Inert filter media for the biofiltration of waste gases – characteristics and biomass control

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Abstract

Soil biofilters and related systems based onthe use of natural filter beds have been usedfor several years for solving specific airpollution problems. Over the past decade,significant improvements have been brought tothese original bioprocesses, among which thedevelopment and use of new inert packingmaterials. The present paper overviews the mostcommon inert packings used in biofiltration ofwaste gases and their major characteristics. Apotential problem recently encountered whenusing inert filter beds is the heterogenousdistribution of biomass on the packingmaterial, and the excessive growth andaccumulation of biomass when treating highorganic loads, eventually leading to cloggingof the biofilter and reduced efficiency.Several strategies that have been proposed forsolving such problems are described in thispaper. Technologies for controlling excessbiomass accumulation can be grouped into fourcategories based on the use of mechanicalforces, the use of specific chemicals, thereduction of microbial growth, and predation.

Keywords:
Air pollution, backwashing, biomass control, biotrickling filter, clogging, filter bed, nutrients, packing material, predation, perlite

1. Introduction

Conventional gas phase biofilters packed with natural carriers, usually compost, peat or soil, have been used for several decades for removing low odour concentrations mainly at wastewater treatment plants and composting facilities. More recently, performance of biofilters has progressively been improved, among others, through the modification of design parameters. Biofiltration can nowadays also be applied to a wider range of pollutants, higher contaminant loads, and an increased number of pollution sources (Kennes & Thalasso 1998). One relatively recent modification is the use of inert and synthetic filter beds, either in conventional biofilters or in trickling biofilters, also called biotrickling filters. In the latter an aqueous phase is continuously trickling over the filter bed while in conventional biofilters packed with inert carriers the addition of an aqueous phase is only occasional (Figure 1). The addition of a nutritive aqueous phase is a prerequisite for optimal bioreactor performance since nutrients, essential for optimizing the microbial activity, are not naturally available in inert filter beds. After describing the characteristics of the new packing materials and the role of the liquid medium, this paper reviews the biofilm characteristics and methods to control excess biomass accumulation.

2. Characteristics of new filter media

Examples of new common carrier materials used in biofiltration are listed in Table 1. Although only inert carriers will be considered here, efforts are presently also being made towards the development of improved organic filter beds. The use of pelletized and structured organic packings are some examples. Structured peat beads containing 30% mineral material were recently used in biofilters in order to try combining the advantages of both organic and inorganic materials (Wu et al. 1999). Inert carriers present several advantages but also some inconveniences when compared to the more conventional natural media. Although inert filter beds are, in most cases, more expensive than natural ones, the higher investment costs are often diluted by their longer lifetime and high performance. The new packing materials are characterized by a higher physical strength than most organic filter beds. The former are chemically and physically inert and do basically not suffer aging or biodegradation over time, contrary to natural organic supports as compost or peat. Therefore, bed compaction is often negligible with the former while it represents a major concern in case of the latter.

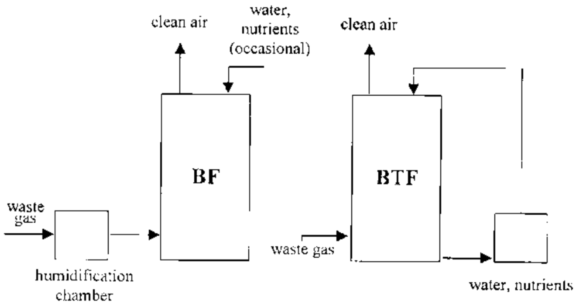

Figure 1. Comparison of the mode of operation of a biofilter (BF) and a biotrickling filter (BTF).

Table 1. Examples of new packing materials suitable for biofiltration of waste gases

Filter bed	Bioreactor (G/L flow)	References
Activated carbon	CBF	Weber & Hartmans (1995)
Ca-Alginate	CBF	Chung et al. (1997)
Celite	BTF (co-current)	Alonso et al. (1998)
	BTF	Song & Kinney (2000)
Ceramic beads	CBF	Yun & Ohta (1998)
Ceramic Raschig rings	BTF (counter-current)	Mirpuri et al. (1997)
Ceramic saddles	—	Davison & Thompson (1993)
Cotton terry cloth	BTF (counter-current)	Zhou et al. (1998)
Glass (Honeycomb tubes, Raschig rings)	BTF (co-current or counter-current)	Kirchner et al. (1991)
Lava stone	BTF (counter-current)	Pol et al. (1998)
Perlite	CBF	Kennes et al. (1996) Cox et al. (1997)
Polyamide beads	BTF (co-current)	Wübker et al. (1997)
Polypropylene Pall rings	BTF (co-current)	Cox & Deshusses (1999)
Polypropylene saddles	BTF (counter-current)	Okkerse et al. (1999)
Polyurethane foam	BTF (counter-current)	Pol et al. (1994)
	CBF	Moe & Irvine (2000)
PVD cubes	BTF (counter-current)	Pedersen et al. (1997)
Steel Pall rings	BTF (counter-current)	Pedersen & Arvin (1995)
Vermiculite	CBF	Oh & Choi (2000)

CBF: Conventional biofilter, BTF: Biotrickling filter, PVD: Polyvinyl difluoride.

Compaction of natural filter beds leads to significant pressure drop, channeling, the formation of anaerobic zones and, consequently, a decreased performance after long term operation. Organic beds have a limited lifetime and usually need to be replaced after less than five year operation. Conversely, basically no compaction problem will be encountered with inert carriers. Therefore, pressure drop will be minimal, provided growth of excess biomass is avoided. Strategies developped to control biomass accumulation will be discussed later in this paper. This is an important topic since plugging problems with the new inert filter beds are mainly linked to excess biomass growth combined to the effect of other important parameters as, for example, media particle size and superficial gas velocity. Excess biomass may also appear in the case of natural carriers but its removal is much more difficult, not to say impossible.

