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Biofiltration of Gaseous Emissions from Forest Products Manufacturing

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Biofiltration of Gaseous Emissions From Forest Products Manufacturing

by

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EXECUTIVE SUMMARY

Biofiltration is a cost-effective, environmentally-friendly air pollution control (APC) technology to reduce and remove odourous, gaseous contaminants from waste gas. It is highly suited to treat large volumes of gases with low concentrations of contaminants, a situation that makes the use of traditional APC technology such as incineration economically unfeasible. Forest products industries, such as pulp mills and oriented strand board mills, produce waste gases often containing low amounts of highly odorous sulphur compounds (e.g. dimethyl sulphide (DMS)). Biofiltration is a good candidate to treat such waste streams. A significant factor that could impede effective treatment of sulphur waste gases by biofilters, however, is the low partition coefficient of these compounds in water. Compounds with a high partition coefficient are easily degraded within a biofilter, but compounds with a low partition coefficient are more difficult to remove. This project investigated biofiltration parameters that could be changed that would enhance the removal of water-insoluble compounds. It was found that the composition of the bed medium plays in important role in biofilter performance. Peat was a better medium than wood chips for the removal of the hydrophobic compounds tested in this project; *n*-hexane and DMS. A mixture of peat and perlite proved to be an even better bed medium for DMS removal than peat alone. As well, bed medium moisture content and pH affected the performance of the biofilters. These findings have implications for the management of wood products industries. The reduction of odourous waste gas is possible with the use of biofiltration technology. In particular, the removal of reduced sulphur compounds, such as DMS, is possible if attention is paid to ensuring the proper moisture content and pH is maintained and that a good bed medium is used. This might entail more operating control and thus increase costs, but the desired removal would be achieved and in the long run cost savings would be realized.

INTRODUCTION

In biofiltration, the waste gas passes through a column packed with a support matrix covered with a biofilm of viable microorganisms. The waste gas undergoes a mass transfer from the gas to the liquid phase, diffuses through the liquid phase (i.e. the biofilm), and is transformed or degraded by the microorganisms. The contaminants are thus transformed to innocuous endproducts such as carbon dioide, sulphate, nitrate, water, and new cell biomass.

For biofiltration to be successful, a crucial step in the process is the mass transfer of the contaminant from the gas to the liquid phase. Compounds such as low-molecular weight alcohols, ketones, esters, and hydrogen sulphide (H_2S) readily diffuse into the biofilm and so are effectively removed by the biofilter. The biofiltration of higher molecular weight compounds or compounds that do not readily dissolve into water have proven to be difficult (Devinney et al. 1999). Removal efficiencies are often below 80%, which is not usually acceptable by regulatory standards (Devinney et al. 1999). Substrate availability to the biofilter microorganisms is reduced in the case of such hydrophobic compounds and so poor removal occurs.

Little work has been done on enhancing the biofiltration of hydrophobic compounds. The objective of this research project, therefore, was to investigate ways of optimizing the biofiltration process to enhance the removal of gaseous hydrophobic compounds, such as DMS, a compound commonly produced by wood processing industries.

The research for this project was divided into two components. The first component investigated different aspects of the biofiltration of *n*-hexane so that decisions could be made on how to enhance the removal of hydrophobic compounds. The effects of silicone oil addition, wet/dry cycling, and using different bed medium were determined. Peat was chosen as the bed medium of choice due to its high surface area for microbial attachment, low pressure drop, and its availability, especially in Alberta (home province). We have also used peat successfully in biofilters removing H_2S. However, we also tested aspen and spruce chips as alternate bed media. *n*-Hexane was used as a model compound in these initial studies due to its relative low toxicity and low odour threshold as compared to DMS. This allowed greater flexibility in conducting the experiments.

The second component of the research project focused on the biofiltration of DMS. Results from the *n*-hexane biofiltration experiments were used to design the biofilter configuration. Different inocula and bed media composition were tested. A biofilter configuration and composition was achieved that produced the desired removal rates for DMS and recommendations for the forest industry to use biofilters for DMS removal are reported.

MATERIALS AND METHODS

Biofilter Design and Construction

The design, specifications and construction of the biofilters used in this project have been reported in Budwill and Coleman (1996, 1997, 1998a), though Table 1 summarizes the essential information on the biofilters.

Table 1. Specifications of biofilters used in project

Parameter	Biofilter "5-cm diameter"	Biofilter "15-cm diameter"
Diameter	5 cm	15 cm
Height	1 m	3 sections of 30 cm, with 15 cm plenum in between sections, 1.35 m total height
Bed Volumes	1,963 cm^3	15,904 cm^3
Air Flow	6-8 l/min	25-75 l/min
EBRT[a]	15-20 sec.	13-40 sec.
Up-flow/Down-flow	Only up-flow	Both
Comments		Sampling ports for each section
Contaminant Delivery	Vapourization, controlled by rotameters	Vapourization, controlled by mass flow controllers
Humidification	Yes	Yes

[a] Empty bed retention time

Microbiology Aspects

The inocula used for the various biofiltration experiments, their growth and maintenance have been described previously (Budwill and Coleman 1997, 1999). Inoculum volumes added to each biofilter varied depending in size of biofilter and experiment. The 1-m high, 5-cm diameter biofilter was usually inoculated with 100 ml of the consortium several times during the first 4 weeks of operation. The 1.35-m high, 15-cm diameter biofilter was inoculated with 900 ml of consortium, again, once every week for the first 4 weeks of operation.

Microbial counts were performed as described in Budwill and Coleman (1996, 1998b). R2A medium (Difco Laboratories, Detroit MI) was used to determine total heterotrophic counts, while S6 medium (Atlas and Parks 1993) was used to select and enumerate *Thiobacillus* species.

Identification and growth studies of the *n*-hexane-degrading bacteria have been described in Budwill and Coleman (1998).

