Biotreatment of Organic and Inorganic Odors

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ABSTRACT

Air emissions from manufacturing operations and waste treatment plants often consist of a combination of odors and volatile chemicals. Odors are inorganic or organic compounds, which are present in low concentrations, typically 20 ppmv or less, which have an unpleasant odor. Volatile chemicals are often present at higher concentrations than odors, but may or may not have any odors associated with them. The major problem with emission of volatile chemicals is the detrimental impact on the environment and adverse human health effects. While several U.S. EPA and OSHA regulations govern the emission of hazardous volatile chemicals in the ambient air and in the workplace, odor emissions are often a major nuisance to the plant workers and surrounding communities. In recent years, biological treatment has emerged as a major contender for in-process or end-of-pipe treatment, as compared with other treatment technologies, such as chemical oxidation, adsorption, gas absorption, or thermal oxidation. Major advantages of biological treatment are ambient temperature and pressure operation, no generation of toxic by-products requiring disposal or further treatment, and favorable economics. Disadvantages associated with biological treatment are upsets due to inactivation of active microbial cultures, and lack of adequate knowledge to operate the process at peak capacity and performance level. In this paper, the application of biotreatment for controlling emissions of odors and volatile organics will be addressed.

INTRODUCTION

Biofiltration refers to the biological transformation or treatment of contaminants present in the gas phase, usually air. The fact that air contaminants can be biodegraded by active bacteria has been known for quite some time. However, it is only in the last 10 years, that biofiltration has begun to emerge as an economically viable treatment process. Initially, biofiltration involved the use of naturally bioactive media, such as soil, peat, compost, etc. In naturally bioactive media, microorganisms present in the soil, peat or compost, have been known to biodegrade contaminants, and this has been successfully employed in bioremediation of contaminated sites. However, when contaminated air is passed through soil, peat, or compost, the naturally present microorganisms also begin to biodegrade the air contaminants. This led to the development of soil biofilters, in which soil with low clay and high organic carbon content was packed in a bed and contaminated air was passed through the soil bed to biodegrade the air contaminants.

However, as more research was conducted on this simple process, it became clear that the biodegradation rates were low and hence the size of the biofilter bed required to achieve high destruction efficiencies was very large. Since, compost had a higher concentration of microorganisms, compost became the media of choice for biofilters.

Major problems encountered were settling of the compost, resulting in increased gas-phase pressure drop, availability of nutrients, such as nitrogen and phosphorus, pH maintenance, and drying of the compost material due to moisture transferring to the flowing gas phase. These problems were countered to some extent by adding wood chips or polymeric beads, which provided mechanical support to minimize settling, humidifying the inlet air to maintain proper water content in the compost material, adding lime pellets for pH control, and fortifying the compost with fertilizers containing nitrogen and phosphorus compounds. Further, in compost beds, it was necessary to have shallow beds (height < 1.5 m or 4.5 feet), to prevent compaction of the material and drying of the bed from the top surface. This required the beds to have large cross-sectional areas, and in many cases were simply left completely open from the top. In some cases, powdered activated carbon was also added to buffer the concentration changes, since activated carbon is known to adsorb contaminants. Currently, there are several companies that offer compost biofilters for treatment of odorous and volatile chemicals.

In recent years, there is growing public awareness of odors from waste water treatment plants, which mainly stems from the following observed trends:

- The public is less tolerant of objectionable odors from waste water treatment plants;
- Many waste water treatment plants have seen residential, commercial, or other developments established near the facility boundaries and fence lines, thereby increasing the population being affected by the odor emissions;
- Plants are treating increased flows, servicing distant locations, which has increased the age of the waste water, and hence its septicity and concentration of reduced sulfur and nitrogen compounds;
- Water conservation efforts have resulted in reduced waste water flows and increased waste water strength; which increases odor production; and
- New or modified waste solids processing systems have created additional odor sources.

New wastewater treatment plants, currently under construction or being contracted for building, are under increased scrutiny, for odor generation and their control methods. There are several myths that have been associated with odor generation, transport and control, which includes the following: (1) the generation of odors is inevitable when treating waste water; (2) odor dilution with ambient air will dissipate the odors with increased distance from the plant; (3) odors can be masked effectively by injecting masking agents; (4) control of odors is expensive; and (5) if plant is being located far from residential areas, odor control is unnecessary. However, it is clear from the above-mentioned trends, that waste water treatment plants operating beyond the year 2000 will have to utilize odor control measures and operate under essentially a self-imposed zero-odor emission requirement, to ensure that no complaints from neighbors are received now or in the future.