Biomass growth and activity relies on the amount of available nutrients, which are absent in inert carriers. This may be considered a drawback since their addition is necessary for reaching and maintaining a combination of optimum Elimination Capacities/ Removal Efficiencies. However, it is to some extent also an advantage as the amount of nutrients added to the system can be exactly regulated and controlled by the operator. This is not possible with more conventional organic carriers which do already naturally contain some nutrients as nitrogen, phosphorus, and other elements needed in trace concentrations by the microorganisms. Nutrients in natural filter beds are most often not present in balanced ratios for an optimal microbial activity. They then need to be added, above all when they get exhausted, after long term biofilter operation (Delhoménie et al. 2001; Morgenroth et al. 1996;Weckhuysen et al. 1993).

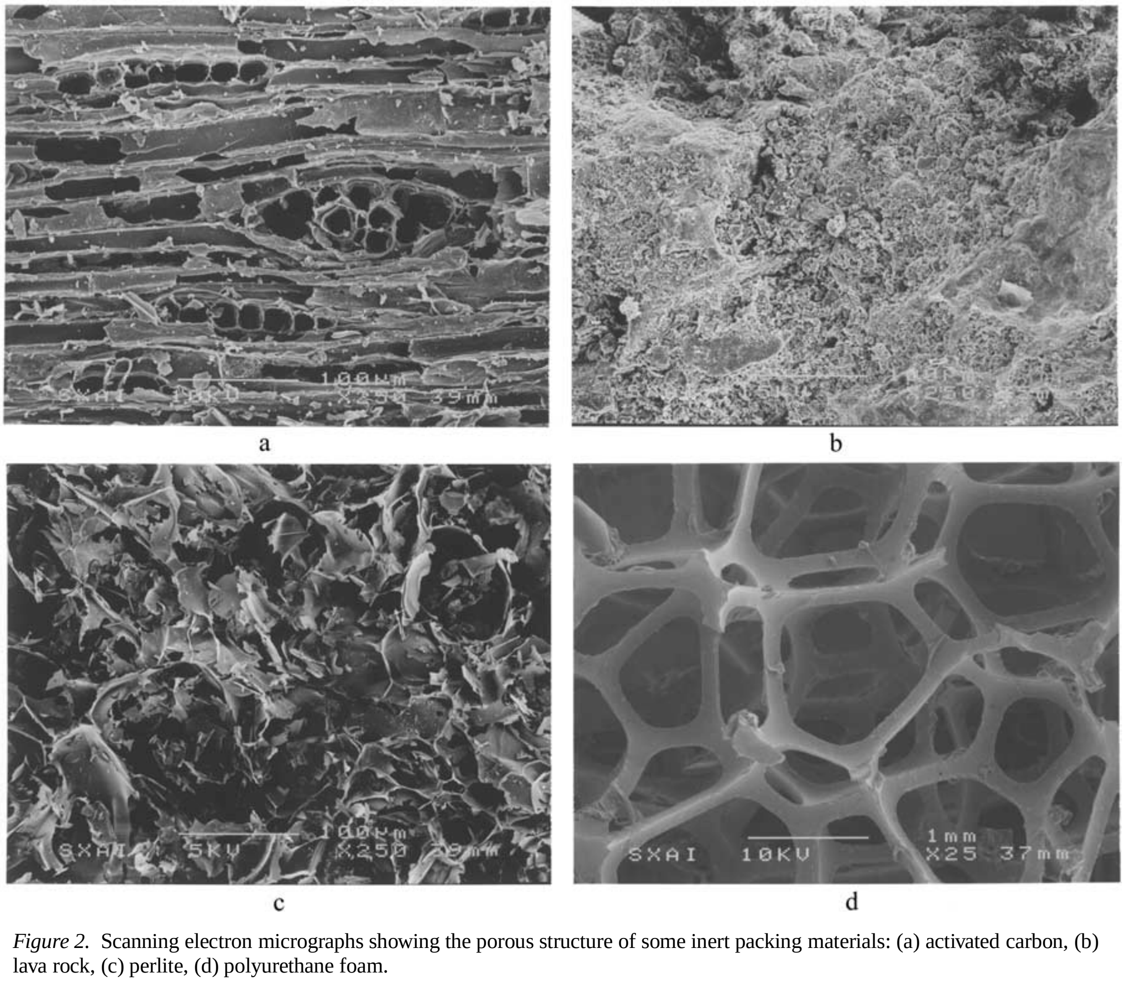

Figure 2. Scanning electron micrographs showing the porous structure of some inert packing materials: (a) activated carbon, (b) lava rock, (c) perlite, (d) polyurethane foam.

Another important characteristic of most inert carriers is that they present a much more regular shape than natural ones, allowing a uniform air distribution, limiting at the same time channeling problems. In case of channeling, only part of the carrier would be efficiently used and the mean air residence time would then decrease, meaning that a higher filter bed would be required for reaching the same performance as in a similar system without channeling. This is also one of the reasons why inert materials are often added in different ratios to organic filter beds (Kennes & Thalasso 1998).