Analytical Analyses

Grab samples of inlet and outlet gases were collected into Tedlar bags (SKG Inc., Eighty Four, PA) and their composition analysed as in Budwill and Coleman (1997) for *n*-hexane and Budwill and Coleman (1999) for DMS.

The moisture content and pH of the bed material were determined at certain times during the course of the experiment and at the end. The moisture content was measured gravimetrically by calculating the change in weight of the bed medium sample before and after drying at 105°C for 24 hr and expressed as percentages. The pH of the bed medium was determined by making a water slurry of the sample and using a pH meter (Accumet pH meter 925, Fisher Scientific Ltd., Ottawa, Ont.) after allowing 30 to 60 minutes equilibration time.

Temperatures of the inlet and outlet gas streams were measured using thermisters every 60 minutes and the values recorded and stored with a datalogger (Ultra-Logger UL-16, Lakewood Systems Ltd., Edmonton, AB).

Calculations and Units Used in Report

The following biofilter operating parameters and their calculations were used (Swanson and Loehr 1997).

- Empty bed residence time (EBRT):
  This is a measure of the biofilter gas residence time and usually reported with units of seconds.
- Mass loading (ML)
  The chemical mass loading rate per unit bed volume. Reported as an average value for the entire bed volume and reported as $g/m^3/hr$.
  QCi/V
- Elimination capacity (EC)
  The chemical mass removal rate per unit bed volume, reported as $g/m^3/hr$. It is a normalized measure of contaminant removal capacity at a given mass loading, and reported as a bed averaged value.
  $Q(Ci-Ce)/V$
- Removal efficiency
  Used as a performance measure and given as a percent.
  $(Ci-Ce)/Ce \times 100\%$

Where:

V= biofilter volume
Q= gas flow rate
A = area
Ci= influent concentration
Ce= effluent concentration

RESULTS AND DISCUSSIONS

n-Hexane Biofiltration

Effects of silicone oil addition biofilter performances

Due to the poor water solubility and low partition coefficient of *n*-hexane, the biodegradation and removal of *n*-hexane vapours by biofiltration has proven to be highly variable but, in general, poor (Morgenroth et al. 1996). In order to enhance the *n*-hexane removal performance, the effects of a surface-active agent (surfactant) addition to the biofilter bed material was investigated. The use of surfactants to enhance the bioremediation of contaminated environments has been extensively reviewed by Rouse et al. (1994). The presence of a surfactant on the biofilter medium should theoretically increase the mass transfer of *n*-hexane from the gas to the liquid phase due to the surfactant's amphipathic characteristics (Volkering et al. 1995). It has been shown that surfactants alter the hydrophobicity characteristics of the microbial cell surface, allowing the microorganisms to adhere to the surfactant (Neu 1996) and, so, in a biofilter setting this could increase contact between the microorganisms and *n*-hexane partitioned into the surfactant layer. Silicone oil was chosen as surfactant due to its high levels of thermal stability and relatively non-toxicity (Ascon-Cabrera and Lebault 1993) as well as the high partition coefficient of *n*-hexane in silicone oil (Cesario et al. 1992).

Figure 1 shows the performance of a biofilter treated with silicone oil to that of an untreated control biofilter. There was a lag period of about 38 days before 50% *n*-hexane removal occurred in the silicone oil-treated biofilter. On day 38, 12.6 g *n*-hexane/m^3 bed material/hr was being removed. The greatest removal recorded was 91.6% (at an air flow-rate of 3.4 l/min). However the elimination capacity was 16.4 g *n*-hexane/m^3 bed material/hr; the highest elimination capacity achieved was 25.5 g *n*-hexane/m^3 bed material/hr on day 53. At the end of the experiment, an average of 60.0% *n*-hexane or 12.2 g *n*-hexane/m^3 bed material/hr (at an air flow rate of 6.5 l/min) was being removed. In contrast, the *n*-hexane removal in the untreated control was much lower. By day 38, *n*-hexane removal was only 24% or 3.6 g *n*-hexane/m^3 bed material/hr. At the end of the experiment an average of 37.1% *n*-hexane or 5.8 g *n*-hexane/m^3 bed material/hr was being removed.

The addition of silicone oil in this experiment, therefore, resulted in an enhanced removal of nearly twice the removal in the untreated control biofilter. Higher elimination capacities than 16.0 g *n*-hexane/m^3 bed material/hr could not be achieved. This value is lower than what was achieved in a compost/perlite/crushed oyster shell-based biofilter treating *n*-hexane (Morgenroth et al. 1996). Elimination capacity values between 21.0-43.0 g *n*-hexane/m^3 bed material/hr were reported depending on the air flow-rate and inlet concentrations.

