number of treatment plants installed in the

Netherlands the total cost is in the range of Dfl. 0.50–2.50 (in US\$ 0.25–1.25) per 1000 m³ waste gas to be treated³⁰. This is low in comparison with the cost of conventional physical and/or chemical processes as adsorption, absorption, combustion (flame or catalytic), the total cost of which varies from Dfl. 5–20 (US\$ 2.5–10) per 1000 m³ waste gas to be treated dependent on the process concerned.

Microbial investigations

Microbial investigations reported

on in systems for waste gas purification have been mainly carried out in filter beds. In these systems, degradation is mainly due to bacteria and fungi. The growth and activity of these saprophytic organisms depend on the physical and chemical conditions in the packing material, such as water, oxygen, and mineral and organic matter content, the pH, and the temperature.

The diversity of the active microbial flora depends on the composition of the waste gas treated. Waste gases from specialized industrial plants, such as lacqueries and chemical plants may contain a very limited number of chemical compounds and the microflora may be restricted to a few species. It has become a common practice to inoculate the filter bed with pure cultures of microorganisms known to actively degrade the pollutants²³, whereas in odorous air discharged by sewage works and livestock a much wider range will be found¹. In contrast, the treatment of waste air streams polluted with numerous chemicals, such as those from sewage works or livestock sources, will require a wide range of microbial catabolic activity. Activated sludge from biological waste water treatment plants may be used as an inoculum in these cases.

In order to determine the microbial composition of a filter bed a method introduced by Cholodny²⁴ in 1930 for the examination of soil is frequently used. According to this method, clean slides are simply pushed vertically into the packing material, covering them and leaving them in the bed for one to three weeks. The slides are then carefully removed and stained.

In addition to microorganisms (Table 3), mites, collembolans and nematodes are frequently found.

Table 3
Frequently identified organisms in filter beds. (Data from Ref. 19)

Bacteria	Fungi
<i>Actinomyces globisporus</i>	<i>Penicillium</i> sp.
<i>Micrococcus albus</i>	<i>Cephalosporium</i> sp.
<i>Micromonospora vulgaris</i>	<i>Mucor</i> sp.
<i>Proteus vulgaris</i>	<i>Circinella</i> sp.
<i>Bacillus cereus</i>	<i>Cephalotecium</i> sp.
<i>Streptomyces</i> sp.	<i>Ovularia</i> sp.
	<i>Stemphilium</i> sp.

(See Ref. 2 for a more comprehensive treatment of this subject.)

Removal of xenobiotics

In recent years biofiltration has been extended to the elimination of xenobiotic compounds discharged by many branches of (the chemical) industry. Although the biota has not previously been exposed to them, some xenobiotic compounds are sufficiently similar to biogenic structures that their biodegradation is rapid. The recalcitrant or persistent xenobiotics however, possess such unnatural chemical structures, that their biological degradation is very slow or even impossible. Fortunately, the continuous adaption of microorganisms to new substrates offers an ever increasing number of opportunities to isolate microbes capable of degrading xenobiotics.

Once a suitable strain or mixed culture has been isolated in the laboratory (e.g., from contaminated soil or wastewater) it can usually be applied in biofiltration: strains selected in this way include organisms belonging to the genera *Nocardia* which degrade aromatics like xylene and styrene etc., a *Hyphomicrobium* sp. which degrades dichloromethane, a *Xanthobacter* sp. which degrades dichloroethane²³ and a *Mycobacterium* sp. which eliminates vinylchloride²⁵. Biofilter beds have the advantage of retaining these laboratory-isolated strains: they are immobilized on the packing material, and cannot drain from the system, as is often the case in freely dispersed systems like biowashers and activated sludge systems of waste water treatment systems.

In addition, waste gas streams containing xenobiotics often have a less complex composition making biodegradation easier. Waste gases containing different biodegradable, xenobiotic compounds can be treated in a multi-staged filterbed in which optimal growth conditions for different microbial populations can be provided at each stage. Multi-stage systems may also be necessary when waste gases include one component in very high concentrations. The dimensions of a filter stage are limited: the height is limited to prevent the compression of the packing material by its own weight

and the cross-sectional area may be limited by the space available.

A pilot scale three-stage plant for the purification of waste gas from a pharmaceutical factory, containing acetone, ethanol, 2-propanol and dichloromethane has been successfully tested²⁷. Each stage consisted of a biofilter 1 m high and 1.5 m in diameter and the gas flow rate in this system was $220 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$. Initially, the different stages were inoculated with an activated sludge suspension from a municipal sewage treatment plant. Acetone was mainly eliminated in the first stage at a maximum rate of $164 \text{ g carbon m}^{-3} \text{ h}^{-1}$. The second stage mainly eliminated ethanol and 2-propanol at a rate of $57 \text{ g carbon m}^{-3} \text{ h}^{-1}$. Degradation of dichloromethane was not recorded at all. After inoculating the third stage with a culture of *Hyphomicrobium* sp. degradation of dichloromethane occurred at a rate of approximately $15 \text{ g carbon m}^{-3} \text{ h}^{-1}$. Based on these results a full scale plant has now been installed.

As the demands for cleaner air become more vocal, and as the improvement of packing materials and microbial strains makes biofiltration more efficient and cheaper, the use of technology is likely to become more widespread. Eventually, it may be possible to provide 'off-the-shelf' biofiltration using the composition of the waste to dictate which of a panel of degradative microorganisms should be used in a multistage apparatus.

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