A quite wide variety of new filter beds has been used and described in the literature (Table 1, Figures 2 and 3). Their properties may significantly vary from one carrier to another. For example, the void fraction of perlite is typically around 40–50% while this parameter may exceed 90% in randomly packed plastic or glass rings (Table 2, Figure 2). Materials of various densities are available, but low density carriers are often prefered because they allow minimizing bed compaction. Other characteristics as, for example, the roughness of the surface will also widely vary depending on the packing material. Again, using perlite and plastic packings as examples, plastics, contrary to perlite, present a rather smooth surface. Depending on the characteristics of the carrier material and its surface, the adhesion of microorganisms to some supports will be more difficult and slower than to others, resulting in longer start-up periods. Start-up periods of only a few hours have been reported in the case of perlite for the treatment of alkylbenzene polluted air, both with and without adapted inocula (Figure 3) (Kennes et al. 1996; Veiga & Kennes 2001). In biotrickling filters packed with four different carriers and seeded with a Pseudomonas strain, Kirchner et al. (1989) observed that twelve hours after inoculation, biomass adsorption was more significant on porous glass rings (GR) and activated carbon (AC) than on clay grains (CG) and stoneware rings (SR), with approximate biomass-density ratios of 1: 2: 4: 5, respectively for SR: CG: AC: GR. However, the authors did not describe the experimental procedure followed for assessing the results, which would have been interesting for accuratly evaluating the reported results.

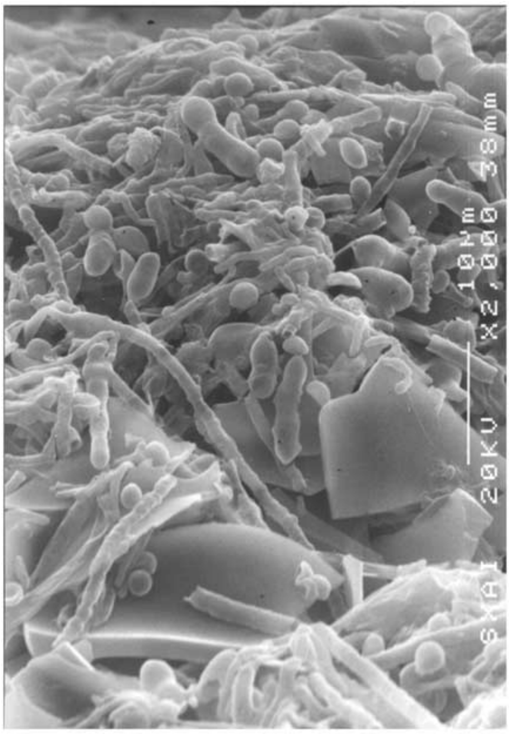

Figure 3. SEM photograph of heavily colonized perlite granules obtained from a gas phase biofilter.

Silicate supports as perlite and celite, and ceramic materials brakemore easily than other syntheticmaterials. Conversely, carriers as plastics are difficult to brake although some of them are less resistant to acidic conditions, which could be a problem in biodegradation processes generating acids and in biofilters in which pH drops down to very low values. Such type of problem has also recently been reported in the case of lava rock. That carrier material appeared to get gradually dissolved at low pH, usually below 2 (Chitwood& Devinny 2001). With respect to drying out problems, almost any inert packing material can be rehydrated after drying out events, while this is not the case with most organic filter beds as compost or peat. Complete irreversible loss of microbial activity is not unusual after drying out of natural carriers while this is not a major concern with inert carriers. The water sorbing capacity varies from one packing material to another, and materials as glass require more frequent supply of aqueous medium than silicate based materials as perlite (Prado et al. 2002).

Regarding the adsorptive capacity of some surfaces, inert packings as perlite are almost completely unable to adsorb pollutants (Kennes et al. 1996) while other tested packings as granular activated carbon strongly retain volatile organic compounds (Weber & Hartmans 1995). This is also the reason why activated carbon columns are sometimes installed as pretreatment units, in which their adsorptive capacity can advantageously be used to reduce the inhibitory effect of high shock loads in the bioreactor when dealing with waste gases characterized by highly fluctuating feed concentrations. Nevertheless, activated carbon beds have hardly directly been used as carrier materials in practice because of their high cost. When used as packing material in a bioreactor, it could favour the contact between the biomass and the pollutant, whenever the latter is present at concentrations below inhibitory levels. Activated carbon can advantageously be packed in biofilters to treat pollutants present at very low concentrations in the waste gas because of the concentration factor introduced.

Finally, when searching for the most appropriate support, it should be taken into account that synthetic filter beds as plastic/polymer packings may representa more serious problem of solid waste generation than packings as perlite or lava rock whenever the filter bed gets exhausted and needs to be replaced. Nevertheless, several inert carriers can be regenerated before requiring replacement.

3. Liquid phase addition

Inert carrier materials may be used both in conventional biofilters and in biotrickling filters (Table 1). In biotrickling filters, an aqueous phase containing nutrients is added continuously to the system (Figure 1). The flow rate and direction of the feed of the nutritive solution need to be optimized. Although the upflow feed of polluted air with counter-current supply of the aqueous phase, in biotrickling filters, might generate stripping problems, it has been shown that generally only minimal differences are encountered between counter-current and co-current operation in terms of performance (Diks & Ottengraf 1991). The steady feed of the liquid phase in biotrickling filters results in a continuous mass transfer of the pollutant(s) from the gas phase to the aqueous phase (absorption) and the biofilm where biodegradation takes place. The influence of the composition of the liquid phase on the performance of a biotrickling filter has been studied by a few authors. Using blast-furnace slags packings in a biotrickling filter, Chou and Wu (1999) observed that, after about four months operation, replacing the nutrient trickling phase by tap water for a 49-day period did not significantly affect reactor performance. Experiments on the effect of nutrients on reactor performance and excess biomass accumulation have been undertaken and are described in section 4.3.