BACKGROUND

Biofiltration has been applied to remediate air contaminated with volatile organic compounds (VOCs) and other gases since the early sixties. Pomeroy[1] received a patent for a soil bed system for treatment of odorous sewage gases. Carlson and Leiser[2] studied the biodegradation of hydrogen sulfide in sewer gases using moist loam soil. Since then, substantial field use of biofiltration has occurred in Europe, especially in Germany and the Netherlands, for control of VOCs and odorous gases[3].

Pertinent references on the development of soil bed biofiltration include Smith et al.[4] evaluating removal of sulfur containing compounds, carbon dioxide, acetylene and ethylene; Bohn[5] and Bohn and Bohn[6] presenting theory and applications for odor control; Prokop and Bohn[7] evaluating odor control at rendering plants; and Kampbell et al.[8] evaluating VOC removals including aliphatics, such as butane and iso-butane.

A variety of biofilters using peat and compost systems have also been developed. Ottengraf and van den Oever[9], Ottengraf et al.[10] and Ottengraf[11] evaluated peat/compost biofilters on a variety of easily degradable VOCs. Don and Feenstra[12] and Don[13] using biofilters with peat/heather and peat/compost media treating toluene, ammonia and aldehydes found removal efficiencies depended on the nutrients in the media.

Leson et al.[14] using a compost biofilter found significant (>90%) removals of ethanol. Allen and Young[15] treating hydrogen sulfide with compost biofilters found removal efficiencies declining with acidification of the media. Ergas et al.[16] treated chlorinated organics, hydrogen sulfide and aromatics in a packed biofilter with compost mixed with perlite and crushed and oyster shells. The oyster shells neutralized mineral acids produced by substrate biodegradation. Prokop and Archer [17] successfully controlled odors from poultry rendering with a compost biofilter. Recently, detailed experimental and modeling studies have been conducted on a peat and compost biofilter[18].

Kirchner et al.[19] using a pelletized activated carbon biofilter for degradation of aldehydes, ketones and esters observed removal efficiencies above 70% even at high flowrates. Kirchner et al.[20,21] also studied different support media such as clay and stoneware-rings and sintered glass raschig rings, typically for applications involving low concentrations (~30 ppmv) stream. Togna and Folsom[22] used ceramic rashig ring and plastic Jaeger-TriPack support in bio-trickling filter for removal of styrene. Other types of media used in biofilters are synthetic materials, such as activated carbon[23], ceramic pellets and extruded monoliths[24,25,26]. These media serve as supports for active immobilized biofilms. However, major disadvantage of synthetic support media is the high cost compared to naturally bioactive media, such as peat, compost, bark, etc. or mixtures of these materials.

ODOR CONTROL MEASURES

There are several odor control methodologies that have been developed for reducing or eliminating odor emissions, which includes the following:

- Chemical addition, which either creates oxidizing conditions or precipitates odorous sulfides as metal salts;
- Biological methods for oxidizing or biodegrading odorous compounds;
- Thermal destruction methods, which utilize high temperatures to destroy odorous gases;
- Chemical oxidation, which uses oxidizing chemicals to oxidize odorous compounds; and
- Physical adsorption on high surface area adsorbents, with periodic regeneration.

Each of the above methods either by themselves or in combination with others have to be designed on a case-by-case basis to minimize cost and maximize effectiveness. Generally, odorous emissions from waste water treatment plants consist of a mixture of organic compounds, such as ketones, aldehydes, etc. and inorganics, such as hydrogen sulfides, mercaptans, etc. Odor control methods must be capable of handling both the organic as well as inorganic odorous compounds.

In recent years, the use of biological control methods has increased mainly due to the following advantages: (1) requires ambient temperatures and pressures; (2) is capable of treating both organic and inorganic odorous compounds; (3) does not require handling of corrosive chemicals; (4) minimal operating cost, when compared with chemical oxidation and thermal destruction methods; (5) robust, and can operate reliably with minimal operator intervention. Another major advantage of biological control methods when compared with chemical oxidation, is that it generates no chemical by-products. For example, use of chlorine gas or hypochlorites, results in the chlorine gas emissions, which has a pungent odor. In some waste water treatment plants, where chlorine gas is being used to control odors, complaints from neighbors are due to the pungent odor of chlorine rather than the sewer odors. Further, chlorine gas chemically combines with organics, present in waste water to form halocarbons, which are known to be carcinogenic compounds and possess objectionable odors. The potential for an increase in chlorinated volatiles should be considered before using chlorine in waste water treatment plants.