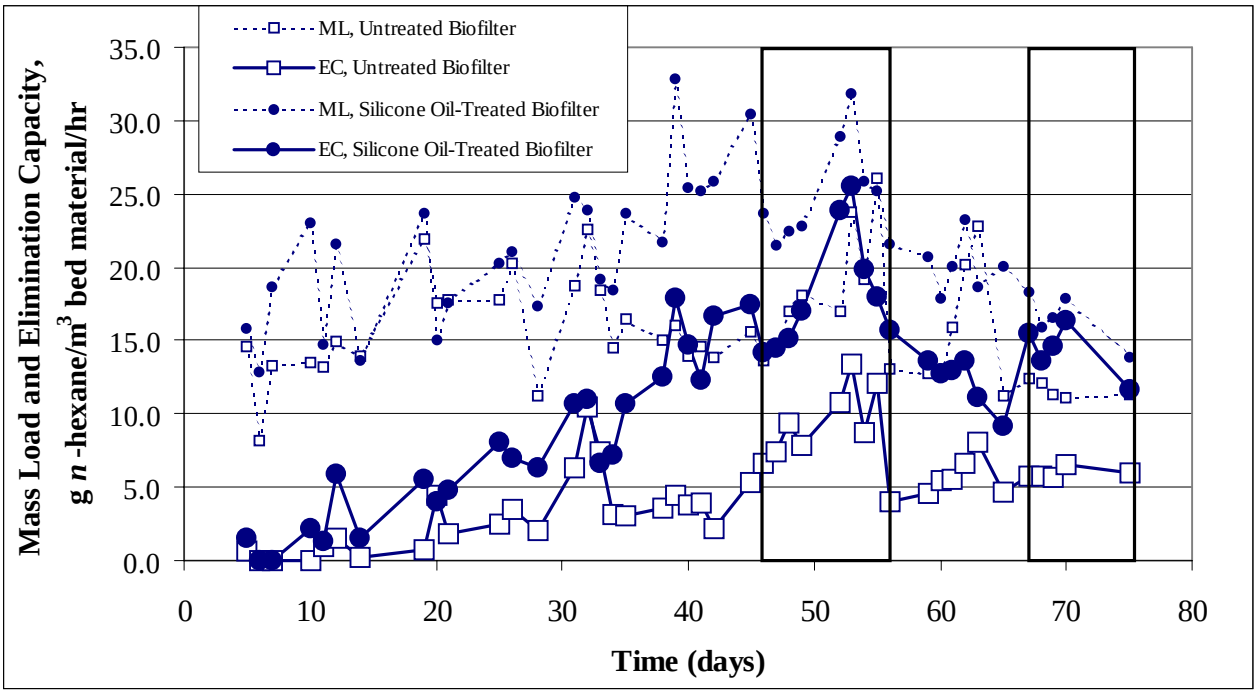

Figure 1. *n*-Hexane removal performances of silicone oil-treated and untreated biofilters. The boxed in areas represent times in the experiment when the air flow was reduced from 6.5 to 3.4 l/min. ML = mass load, EC = elimination capacity.

The lag period before 50% removal occurred could be effectively be reduced from 38 to 5 days (Figure 2) by re-using the silicone oil-treated peat from the previous *n*-hexane-treating biofilter. This peat had heterotrophic bacterial numbers of 10^8 colony forming units (cfu)/g peat. As well, an average of 90% *n*-hexane or 26.8 g *n*-hexane/m^3 bed material/hr removal was achieved. A non-silicone oil-treated control biofilter packed with uninoculated peat showed a 25-day lag period before the *n*-hexane removal rate increased above 40%. Removals, however, never rose above 50% during the course of the experiment, and at the end of the experiment 9.1 g *n*-hexane/m^3 bed material/hr was being removed in this biofilter. Interestingly, the bacterial numbers in both biofilters at the end of the experiment ranged from 10^7 to 10^8 cfu/g of wet peat. This would suggest that perhaps the re-used peat had acclimated bacteria that could degrade *n*-hexane whereas the uninoculated, new peat did not despite the equal number of bacteria. A longer operation time may have allowed *n*-hexane-degrading bacteria in the untreated biofilter to evolve and increase in numbers.

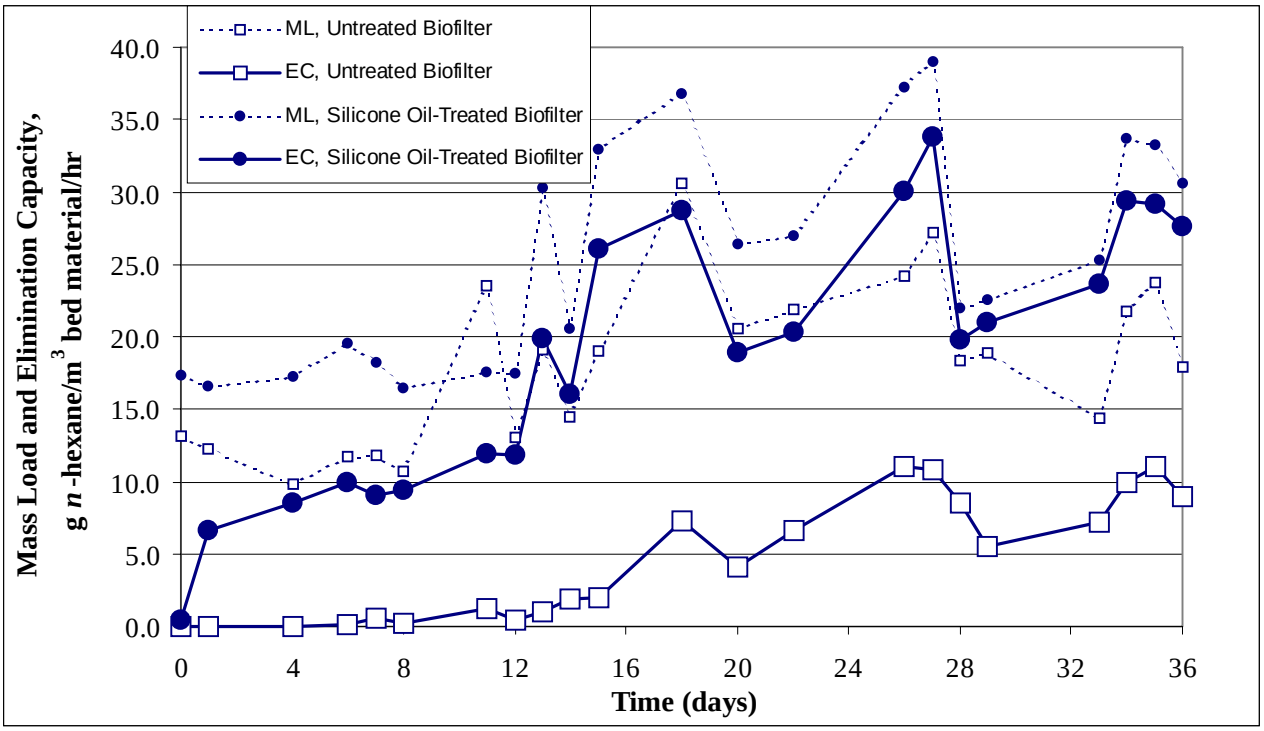

Figure 2. *n*-Hexane removal performances of an untreated biofilter and a silicone oil-treated biofilter packed with precolonised peat. ML = mass load, EC = elimination capacity.