Biotrickling filters are often prefered over biofilters for the treatment of air pollutants generating toxic or inhibitory metabolites, because the trickling phase allows for a steady removal of such products, thus alliviating inhibition problems. Examples of important air pollutants that can better be treated in biotrickling filters include ammonia, as well as halogenated and several sulphur-containing compounds, generating acidic products. The continuous supply of an alkaline solution for pH regulation and washout of unwanted metabolites is sometimes necessary to avoid pH drop down to inhibitory levels. Nevertheless, some microorganisms as, for example, most hydrogen sulphide oxidising bacteria, are active down to pH values as low as 1 or 2. It has also been shown that biofilters can sometimes reach very highVOC removal efficiencies at quite a low pH (< 4), above all – though not exclusively – in presence of fungi (Cox et al. 1997; Kennes et al. 1996; van Groenestijn & Hesselink 1993; Veiga & Kennes 2001). A similar pH regulating procedure as in biotrickling filters is possible in bioscrubbers but it is not applicable to biofiltration in conventional biofilters. The trickling phase usually allows for some removal of excess biomass as well.

Table 2. Typical void fractions and densities of some inert packings used in bioreactors for waste gas treatment

Packing	Void fraction* (%)	Specific surface area* ($\times 10\ m^{-1}$)	Density* (g/cm^3)
Celite pellets (6 mm)$^{(+)}$	30–40	12	0.60–0.70
Ceramic rings (50 mm)$^{(+)}$(Pall, Hiflow)	70–80	8–12	0.45–0.65
GAC	30–60	13–16	0.30–0.45
Glass rings (50 mm)$^{(+)}$	85–95	11	—
Plastic saddles/rings** (25 mm)$^{(+)}$(Pall, Hiflow)	90–95	20–24	0.06–0.08
Perlite (4–6 mm)$^{(+)}$	40–50	—	0.10
PU foam (20 mm)$^{(+)}$	85–95	60	0.02

*Orientative values, **Polypropylene.
GAC: Granular Activated Carbon, PU: Polyurethane.
$^{(+)}$Typically, larger size particles result in lower densities and lower specific surface areas.

4. Biomass control strategies

It is difficult to establish the optimal amount of biomass needed in a biofilter and the most suit able biofilm thickness for optimal biofilter performance in terms of minimal pressure drop and maximal removal efficiency, above all because other factors than thickness have a significant impact on reactor performance as the porosity, density, or level of compaction of the biolayer. Such factors will define if a biofilm will be fully penetrated (no concentration gradient), shallow, or deep (high resistance to substrate diffusion) (Figure 4). Besides biofilm characteristics, hydrodynamic conditions do also play a role in mass transfer, including the gas flow rate as a key parameter. Nevertheless, it has been reported that a biofilter may typically become nutrient – or pollutant – diffusion limited at biofilm depths exceeding 100 μm, although occasionally biomass layers of more than 0.5 mm or even 1 mm can easily be reached, and have been reported in long term operation studies (Cox et al. 1997; Kirchner et al. 1992; Schönduve et al. 1996). Since biofilm thickness does usually not exceed a few millimeters, designing packing materials with bed particles separated by a free space of a few millimeters should, theoretically allow simultaneously maximizing biodegradation capacity while minimizing pressure drop. Increasing the free space will, for sure, avoid pressure drop, though only to a given level. Above such treshold level, it would, at the vary with the type of pollutant, although that parameter directly depends on the waste gas and cannot be modified.

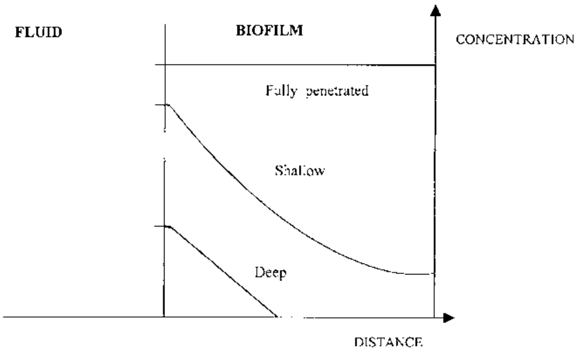

Figure 4. Typical concentration profiles in biofilms.

The period of time a biofilter can be operated before reaching a high pressure drop and, eventually, getting clogged as a result of excess biomass accumulation, is highly dependant on the characteristics of the packing material and on the operating conditions. In a conventional biofilter packed with perlite and treating toluene polluted air, it was shown that a highly satisfactory performance could be maintained for over one and a half year without performing any biomass control, at inlet pollutant concentrations ranging between 100 and 1000 mg/m3 and at relatively high loads of up to 120 g/m^3.h (Veiga & Kennes 2001). Biomass control appeared to be useful after that period, when pressure drop started affecting performance. Higher feed concentrations resulting in higher loads will lead to faster clogging under otherwise similar conditions.

It has sometimes been reported that trickling biofilters packed with inert carriers allow to reach slightly higher efficiencies than conventional biofilters based on organic filter beds, mainly as a result of the higher biomass concentration in biotrickling filters. Also, at higher microbial growth rates higher maximum elimination capacities would be reached faster as a result of the higher biomass concentration. However, high growth rates result in a fast excessive biomass accumulation and subsequent operating problems as the reduction of the specific surface area of the biofilm for mass transfer, pressure drop increase and, finally, clogging and poorer bioreactor performance. Provided excess biomass accumulation is avoided low pressure drops can be maintained for extensive periods both in biofilters and biotrickling filters packed with inert packing materials. Excess biomass growth is usually not a problem in case of waste gases containing low concentrations of pollutants, but it becomes a matter of concern when dealing with concentrated effluents. Several methods have been proposed for regulating biomass accumulation. They all present some advantages as well as drawbacks (Table 3). Four main groups of alternatives may be considered, based on:

(i) the use of mechanical forces to remove accumulated biomass,
(ii) the use of specific chemicals to remove excess biomass,
(iii) methods aimed at slowing down microbial growth,

(iv) biological methods (predation).