Traditionally, biological control methods have used naturally bioactive media, such as compost, peat, wood chips, etc., which have tended to be large size, shallow beds, with limited neutralizing capacity. Generally, these biological processes, called biofilters, have required the naturally bioactive media to be changed periodically, due to increased pressure drop, and limited availability of nitrogen and phosphorus nutrients.

In contrast to biofilters using naturally bioactive media, biotrickling filters, use synthetic media, which are inoculated with active bacteria resulting in surface attached biofilms. While the biotrickling filters do not suffer from the disadvantages of the naturally bioactive media biofilters, the design of the synthetic support media is critical to its effectiveness and significantly impacts the required volume of the biotrickling filter. Further, methods to control biomass are needed to prevent biomass buildup and increased gas-phase pressure drop.

TYPES OF BIOFILTER MEDIA

There are two kinds of air contamination problems: (1) when the air contaminants are present at low concentration (< 25 ppmv); and (2) when the concentration of the air contaminants is higher (> 25 ppmv). The reason for making this distinction is that soil, peat and compost materials exhibit low biodegradation rates, have limited supply of nitrogen and phosphorus, eventually begin to plug due to growth of microorganisms, and have limited capacity to neutralize acidic products of degradation. Hence, compost biofilters are capable of treating low concentration contaminants (< 25 ppmv) and are not ideally suited for treating air contaminated with high concentration organics.

Other types of support media used in biofilters are synthetic media, such as ceramic, plastic, etc., with active bacteria immobilized on the surface in the form of biofilms. These synthetic media biofilters, known as biotrickling filters, are shown schematically in Figure 1. Synthetic support media are used in trickling filters for wastewater treatment, gas absorption towers, catalytic reactors, etc. However, the design of support media in biotrickling filters is different than in any other application, the major difference being the growth of biomass. In trickling filters, used for waste water treatment, the water flows as a liquid film on the biofilm surface, and sufficient distance between the support media is designed to accommodate biomass growth and air, which provides oxygen for the biodegradation reaction. The contaminants, present in the waste water, diffuse into the biofilm as the water flows over the biofilms, and biodegrades. In a biotrickling filter, the contaminants, present in air, diffuse perpendicular to the direction of flow, and biodegrade in the supported biofilms. Since the process is diffusion controlled, designing a large distance between the supported biofilms reduces the overall degradation rate in the filter. Further, unlike the submerged biofilms in the case of the wastewater trickling filter, the biofilms in a biotrckling filter have to be kept moist to maintain bioactivity. Air flowing through the biotricling filter draws moisture away from the biofilms, and a trickling flow of aqueous nutrients has to be maintained to provide nutrients and water to the active bacteria in the biofilms.

Synthetic support media can be in the form of high surface area pellets, with either a porous or non-porous surface. In some cases, the support media may be coated with activated carbon, to enhance adsorption of contaminant(s). The synthetic support media can be synthesized from plastic, ceramic, metallic, or any other composite material.

The desired features of a good support media are as follows:

1. High void fraction, i.e., the fraction of empty space in the synthetic media should be large (> 80%). This provides greater space for the biofilms to grow and biomass growth does not easily clog up the support media.
2. High surface area per unit volume of the biofilter bed. The biofilms grow only on the surface of the support media. Hence, if this exposed surface area is large, the contact between the biofilms and the gas phase contaminants is also large.
3. Low gas-phase pressure drop. Gas-phase pressure drop is very critical, since the operating cost is proportional to the pressure drop across the biofilter bed. In a typical biofilter bed, the total gas pressure drop is less than 0.3 inches of water.
4. Hydrophilic surface, to allow good water wettability. It is very important to maintain water in the attached biofilms. Hence good water wettability of the support media enhances biofilm attachment, retains water within the biofilm, and does not dry easily.Low overall density. The total weight of the biofilter bed depends on the bulk density of the support media. To reduce the cost of the supports for the biofilter bed, a lighter support media is preferred.
5. Low cost. Cost of biofilter media is very important, since compost in compost biofilters is a low cost media.

MECHANISMS IN BIOFILTER OPERATION

There are various transport mechanisms which operate simultaneously or sequentially in a biotrickling filter and these mechanisms, schematically shown in Figure 2, include: (1) diffusion of the contaminant(s) from the bulk gas flow to the active biofilm surface; (2) sorption of the contaminants directly on the biofilm surface; (3) solubilization of the contaminant(s) into the water content of he biofilms; (4) direct adsorption of the contaminant(s) on the surface of the support media; (5) diffusion and biodegradation of the contaminant(s) in the active biofilm; (6) surface diffusion of the contaminant(s) in the support media surface; and (7) back diffusion of the adsorbed contaminant(s) from the support media surface into the active biofilms. The effect of adsorption of contaminant(s) on support media surface, surface diffusion, and back diffusion of the adsorbed contaminant(s) from the support media surface into the active biofilms, predominantly occurs in activated carbon-coated support media and contaminant(s) which have affinity for the support media surface.