The moisture content of the untreated control biofilter was on average 82% and was higher than in the treated biofilter (65%). Moisture content is an important factor in biofiltration performance. For optimum conditions, the moisture content of a biofilter bed medium should be between 40 to 60%. At moisture contents above 60%, the gas/liquid surface area decreases, potentially causing mass transfer problems (van Groenestijn et al. 1995). Therefore, the mass transfer of *n*-hexane from the gas phase to the liquid phase could have been impeded by the high moisture content of the peat. The lower moisture content of the silicone oil-treated biofilter may have been due to the silicone oil acting as a barrier to water adsorption by the peat.

Relatively low moisture content and the presence of silicone oil probably allowed greater amounts of *n*-hexane to dissolve into the silicone oil layer/water layer than if there was just a water layer. At the same time the presence of the silicone oil may have produced hydrophobic sites on the microbial cell surface thus allowing the cells to attach to the water-silicone oil interface (Ascon-Cabrera and Lebeault 1993) and come into contact with the dissolved *n*-hexane. This may explain why a greater amount of *n*-hexane removal was observed in this biofilter than in the untreated control biofilter.

Wet/dry moisture cycling within a biofilter

As the previous section demonstrated, the use of silicone oil can enhance the removal of a hydrophobic compound in a biofilter. However, as silicone oil is costly its price would be prohibitive for its use in a full-scale, on-site biofilter. In order to maintain the attractiveness of biofilters' low operating costs, we focused the research project on manipulating the moisture content of the filter bed medium.

In this experiment, two peat-based biofilters were operated in parallel. One biofilter served as the control and received a constant amount of moisture via humidification of the air stream. The second biofilter was subjected to a wet/dry cycling of the air stream. This was done by installing an in-line condenser after the humidifier to condense out some of the water from the humidified air.

As can be seen from Figure 3, the moisture contents in the wet/dry biofilter throughout the experiment were, in fact, quite high. Condensing of the air stream only slightly lowered the moisture content of the peat. The high moisture content in the biofilter led to increased pressure drop and necessitated that the peat be removed and repacked to prevent compaction. This was done several times during the course of the experiment. It was observed, and can be seen in Figure 4, that there was always an increase in the *n*-hexane removal rate whenever the peat was repacked. This would indicate that mixing and repacking of the peat created loft for good air passage and thus good adsorption and contact of the contaminant with the microorganisms. The microbial population on the peat did not seem to be adversely affected by the disturbance of the bed material as *n*-hexane removal rates did not drop.

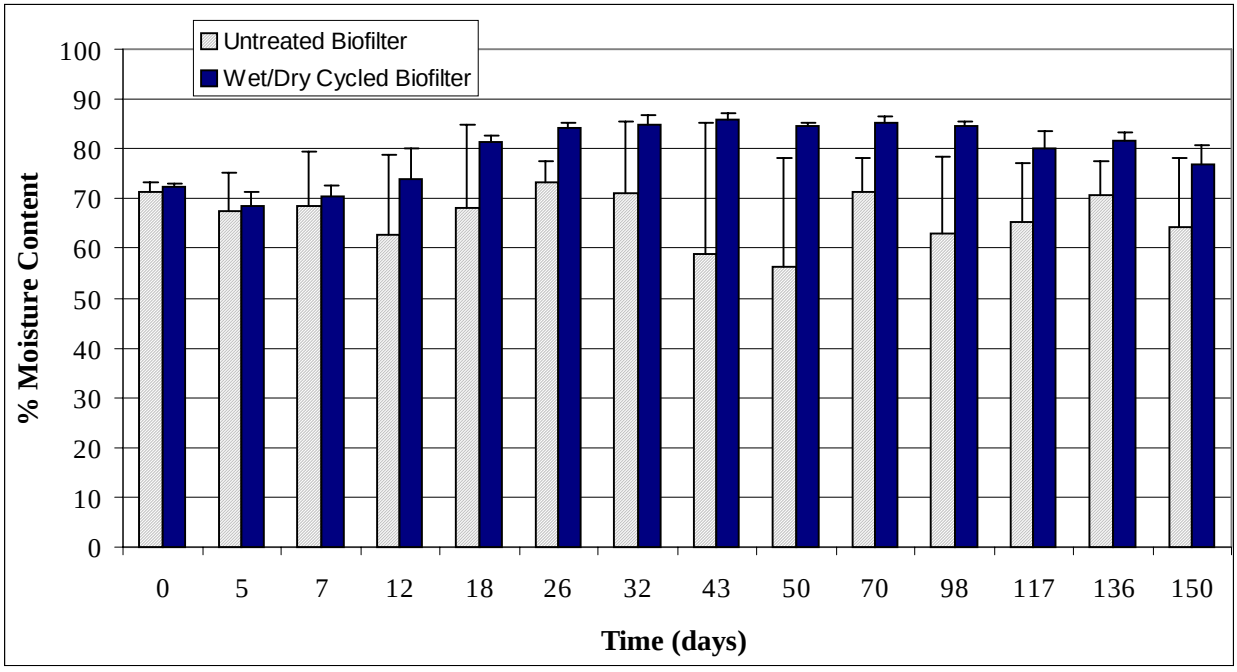

Figure 3. Percent moisture content of peat from untreated biofilter and biofilter subjected to wet/dry cycling of in-coming air moisture.