For methods aimed at removing excess biomass (methods (i) and (ii)), it should be mentioned that, each time the treatment is applied, the highest the biomass removal the lowest the required treatment frequency and costs, provided bioreactor performance is not adversely affected.

4.1 Mechanical forces

4.1.1 Backwashing with or without media fluidization

Backwashing is a method that has been used for several decades in water treatment. In biofiltration of waste gases, backwashing consists in feeding water to the bioreactor at a relatively high flow rate, often leading to media fluidization. Alternatively, hot water or water containing chemicals may be used as well (see section 4.2 on chemical treatments). The application of mechanical forces resulting from the backwashing procedure leads to the partial removal of excess biomass. This method has succesfully been used in a few research groups (Alonso et al. 1998; Mendoza 2002; Smith et al. 1996). Several parameters play a key role in the optimization of this technique, among which the specific flow rate of the backwashing solution as well as the frequency and duration of the procedure (Alonso et al. 1998). These parameters will strongly affect both biomass removal and bioreactor performance.

Table 3. Comparison of different common biomass control strategies

Methods	Typical advantages	Typical drawbacks
Mechanical	No inhibition of biomass	High costs related to energy input Increased reactor height* Possible breaking of bed particles
Chemical	No filter bed destruction	High costs due to the use of chemicals Strong inhibition of microbial activity Decreased efficiency after the treatment
Growth limitation	Low cost technology	Reduced efficiency
Biological	Low cost technology	Not yet optimized

* In case of media fluidization.

One disadvantage of the backwashing method is that larger biofilters are sometimes needed, whenever bed expansion takes place as a result of fluidization. A 40% bed expansion was reported when applying a specific liquid flow rate of 190 m/h for 1 hour twice a week in a celite-based biofilter (Smith et al. 1996). However, it is also possible to work with lower flow rates and negligible bed expansion reaching satisfactory biomass removal as well. No fluidization was observed with perlite, when applying specific flow rates of up to 75 m/h, although relatively good biomass removals were observed, reaching between 1–2 kg VSS removed per m^3 reactor (Mendoza et al., submitted). Higher values were reached when adding chemicals (>3–4 kg VSS/m^3 reactor, section 4.2). High liquid flow rates, allowing the removal of more biomass, may be necessary in case of high pollutant concentrations in the waste gas and high loads, leading to fast biomass build-up. Nevertheless, it is worth recalling that many biofilter applications deal with relatively low pollutant concentrations as, for example, in the case of publicly owned treatment works; and that, in such cases, plugging of inert filter beds may take quite a long time. The level of bed expansion depends, among others, on the density of the packing material. Also, the weight of a given carrier particle will increase when a thick biofilm develops on the bed particles. With respect to the feed of the backwashing solution, too high a specific liquid flow rate should be avoided since this could brake some bed particles into smaller ones, generating high pressure drops. After the backwashing treatment, a temporary drop in the removal efficiency is generally observed but the system recovers its original performance after a few hours if no chemicals are added (Smith et al. 1996; Prado et al. 2002).

4.1.2 Air sparging

Another recently studied method, which yielded interesting results in the case of a conventional perlitebiofilter fed toluene, consists in filling the bioreactor with water and sparging air through it at a given specific air velocity. Such technique has hardly been mentioned in the literature. Gas velocities of up to 180 m/h were applied to the biofilter, reaching biomass removals between 1 and >3 kg VSS/m^3 reactor (Mendoza et al., submitted). Much higher air velocities were not used with perlite because of the low density of that carrier (Table 2) resulting in bed fluidization and the need for larger reactors. This same method was previously also applied to a biotrickling filter treating a mixture of dichloromethane and methylmethacrylate, using polypropylene saddles as packing (Okkerse et al. 1999). Applying a gas velocity of 600 m/h appeared to give good results in that study although no details were published on the procedure (exact methodology) and its performance (amount of biomass removed, etc.) and effects on the system. As in the previous case, dealing with backwashing, mechanical forces are applied in air sparging processes, avoiding the chemical destruction and inactivation of the biomass, contrary to the chemical methods described hereafter.

4.1.3 Other methods

Some other strategies based on the use of mechanical forces have been proposed. The effect of regular stirring or mixing of the filter bed on bioreactor performance has been investigated either with the purpose of avoiding excess biomass accumulation (Wübker et al. 1997; Mendoza 2002) or for homogenization of a peat biofilter in which clogged zones had appeared (Auria et al. 2000). However, only very few data have been reported in the literature on the impact of such alternatives. These methods seem, at this stage, quite difficult to implement in full-scale biofilters. They would probably not be cost-effective. Also based on mechanical forces, Moe and Irvine (2000) suggested to use filter media, as polyurethane foam, that could be wringed out as a sponge or compressed for removing excess biomass.

4.2 Chemicals

4.2.1 Common chemicals

Several chemicals, including oxidants, surfactants, bactericidal and hydrolyzing compounds, have been proposed for the removal of biomass in biofilters. However, only a few studies report on their suitability in biofiltration of waste gases. Some common chemicals include NaOH, NaClO, hydrogen peroxide, ozone, sodium dodecylsulfate (SDS), hexadecyltrimethylammonium (HTAB), I2 and NaN3. Those chemicals have been used in backwashing (Cox & Deshusses 1999; Weber & Hartmans 1996; Mendoza et al., submitted), and in some air sparging experiments (Mendoza et al., submitted), allowing further increasing the level of biomass removal compared to the experiments with pure water. One major drawback of applying a chemical treatment is that it basically always inhibits the microbial activity of the cells remaining attached on the carrier material after the treatment. Decreased removal efficiencies are often observed during several days, following the treatment. The cost of such a procedure is in many cases not negligible, depending mainly on the type and concentration of chemical(s) used. Some authors mentioned that, according to the information presently available, no chemical can reach a high biomass removal without affecting the activity of the microorganisms remaining in the bioreactor after the treatment (Cox & Deshusses 1999). According to recently published results, only NaOH, NaClO and H_2O_2 showed significantly higher removal of biomass than pure water (Cox & Deshusses 1999; Mendoza et al., submitted). Some results are reported and compared in Table 4. Rinsing the packing with some of those compounds (sodium hydroxide, HTBA) may also cause unwanted foam formation (Weber & Hartmans 1996; Okkerse et al. 1999; Mendoza 2002).