In the case of compost biofilters (refer to Figure 3) the contaminant(s) diffuse into the porous compost particles, dissolve into the sorbed water films, adsorb on the organic and inorganic fraction of the compost, and biodegrade by the attached active compost bacteria, entrapped within the compost particles.

EFFECT OF SUPPORT MEDIA

The main advantages of the biotrickling filter compared to the compost biofilter are as follows:

1. The biotrickling filter had no height limitation, and hence could be designed as a tower, with a reasonable diameter. The problem of support media drying , as in compost biofilters, is inapplicable to biotrickling filters, since there is a constant aqueous nutrient stream trickling down the surface of the synthetic media;
2. The media never has to be replaced, as in the case of compost, since the mineral nutrients are supplied from an external source. In the case of compost, once the nitrogen and phosphorus, initially present in the compost are exhausted, the compost has to be changed. Since the air contaminants adsorb to the organic fraction of the compost, the compost, when disposed, would be contaminated, and has to be treated as solid waste;
3. The compost eventually begins to compact, inspite of adding wood chips to provide support. Growth of biomass (microorganisms) due to biodegradation, also causes the compost to become heavier and settle. This type of settling results in increased gas-phase pressure drop, which causes the gas flow to actually decrease, since the gas blower has to operate against a higher pressure drop. In the case of biotrickling filters, employing synthetic support media, settling is not a problem; however, plugging of the media due to biomass growth, which results in increased gas-phase pressure drop is a major problem.
4. In some cases, when air contaminants contain nitrogen or sulfur or oxygen, intermediate products of biodegradation (biotransformation) may be acidic, which causes the pH in the biofilter bed to decrease. For example, when hydrogen sulfide is biotransformed to sulfate, the pH in the bed decreases. In compost beds, declining pH results in decreased bioactivity, which eventually causes the entire bed to acidify and shut-down. In biotrickling filters, the

pH can be controlled by adding buffers in the nutrient flow. In the case of hydrogen sulfide, the sulfate formed is continuously removed from the process by the flowing nutrient stream, and this sulfate is neutralized before the nutrients are recycled back to the biotrickling filter bed.

5. The biodegradation rates in a biotrickling filter are much higher than in compost beds. This is mainly due to higher surface area and increased concentration of immobilized microorganisms in biotrickling filters when compared to compost media. Hence, the volume of biotrickling filter bed is much smaller than the volume of compost required for the same destruction efficiency.
6. In compost biofilters, the compost has to replaced periodically, to replenish the nitrogen and phosphorus and remove the excess biomass which results in plugging and settling. In biotrickling filters, the media does not have to be replaced.
7. In compost biofilters, the inlet gases have to be humidified to prevent bed drying. Since 100% humidity is difficult to achieve in practice, some bed drying always occurs, and this results in reduced bioactivity. In some compost beds, water is also sprayed from the top of the bed, although this is kept to a minimum to prevent bed settling;
8. In compost beds, gas channeling is a big problem, especially since compost beds are shallow with large cross-sectional areas. As biomass growth begins to plug the bed, gas begins to bypass compost regions which have increased biomass concentrations. Since biotrickling filter beds are smaller diameter and taller, gas channeling is not a major issue.
9. Compost biofilters require large areas for installation, due to large footprints. They are also very heavy, and often require structural modifications, especially when installed on building roofs. Biotrickling filters are much lighter, since the support media is synthetic and has a large void fraction. The footprint of a biotrickling filter is also much smaller, and can be easily installed on building roofs.
10. Transfer of oxygen into compost materials is very inefficient, since oxygen is also consumed by compost due to intrinsic biodegradation of the organic fraction, present in compost media. Hence, if air is blown through moist compost media, the air leaving will have increased levels of carbon dioxide gas. Due to inefficient oxygen transfer, if the water content of compost material is not maintained in a narrow range, anaerobic regions are created in the compost material, wherein anaerobic microorganisms begin to thrive and anaerobic microorganisms are known to create acidic by-products, which creates pH in the compost material to decrease. In biotrickling filters, since the synthetic media is very open, and high gas velocities can be maintained, the oxygen transfer is much higher, and hence anaerobic regions are not created in the biofilter bed.