Higher removals were observed in the wet/dry biofilter than in the control biofilter only towards the end of the experiment (Figure 4). Despite the high moisture content, a maximum elimination capacity of 34.0 g *n*-hexane/m^3 bed material/hr was obtained while a maximum elimination capacity of 21.0 g *n*-hexane/m^3 bed material/hr was obtained with the control biofilter. The peat from the inlet section of the control biofilter was in fact quite dry. A range of 30 to 70% moisture content was measured over the course of the experiment and accounts for the large standard deviation seen in Figure 3. The peat from this section had a pH of 6.5. A combination of these factors may have affected the poor removal rates.

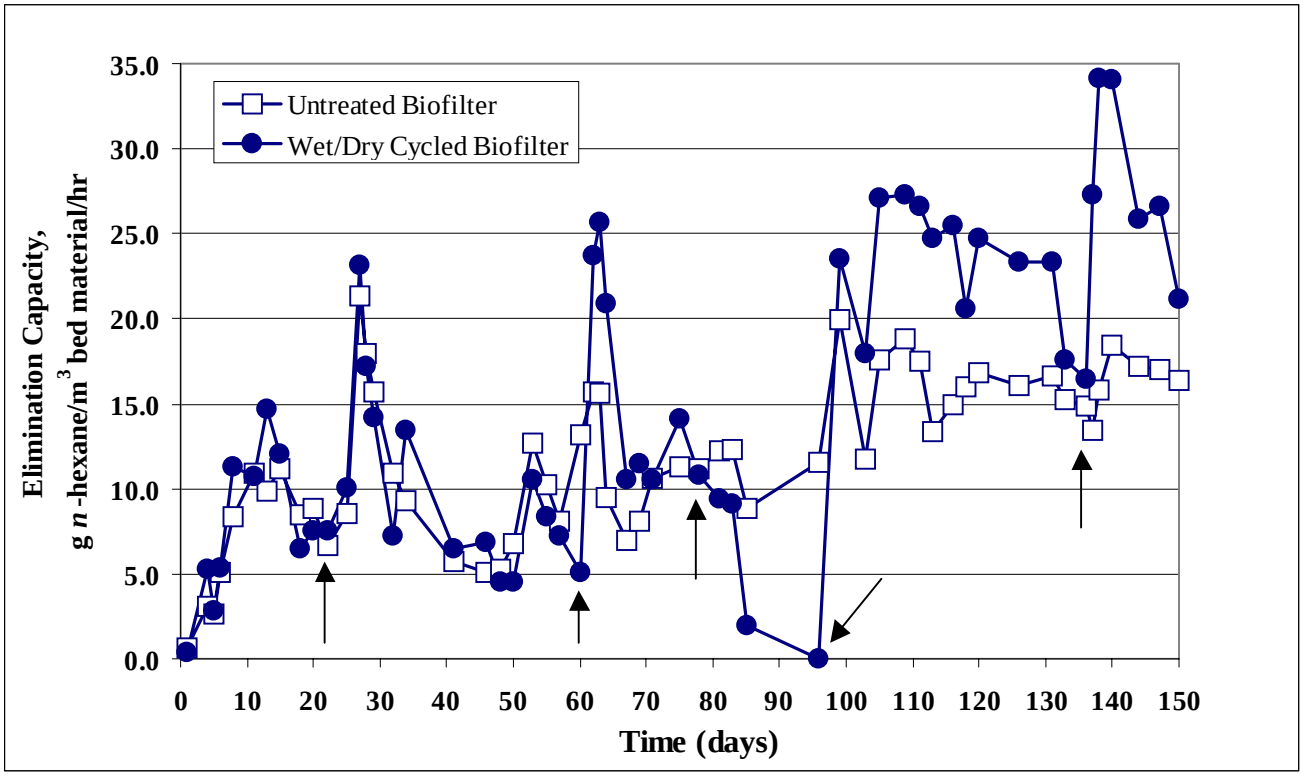

Figure 4. *n*-Hexane removal performances of an untreated biofilter and a biofilter subjected to wet/dry cycling of in-coming air stream. Arrows indicate times when the biofilter bed media were removed and then repacked into the columns.

In conclusion, it was very difficult to control the moisture content of the biofilter peat by trying to create wet/dry cycles. Peat, once wet, can soak up a lot of moisture and remain wet for long periods of time. The control biofilter started off fairly dry and channeling was observed. This may have negatively affected the bacteria and recovery was slow once the peat became moister. The very moist peat in the test biofilter probably provided a good environment for microbial growth but this biofilter was prone to compaction. Repacking helped to restore the high levels of *n*-hexane removals but these removal rates could not be sustained for very long as compaction occurred quickly.

Comparison of peat and waste wood as biofilter bed material

A good bed material must have 1.) a large specific surface area for microbial attachment and contact area between gas and liquid phases, 2.) resistance to compaction, and 3.) a high porosity to allow for passage of air-stream and water through the biofilter without increasing the pressure drop (Swanson and Loehr 1997). Other qualities of a good bed material include providing an optimal microbial environment in terms of nutrient availability, pH control and moisture and allow for the adsorption of contaminants thereby increasing the concentration of contaminants available to the biomass. Finally, the choice of bed material depends on the cost and maintenance requirements (Oosting et al. 1992).

Due to the problems controlling the moisture content of peat and also due to its acidic nature, we investigated the use of wood chips as an alternate biofilter bed medium. The use of wood chips may alleviate the moisture and pH problems associated with peat and may also offer a cost saving factor in that waste wood chips are readily available on site at forest products manufacturing industries. Therefore, aspen and spruce waste wood chips were collected from an oriented strand board mill for use in the biofiltration experiment to treat *n*-hexane. Both bed media were adjusted to a pH of between 6.0-7.0, and inoculated with the *n*-hexane-degrading consortium before packing them into the biofilter column.