In many cases, relatively high concentrations of chemicals must be used in order to remove enough biomass, and non negligible concentrations of the chemicals remain in the system after the treatment which exerts a strong inhibition on the remaining cells. A washing step with water could be applied after the chemical treatment, although this would increase costs at industrial scale and, unless using a relatively agressive washing procedure, some residual concentrations of the chemical will still be retained in the bed. It has also been suggested to perform an additional chemical post-treatment (Cox & Deshusses 1999), but such a procedure would again significantly increase costs in full-scale applications, and might induce other problems. For example, the use of a posttreatment with an acid after an alkali treatment will result in the release of relatively high salt concentrations in the medium, increasing the ionic strength and thus reducing the overall removal efficiency, unless strictly controlling the salt concentration. In fact, it has sometimes been suggested to reduce the microbial growth rate by maintaining a high ionic strength, for example by feeding high sodium chloride concentrations (Diks et al. 1994a; Schönduve et al. 1996; Weber & Hartmans 1996). The use of a 0.4 M NaCl solution in a biotrickling filter yielded a strong inhibition of biomass formation combined to a, proportionally, less significant inhibition of VOC biodegradation (Schönduve et al. 1996).

Table 4. Biomass removed from inert packing materials, applying different biomass-control strategies

Packing	Technology	Biomass removed (mass/m^3 packing)	References
Celite pellets (6 mm)	Backwashing (190 m/h) Water	N.R.	Smith et al. (1996)
Perlite (4–6 mm)	Washing (8 m/h) Water (RT)	0.1 kg_{VSS}	Mendoza (2002)
PP Pall rings	Washing (7.9 m/h) Various chemicals	N.R.	Cox & Deshusses (1999)
Pall rings	Chemical washing NaOH (0.1%)	3.28 $kg_{\text{dry biomass}}$	Weber & Hartmans (1996)
Perlite (4–6 mm)	Backwashing (56 m/h) NaOH (0.1%)	4.4 kg_{VSS}	Mendoza (2002)
Perlite (4–6 mm)	Backwashing (77 m/h) NaOCl (0.01%)	4.7 kg_{VSS}	Mendoza (2002)
Perlite (4–6 mm)	Air sparging (60 m/h)* NaOH (0.1%)	3.0 kg_{VSS}	Mendoza (2002)
Perlite (4–6 mm)	Air sparging (60 m/h)* NaOCl (0.01%)	3.5 kg_{VSS}	Mendoza (2002)
Polyurethane foam	Dismantling and squeezing	0.23–4.88 kg_{VSS}	Moe & Irvine (2000)
Perlite (4–6 mm)	Dismantling and mixing	5.4 kg_{VSS}	Mendoza (2002)

*Specific air velocity, N.R. = Not reported, RT = Room temperature.

4.2.2 Other compounds and methods

The possibility of using enzymes has been mentioned in the literature although costs would be prohibitive for their eventual application in large scale bioreactors.Furthermore, the combination of pepsin, a protein degrading enzyme, and hydrogen chloride led to similar foaming problems as in the case of sodium hydroxide treatments (Okkerse et al. 1999).

Simply feeding hot water allows biomass removal as well, sometimes with a similar efficiency as with some of the chemicals mentioned above. It was observed that in a toluene-fed biofilter, increasing the temperature applied during backwashings with water to 60 ◦C allowed the removal of up to 5–10 times more biomass than at 30 ◦C, depending on the flow rate of the water phase (Mendoza 2002). It is worth mentioning that exposure to hot water may generate a shift in dominant microbial populations and a temporal decrease of the efficiency (unpublished data).

4.3 Restriction of microbial growth

To avoid clogging problems, methods aimed at reducing the microbial growth rate have been studied and proposed in the literature, mostly in the case of biotrickling filters, although similar techniques are also suitable for conventional biofilters packed with inert carrier materials. The most popular strategy consists in limiting the supply of one or several important nutrients, such as the nitrogen source, by reducing its concentration in the aqueous phase. Nitrogen limitation does, indeed, result in a reduction of the microbial growth rate, but several studies have shown that drastically reducing the nitrogen supply also led to a decay of the removal efficiency, yielding lower maximum elimination capacities (Weber & Hartmans 1996; Weckhuysen et al. 1993). Nevertheless, according to published data, it appears that the concentration of nitrogen supplied widely varies from one study to another, as illustrated in Table 5 for some lab-scale experiments. The amount of nitrogen fed can sometimes drastically be reduced down to a given level still allowing to maintain a highly satisfactory reactor performance with limited growth when trying to find out, experimentally, the optimal rate of supply for a specific application.