Hence, it can be concluded that compost biofilters have significant disadvantages when compared with synthetic media biotrickling filters. However, not all biotrickling filters are created equal. The design of the support media is very critical to the performance of the biotrickling filter. Figure 4 [26] shows the relative performance of various support media.

COMMERCIAL POTENTIAL OF BIOFILTRATION

Biofiltration is capable of biodegrading a wide variety of air contaminants. Table 1 shows a list of the types of organic and inorganic air contaminants that can be treated in a biofilter. Table 2 shows the applicability of various air pollution control technologies, including compost biofiltration and biotrickling filters. Figure 5 shows the differences in investing and operating costs for biofiltration, when compared with catalytic oxidation and adsorption. The future of biofiltration (compost and biotrickling filters) depends on the regulatory requirements placed on industry. However there are specific trends which will impact the market for biofiltration technology, and these trends are:

1. Increased regulatory concern about emission of nitrogen oxides, which are emitted from thermal treatment processes. Biofilters do not create any additional nitrogen oxides;
2. Increased public complaints about odorous emissions from public owned wastewater treatment plants, manufacturing industries, solid waste treatment facilities, etc.;
3. Implementation of pollution prevention methodologies which has resulted in greater use of biodegradable solvents, reduced concentration of air emissions, and emphasis on achieving zero discharge processes; and
4. Increased concern about emission of air contaminants, worker exposure to organics, emphasis on environmentally friendly and low-cost treatment technologies.

The application of biofiltration technology has increased rapidly during the latter part of the twentieth century and will continue to grow throughout the twenty-first century. Though recent studies vary, depending on the underlying assumptions, the U.S. biofiltration market for 1996 was estimated to be about $10 million[27], and economic models speculate that by the year 2000, the market may reach over $100 million[28].

Potential markets for biofiltration include the following:

(1) treatment of odors;

(2) treatment of volatile organic compounds (VOCs) / hazardous air pollutants (HAPs); and

(3) treatment of petroleum hydrocarbons.

Odor treatment is a significant portion of the marketplace. Industries that produce odorous emissions include wastewater treatment plants, composting and sludge treatment facilities, foundries, pulp and paper plants and tobacco products manufacturing plants. In recent years, communities have begun to encroach near the fence lines of wastewater treatment plants. Wastewater treatment plants are treating increased flows, thereby increasing odor loads at the plant. Further, since flows are being pumped from greater distances, the age of the wastewater and its septicity is increasing, resulting in greater amounts of reduced nitrogen and sulfur compounds. In addition, water conservation has resulted in decreasing water flow rates with increased strength, which results in greater odor production. Many wastewater treatment plants have begun to implement odor control strategies, and biofiltration will play a major role in many such cases. Recently, biotrickling filter technology was shown to be effective in treating odorous emissions from the “Zimpro” sludge heat treatment process, which has been known for creating very high intensity odors[29].

Biofiltration of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) is an important problem in the wood products, pulp and paper, and surface coating operations. In the case of surface coating operations, exposure of workers to organic chemicals, such as styrene, is an important issue. While attempts are being made to develop low VOC emitting solvent formulations, some worker exposure is inevitable, and the use of biofiltration systems on the shop floor can reduce concentrations of organics in the ambient air. Recently, a pilot-scale study was conducted to demonstrate biotrickling filter technology for treating ethanol emissions from bakeries[30].

Petroleum hydrocarbons are released during refining, transfer operations, from storage tanks, etc. Most of these hydrocarbons consist of aliphatic and aromatic compounds, which are easily biodegraded in biofilters. Leaking underground storage tanks pose another environmental hazard, where the hydrocarbon contaminant can be separated from the soil and/or groundwater table using air sparging, bioventing or vapor extraction. The volatile hydrocarbons are transferred into the air phase, wherein they can be effectively treated using biofiltration.

As knowledge on biofiltration increases, and more pilot-scale studies are conducted, the market for biofiltration is expected to increase in the future. Increasing number of industries are already beginning to realize the potential advantages of biofiltration, which include:

1. The only by-product of biofiltration is waste biomass, which can be easily disposed in the sewers. Thermal processes produce nitrogen oxides, which causes ozone depletion and smog formation. Chemical oxidation processes which use hypochlorite produce chlorine and chlorinated products.
2. Biofiltration is an ambient temperature and pressure process, which produces minimal carbon dioxide, a greenhouse gas. Thermal processes require additional natural gas for achieving high temperatures, which significantly increases carbon dioxide production, a greenhouse gas.
3. The investment and operating costs of biofiltration are lower than for thermal and chemical oxidation processes. There is no chemical handling in biofiltration, whereas in chemical oxidation, chemicals, such as hypochlorite, hydrogen peroxide, chlorine dioxide, etc. have to be stored and handled.