Figure 5 shows the biofilters' performances. The great variability in removal rates can be attributed to the fact that biofilters are biological systems and so a great number of factors could have affected the biofilter performances on a daily basis. Increases in elimination capacities of the aspen chip-based biofilter seemed to correspond with the addition of the nutrient solution thus indicating that nutrient limitation was occurring in this biofilter. A maximum elimination capacity of 8.3 g *n*-hexane/m^3 bed medium/hr was achieved with the aspen chip-based biofilter and 7.9 g *n*-hexane/m^3 bed medium/hr with the spruce chip-based biofilter. Overall, however, the aspen chip biofilter outperformed the spruce chip biofilter. A comparison of the mass load to the elimination capacity (Figure 6) shows that the aspen chip based-biofilter achieved a higher elimination capacity than the spruce chip-based biofilter at similar mass loads. Other operating parameters such as moisture content, pH of bed material, and gaseous flow rate were similar between the two biofilters (data not shown).

The poor performance of the spruce chip-based biofilter could be attributed to contamination of the chips by fungi. The increase in the elimination capacity in the spruce chip-based biofilter towards the end of the experiment may have been a result of the decline of the fungal contamination due to nutrient depletion and the increase in bacterial numbers capable of using *n*-hexane. In contrast, the aspen chip-based biofilter did not have this fungal contamination and never had as low elimination capacities as the spruce chip-based biofilters.

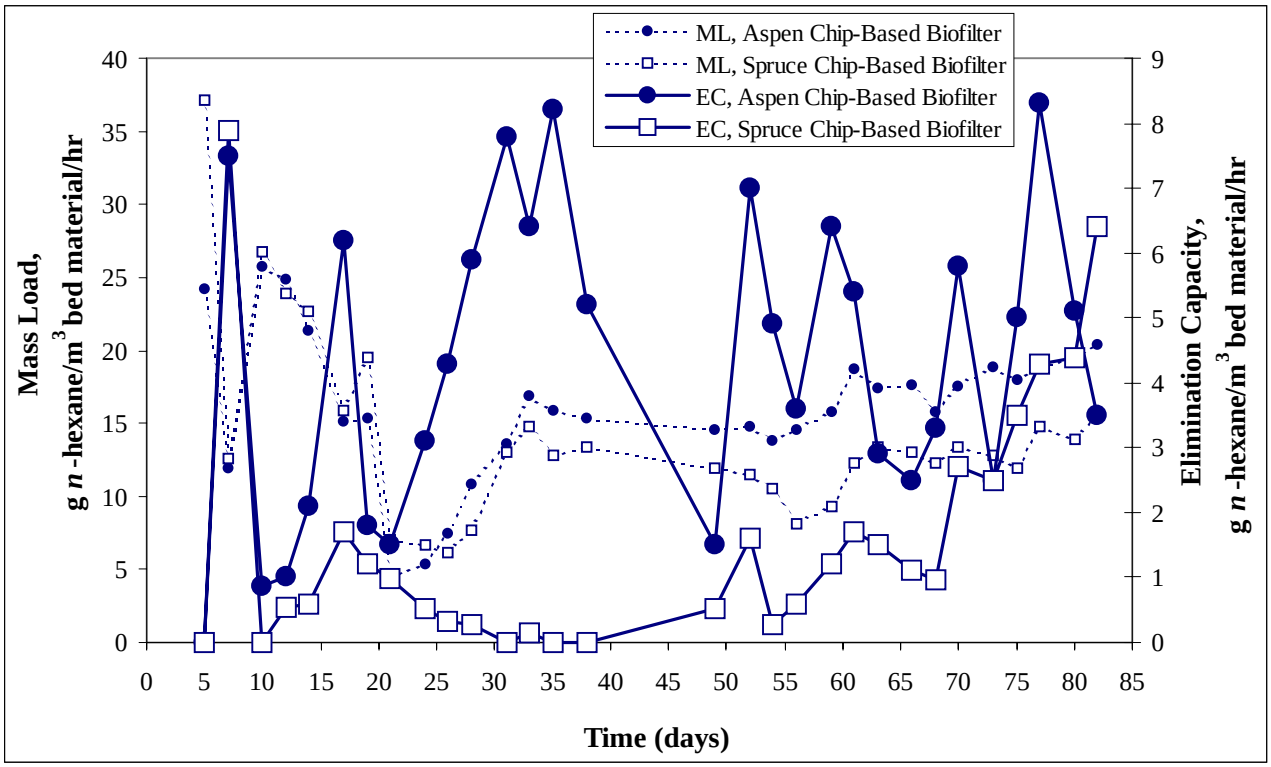

Figure 5. *n*-Hexane removal performances of aspen and spruce chip-based biofilters. ML = mass load, EC = elimination capacity.