Table 5. Nitrogen concentration and frequency of supply during biofiltration (note that some published data are expressed as amount of NH_3 or NO_3 and others as amount of -N)

Carrier	Nitrogen supply	Frequency of supply	Pollutant EC/RE$^{(x)}$ (g/m^3.h /%)	References
Celite R-635*	114 mmol NH_3-N/day	BTF**	Toluene 60 / 94–98	Smith et al. (1996)
Celite R-635*	114 mmol NO_3-N/day	BTF**	Toluene 60 / >99	Smith et al. (1996)
Celite R-635*	25 mmol$^{(xx)}$ NO_3/day	BTF**	Toluene 45.5 / >99	Song & Kinney (2000)
Pall Rings	216.2 mol NH_3/14 days	BTF**	Toluene 30-35 / 50	Weber & Hartmans (1996)
Polyvinyl difluoride cubes	5 mmol NH_4NO_3/day	BTF**	Toluene 9 / 66	Pedersen et al. (1997)
Perlite	18.7 mmol NH_3/month	Monthly	Toluene >50 / >90	Prado et al. (2002)
Perlite	18.7 mmol NH_3/week	Weekly	T, E, X 120 / >99	Veiga & Kennes (2001)

*Silicate pellets, **BTF = Biotrickling filter with continuous supply of the nutrient-solution.

$^{(x)}$ This value gives also an idea of the C:N ratio.

$^{(xx)}$ Concentration retained in the bed, corresponding to 27% of the actual nitrogen concentration fed to the reactor (obtained by substracting the amount of nitrogen measured in the leachate).

In fact, not only the concentration of specific nutrients is important but also the form in which they are present. Indeed, it is well known that biomass yield is usually higher when using ammonium rather than nitrate as nitrogen source (Moo-Young 1985). In case of toluene-fed biofilters, biomass yields of 0.115 and 0.067 gVSS/gCOD were obtained in presence of, respectively, ammonium and nitrate (Smith et al. 1996). However, here again, the nature of the nitrogen source will also affect reactor performance. Different, sometimes contradictory, data have been reported in the literature suggesting that using nitrate instead of ammonium may either increase or decrease the removal efficiency (Schönduve et al. 1996; Smith et al. 1996). Both results may be logical considering that the nature of the microbial populations becoming dominant, which will affect bioreactor performance, is to some extent unpredictable. Indeed, experimental results have shown that for two biofilters fed ammonium as nitrogen source, either fungi or bacteria appeared to become dominant when feeding, respectively, styrene or alkylbenzenes as carbon substrates, for otherwise very similar running conditions (Kennes et al. 1996; Cox et al. 1997; Veiga et al. 1999). Still in another identical biofilter treating alkylbenzenes, the level of eukaryotic and prokaryotic cells was basically identical (Veiga et al. 1997).

Potassium limitation as well as phosphate reduction are other means to decrease cell yield and biomass accumulation. It was reported that both alternatives resulted in increased specific toluene degradation rates (gtoluene/gcell.h), although the overall pollutant removal efficiency decreased (Wübker & Friedrich 1996; Wübker et al. 1997). Under phosphate or potassium limitation, higher concentrations of the carbon source, i.e., the pollutant, were used to satisfy the needs for maintenance energy. However, more studies on the effect of phosphate or potassium deficiencies would be necessary in order to allow comparisonwith published data and draw conclusions.

In biotrickling filters, limitation of the amount of nutrients is performed by lowering their concentration in the trickling phase. In conventional biofilters packed with inert carriers, both the frequency of the nutrient supply and the feed-nutrient concentrations may be modified in order to reduce the microbial growth rate. This has been reported in the case of perlite-based biofilters to which mineral solutions were added at frequencies ranging from once a week to less than once a month, allowing in all cases to maintain satisfactory efficiencies. Feeding 18.7 mmol ammonium once a month to the biofilter allowed maintaining toluene elimination capacities above 50 g/m3.h with removal efficiencies above 90% (Table 5) (Prado et al. 2002). The addition of vitamins or trace minerals to the nutritive solution had hardly any effect on reactor performance. Biomass decay did most probably take place, allowing the remaining living cells to obtain important nutrients from decayed biomass. Once the biofilter efficiency started dropping significantly, the nutrient solution was again supplied, reaching the same performance as before (Kennes et al. 1996; Veiga et al. 2001). Usually, after one month without feeding any aqueous phase, besides the effect of nutrient limitation, it is observed that the water content of the filter bed sharply decreases contributing also to the decline of biofilter performance (Veiga & Kennes 2001). The optimal frequency of addition of the aqueous phase depends on its composition; such frequency being lower when feeding a richer nutrient solution (Veiga et al. 2001). In the perlite-biofilter mentioned above, whenever omitting the addition of vitamins and trace minerals to the aqueous phase fed to the biofilter or when using tap water, the maximum elimination capacity remained basically unchanged although biofilter performance dropped slightly faster over time and a weekly supply is recommended in such cases in order to maintain above 90% removal efficiency at high loads (above 40 g/m^3.h) (Kennes et al. 1995; Veiga et al. 2001). The optimum nutrient concentrations and frequency of supply of the aqueous solution appear also to be different during start-up, short term, or long term operation stages (Veiga et al. 2001; Prado et al. 2002).

Both in biofilters and biotrickling filters, it is probable that temporarily omitting the addition of nutrients will have no adverse effect on reactor performance as described above whenever the microorganisms attached on the carrier material are able to use nutrients stored in the biofilm. This is also the reason why the effect will be different depending on the operation stage. It is worth recalling that substituting a nutritive solution by tap water for 49 days in a biotrickling filter did hardly affect performance (Chou & Wu 1999).