CONCLUSIONS

Biofiltration will play a major role in the treatment of organic and inorganic emissions from a variety of industrial and waste water treatment processes. Biofiltration, when compared to other available technologies, has significant technical and cost advantages. Compost biofilters are better suited for treatment of odors and low concentration (< 25 ppmv) contaminants. Biotrickling filters have significant advantages over compost biofilters and are capable of handling significantly higher contaminant concentrations (20 ppmv – 5,000 ppmv). The major issues in biotrickling filters is the design of the support media and handling of biomass growth. Support media design has a significant impact on biotrickling filter performance. The market for biofilters will increase in the next millennium, as new applications arise in the future.

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Table 1. Types of Organic and Inorganic Contaminants that can be Biotreated.

Contaminant	Biodegradability	Contaminant	Biodegradability
Aliphatic Hydrocarbons (*Methane, Propane, etc.)*	**1-2**	**Aldehydes**	**3**
Aromatic Hydrocarbons *(Benzene, Phenol, Toluene, etc.)*	**2-3**	**Esters**	**3**
Chlorinated Hydrocarbons		**Inorganic Compounds**	
Carbon tetrachloride	**1**	*Ammonia*	**3**
Chloroform	**1**		
Trichloroethylene (TCE) **(co-metabolic)**	**2**	*Hydrogen Sulfide*	**3**
Perchloroethylene (PCE)	**Recalcitrant**	*Nitrogen oxide*	**1**
Amines	**3**	**Ketones**	**3**
Nitriles	**1**	**Sulfur containing Compounds**	**1-2**
Alcohols	**3**	**Terpenes**	**1-2**

Note: 1 = Some Biodegradability; 2 = Moderate Biodegradability; 3 = Good Biodegradability

Table 2. Applicability of Various Air Pollution Control Technologies.

Type of Technology	Air Flowrate	Concentration in ppmv
Condensation	200 – 20,000 m^3/h (120 – 12,000 SCFM)	50 – 200 g/m^3 (2.8% - 11.2% by volume)
Cryo-Condensation	30 – 600 m3/h (20 – 400 SCFM)	5 – 90 g/m3 (0.28% - 5% by volume)
Scrubbing	200 – 20,000 m3/h (120 – 12,000 SCFM)	10 – 40 g/m3 (0.56% - 2.3% by volume)
Incineration	10,000 – 100,000 m3/h (6000 – 60,000 SCFM)	8 – 140 g/m3 (0.5% - 8% by volume)
Catalytic Oxidation	10,000 – 100,000 m3/h (6000 – 60,000 SCFM)	1 – 10 g/m3 (500 ppmv – 6,000 ppmv)
Regenerative Adsorption	100 – 10,000 m3/h (60 – 6,000 SCFM)	1 – 10 g/m3 (500 ppmv – 6,000 ppmv)
Non-Regenerative Adsorption	10 – 60 m3/h (6 – 40 SCFM)	0 – 5.0 g/m3 (< 1 ppmv – 2,800 ppmv)
Compost Biofiltration	60 – 300,000 m3/h (40 – 180,000 SCFM)	(< 1 ppmv – 25 ppmv)
Biotrickling Filter	10 – 300,000 m3/h (6 – 180,000 SCFM)	(0 - 8.3 g/m3 (20 ppmv – 5,000 ppmv)

Figure 1. Schematic of a Biotrickling Filter Using Synthetic Support Media.