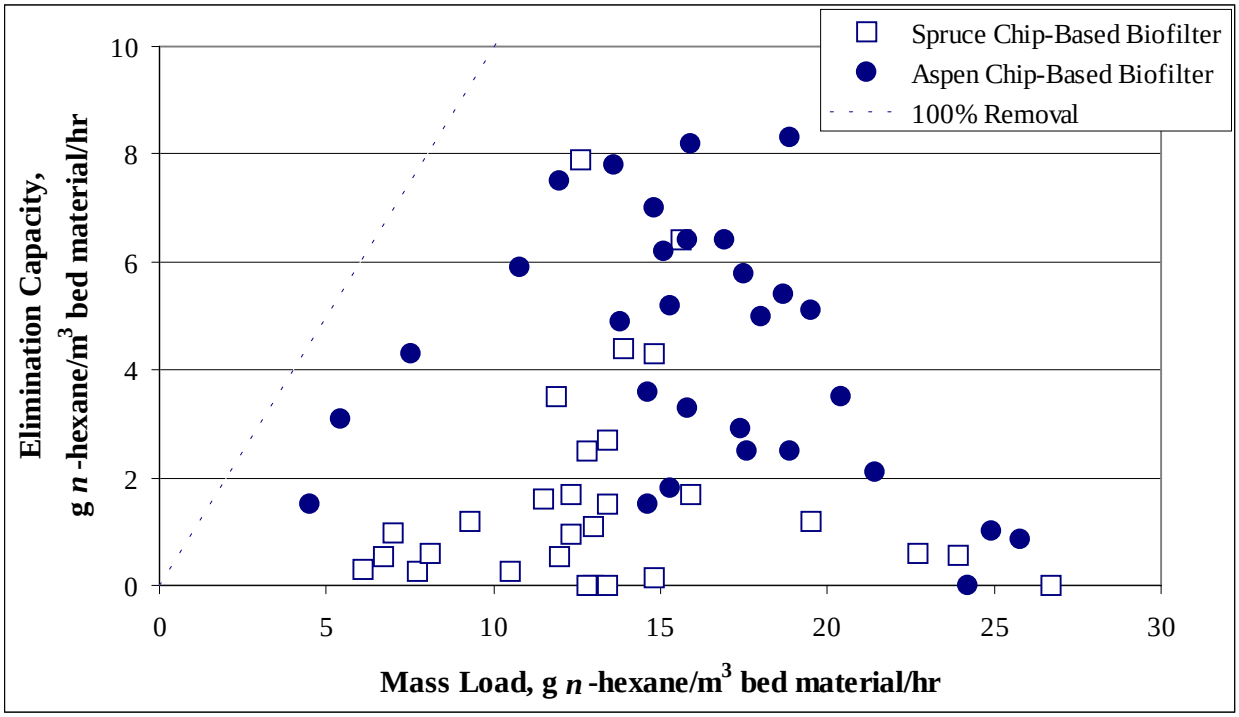

Figure 6. Relationship of elimination capacities to mass loads in the aspen and spruce chip-based biofilters.

When the elimination capacities achieved by the wood chip-based biofilters are compared to those achieved by the peat-based biofilters under similar operating conditions, the peat-based biofilters clearly outperformed the wood chip-based biofilters, with removal values usually double to those of the wood chip-based biofilters.

A lower moisture content (70-75%) could be maintained than what usually occurred with peat biofilters (greater than 80%). As well, a better buffering capacity could be achieved with the wood chips than with the peat. However, due to peat's fibrous structure, the surface area to volume ratio is higher than with the wood chips, thus providing greater number of sites for attachment and contact site for the contaminant. Microbial numbers were approximately 10^7 cfu/g wood chips, whereas microbial counts on the peat were slightly higher at 10^7-10^8 cfu/g. There were fewer problems, however, with contaminating fungi when peat was used than with the wood chips.

A mixture of peat and aspen wood chips (in an 80-20% ratio) was used as a filter bed medium to determine whether the presence of peat would allow for good microbial attachment whereas the presence of the aspen wood chips would contribute towards moisture and pH control. This combination should, therefore, enhance biofilter performance over that observed with a wood chips only biofilter.

Figure 7 shows the performance of the two biofilters over an 88 day operating period. Overall, both biofilters had similar elimination capacities, although it appeared that the aspen chip/peat-based biofilter was outperforming the aspen chip-based biofilter in the first 40 days of operation. It is not known why there was a sudden and irretrievable decline in *n*-hexane removal in the mixed bed reactor. It is speculated that the biofilter was affected by the mass loads that changed daily. The switch from a high mass load to a low mass load than back to a high mass load may have been detrimental to the microbial population. The addition of more inocula and adjusting the pH did not have any positive effect on the elimination capacities.

As will be presented later, the use of a mixture of peat and aspen chips as filter bed medium in the biofiltration of DMS did not enhance removal performances either. Overall, then, the use of waste wood chips in biofiltration is questionable. Although it may be a readily available and an inexpensive filter bed source, it was demonstrated not to be effective in removal of hydrophobic compounds such as *n*-hexane and DMS.