Another important parameter linked to biomass accumulation is biomass yield and decay. Besides the effect exerted by the composition of the nutritive solution, biomass yield highly depends on the microbial strain. For different strains of the same genus, i.e., Pseudomonas, grown on toluene or related alkylbenzenes, biomass yields ranging from 0.16 to 1.88 gram biomass per gram substrate have been reported (Chang et al. 1993; Veiga et al. 1999; Wübker et al. 1997). However, although estimations of biomass yields are usually undertaken in nutrient rich aqueous solutions, it should be remembered that the yield also depends on the environmental conditions. Biomass yield of microorganisms growing slowly as a result of carbon or nutrient limitation is usually lower because part of the substrate is used for maintainance energy requirements rather than for cell growth. Inoculating strains with high biodegradation activities and low biomass yields would be favourable in order to slow down the appearence of clogging problems. However, as bioreactors for air pollution control are operated under non sterile conditions, other microbial populations with higher yields may overgrow the inoculated strains. Concerning the nature of the microbial populations, the dominance of filamentous fungi rather than unicellular bacterial populations is expected to result in faster clogging.

Figure 5. SEM photograph of mites on perlite granules in biofil- ters (Wageningen University; research project of TNO Environment, Energy and Process Innovation and Bioway).

4.4 Predation

Besides the three groups of biomass control technologies cited above, some new alternatives have also recently been studied although they are still in an exploratory phase, such as the application of protozoan predation in bacterial communities (Cox & Deshusses 1999) or the use of mites grazing on fungal mycelia (Figure 5). The use of mites in a toluene-fed fungal biofilter allowed to maintain, simultaneously, a low pressure drop together with a sligthly higher reactor performance than in a control biofilter without mites (van Groenestijn et al. 2001). Although these methods may be promising, they do still need to be optimized. It should also be remembered that mixed microbial communities composed of various bacterial and filamentous or non-filamentous fungal species are often present in biofilters. It is not yet clear to what extent predation could more significantly affect useful populations rather than unwanted target populations or inactive biomass. Further research on methods for controlling the rate and extent of predation would certainly be of interest.

4.5 Concluding remarks on regulation of biomass accumulation

Some published results regarding biomass removal are summarized in Table 4. From all the above data on biomass control, it may be concluded that a few methods yield good results, although most techniques still need to be optimized. Each one presents its own advantages and inconveniences. Further research on control of biomass accumulation is certainly needed. The selection of a specific technique can, at this stage, best be performed on a case by case study. For example, when using very low-density packing materials, methods based on the application of mechanical forces might not be the best choice if high specific liquid flow rates need to be applied, as significant bed expansion may be observed, and some bed particles could brake. Conversely, when dealing with waste gases with high pollutant loads, predation or the use of pure water combinedwith mechanical methods may be prefered over the use of chemicals, as the combination of high air pollutant concentrations and residual concentrations of chemicals in the filter bed after the treatment could fully inhibit the system or lead to the need for a quite long period before reaching complete recovery of the microbial activity.

The application of a combination of techniques may represent a nice alternative although this has not been reported so far in the literature. For example, by applying a relatively gentle chemical treatment for the removal of part of the cells followed by a washing step for further removing accumulated biomass; eliminating, at the same time, most of the residual chemicals by means of the aqueous phase used for washing. Although combining two methods would increase costs, in such case the treatment frequency could also be reduced, keeping the overall costs similar to those resulting from the more frequent use of a single chemical treatment. Methods based on predatory-prey relationships have little been studied so far. Future research should show if they can yield promising results. The selection of a specific predator will depend on themicrobial populations present in the biofilter.

4.6 Biomass distribution

An interesting phenomenon that has been observed in experiments undertaken with new inert carrier materials is that biomass distribution along the bed height is basically never homogenous, resulting in higher biomass concentrations and thicker biofilm layers near the inlet of the reactor were higher pollutant concentrations are available to the microorganisms (Cox et al. 1997; Song & Kinney 2000; Veiga & Kennes 2001). It has occasionally been reported that less than half of the bed volume (closest to the inlet port of a biotrickling filter) may remove up to 80–90% of the pollutant load, while the other half of the filter bed is needed for degrading the remaining 10–20% of the feed concentration (Lu et al. 2001). A heterogenous qualitative distribution of microbial populations may also appear after a few months operation above all when feeding a mixture of pollutants sequentially degraded by different microorganisms (Veiga & Kennes 2001). Besides the active pollutant-degrading populations, the presence of significant amounts of inactive biomass in the biofilm is not unusual and has been reported by several groups as well (Arcangeli & Arvin 1992; Cox et al. 1997; Juteau et al. 1999; Veiga et al. 1999). More than 50% of the cells fed volatile substrates may be inactive in biofilms growing on inert packing materials. In a biofilter packed with celite it was observed that the inactive biomass concentration gradually increased over a three months operation period while the viable biomass concentration remained constant (Song & Kinney 2000). In that study, the endogenous respiration rate remained also constant over the 96-day experimental period. In contrast, Diks et al. (1994b) report a steady increase of the endogenous respiration rate in a biotrickling filter in which that process eventually became the major carbon dioxide generating process.

Only little research has been devoted to solving the problem of accumulation of large amounts inactive biomass and to trying reaching a more homogenous biomass distribution for a more efficient use of the total bed volume. One recently reported strategy consisted in operating a bioreactor in a directionally-switching mode, feeding the polluted air alternatively through either the top or the bottom of the bioreactor. The use of such strategy led to a more homogenous quantitative biomass distribution (Song & Kinney 2000). The method presents its own drawbacks and still needs to be further optimized. Just after switching the feed direction, the system usually needs some time to fully restore its original biodegradation capacity (Song & Kinney 2001). The switching frequency seems to be an important parameter to be optimized since a 1-day switching frequency, contrary to a 3- day switching frequency, appeared to lead to biofilter instability (Song & Kinney 2001). Other strategies consisting in splitting the feed are possible and are being studied in biofilters equipped with multiple feed ports (Mendoza 2002). Splitting the feed into two equal streams fed, respectively, to the upper part of the reactor and to the middle part of the system, led to a more homogenous biomass distribution and improved bioreactor performance compared to biofilters with a single feed port.

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