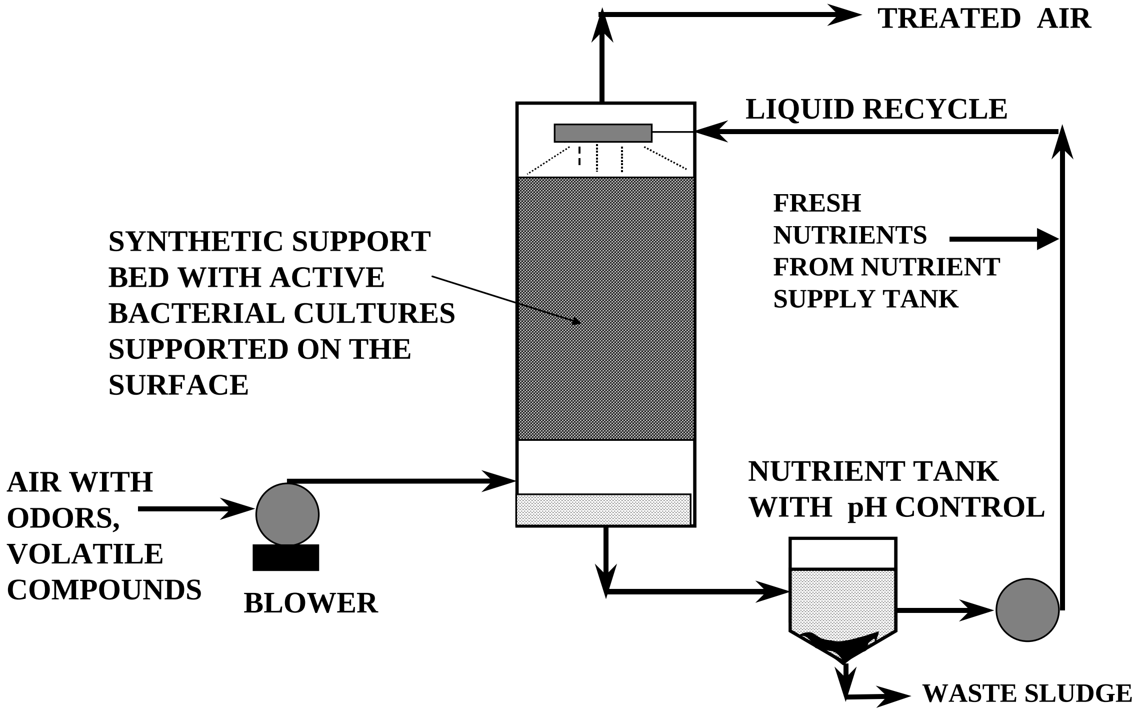
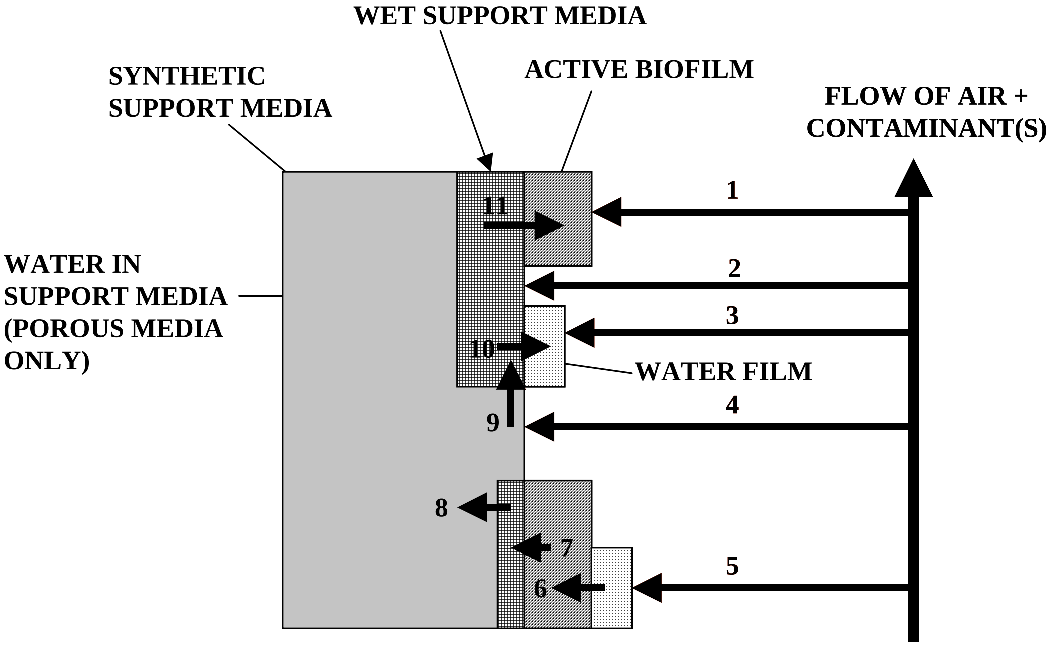
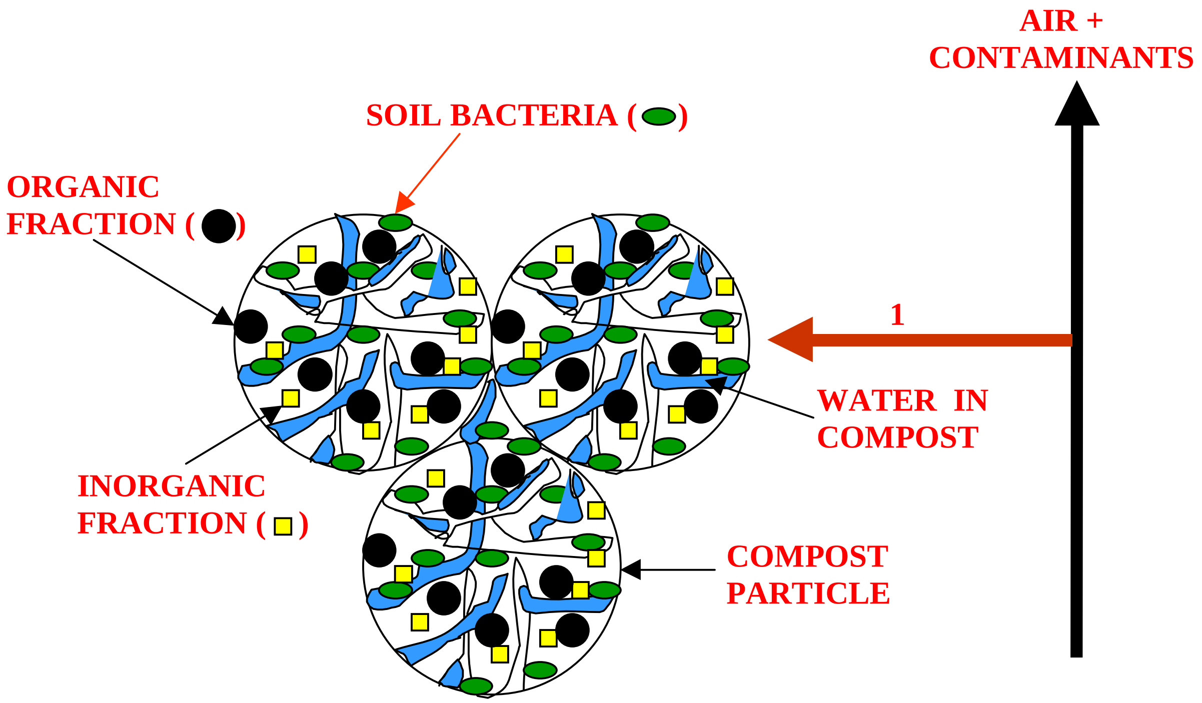


Figure 2. Operating Mechanisms in a Biotrickling Filter Using Synthetic Support Media.



Mechanism	Description
1	Diffusion from bulk gas to biofilm surface
2	Diffusion from bulk gas to water in support media
3	Diffusion from bulk gas to water film on support media
4	Diffusion from bulk gas to dry support media
5	Diffusion from bulk gas to water layer on biofilm
6	Diffusion from water layer into active biofilm
7	Diffusion through biofilm with biodegradation and into water in support media
8	Diffusion from water in support media into support media
9	Surface diffusion in support media
10	Back diffusion from water in support media into water film
11	Back diffusion from wet support media into biofilm

Figure 3. Operating Mechanisms in a Peat / Compost Biofilter.



Mechanism	Description
1	Diffusion from bulk gas to compost
2 (not shown)	Diffusion within compost particle
3 (not shown)	Solubilization in water within compost
4 (not shown)	Adsorption to organic fraction of compost
5 (not shown)	Adsortion to inorganic fraction of compost
6 (not shown)	Biodegradation by bacteria in compost
7 (not shown)	Diffusion between organic fraction, water content and inorganic fraction

Figure 4. Relative Performance of Various Biofilter Support Media.

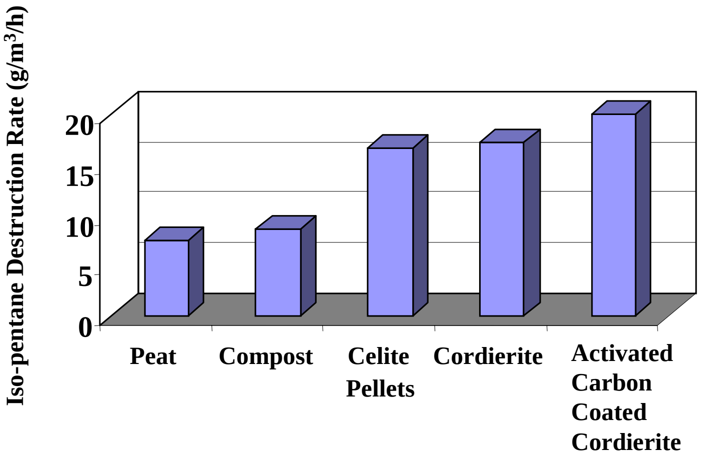


Figure 5. Cost Comparosin of Biofiltration with Catalytic Oxidation and Adsorption.