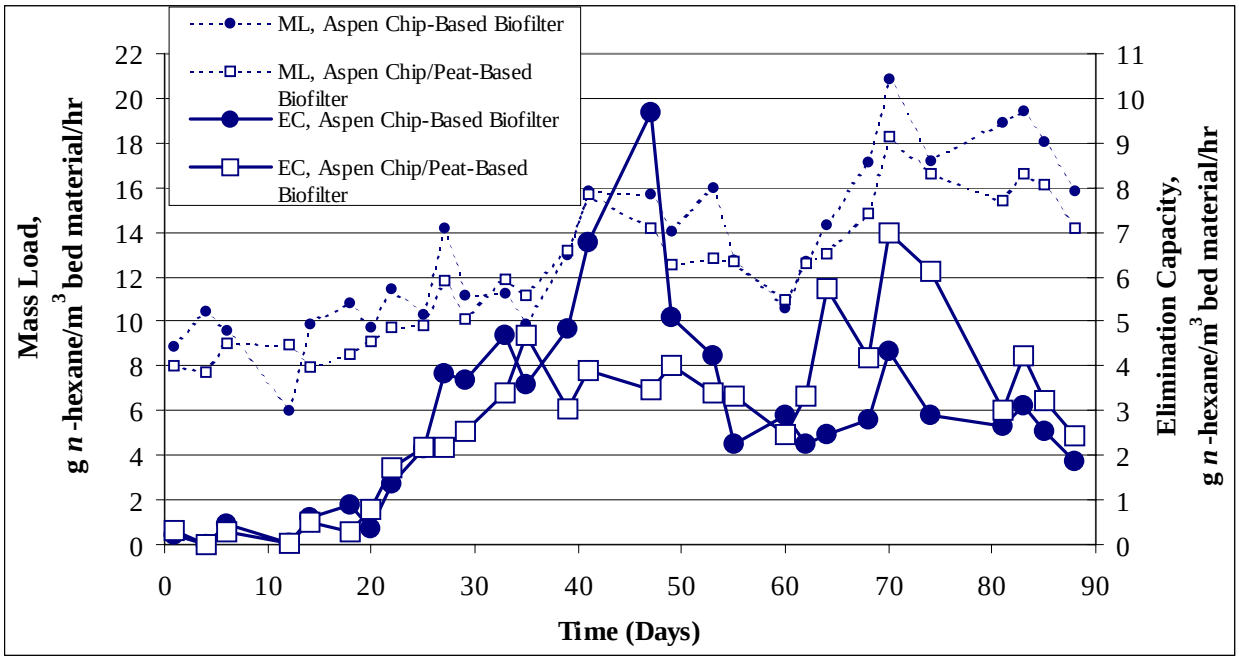

Figure 7. *n*-Hexane removal performances of aspen chip- and aspen chip/peat-based biofilters. ML = mass load, EC = elimination capacity.

Identification of heterotrophic bacteria isolated from peat-based biofilters treating n-hexane.

Despite the importance microorganisms have in biofiltration, little is known about the microbial ecology of biofilter systems. Microbial communities capable of degrading the pollutants often evolve spontaneously from indigenous microorganisms found in the packing material upon continuous exposure to the waste gases (Ahrens et al. 1997). Biofiltration can also be enhanced with the inoculation of specific microorganisms (Coleman and Dombroski 1995a). Knowledge of the microbial species involved in a given biofiltration system would enable optimization of the biofilter by adjustment of operating parameters such as pH and nutrient additions.

In order to gain further knowledge of the microbial ecology of the peat-based biofilters treating *n*-hexane, we isolated and identified heterotrophic bacteria from the peat at the end of a biofilter run. Bacterial isolates were identified on the basis of their fatty acid profiles (see materials and methods section for details). The biofilter isolates identified were compared to those isolated from fresh peat prior to its being used in a biofilter, and from those isolated from an *n*-hexane-degrading enrichment culture used to inoculate the biofilters. Biofilter microbial isolates came from either silicone oil-coated peat or from silicone oil-free peat.

A large number of isolates were obtained from the biofilters, fresh peat and enrichment culture. In total 74 isolates from these sources were obtained, however for this study, these were narrowed down to only those capable of growing in liquid cultures in the presence of *n*-hexane as sole carbon source. Therefore, the number of isolates was reduced to 50, and of these, fatty acid profiles could be generated for 40 isolates (Table 2). Some isolates may have been isolated

twice from a given source, for example, the two *Xanthomonas maltophilia* from the enrichment culture.

Table 2. Isolates used in study, their source, and growth in basal salt medium with 1% (v/v) *n*-hexane. Turbidity was used as an indicator of growth, the more turbid the culture, the greater the growth: +++, very turbid; ++, turbid: +, somewhat turbid.

Isolate	Source	Identification (by MIDI system)	Growth in BSM, 1% (v/v) n-Hexane
HB 1	Control Biofilter, run#1	*Cellulomonas* sp.	+++
HB 2	Control Biofilter, run#1	*Bacillus* sp.	+
HB 9	Silicone Oil-Treated Biofilter, run#1	*Micrococcus varians*	++
HB 12	Silicone Oil-Treated Biofilter, run#1	*Oerskovia* sp.	+++
HB 22	Control Biofilter, run#2	*Alcaligenes xylosoxydans*	++
HB 23	Control Biofilter, run#2	*Cellulomonas* sp.	+++
HB 26	Control Biofilter, run#2	*Arthrobacter* sp.	+
HB 27	Control Biofilter, run#2	*Rhodococcus* sp.	+++
HB 28	Control Biofilter, run#2	*Alcaligenes* sp.	+++
HB 29	Control Biofilter, run#2	*Oerskovia* sp.	+++
HB 33	Control Biofilter, run#2	unknown	++
HB 34	Control Biofilter, run#2	*Alcaligenes* sp.	+
HB 35	Control Biofilter, run#2	*Agrobacterium* sp.	+
HB 36	Silicone Oil-Treated Biofilter, run#2	*Oerskovia* sp.	++
HB 37	Silicone Oil-Treated Biofilter, run#2	*Cellulomonas* sp.	+++
HB 38	Silicone Oil-Treated Biofilter, run#2	*Pseudomonas mendocina*	+++
HB 39	Silicone Oil-Treated Biofilter, run#2	*Arthrobacter* sp.	+++
HB 75	Control Biofilter, run#3	*Bacillus* sp.	++
HB 77	Control Biofilter, run#3	*Aureobacterium* sp.	+++
HB 78	Control Biofilter, run#3	*Pseudomonas putida*	+
HB 79	Silicone Oil-Treated Biofilter, run#3	*Pseudomonas* sp.	++
HB 81	Silicone Oil-Treated Biofilter, run#3	*Aureobacterium* sp.	++
HB 117	Control Biofilter, run#4	*Curtobacterium* sp.	+
HB 118	Control Biofilter, run#4	unknown	++
HB 119	Control Biofilter, run#4	*Arthrobacter* sp.	++
HB 121	Silicone Oil-Treated Biofilter, run#4	*Flavobacterium* sp.	+++
HB 122	Silicone Oil-Treated Biofilter, run#4	*Pseudomonas putida*	++
HB 123	Silicone Oil-Treated Biofilter, run#4	*Pseudomonas putida*	+++
HC 14	n-Hexane Enrichment Culture	*Pseudomonas fluorescens*	+++
HC 15	n-Hexane Enrichment Culture	*Xanthomonas maltophilia*	+++
HC 16	n-Hexane Enrichment Culture	*Escherichia coli*	++
HC 17	n-Hexane Enrichment Culture	*Pseudomonas fluorescens*	+++
HC 18	n-Hexane Enrichment Culture	*Xanthomonas maltophilia*	+++
HC 19	n-Hexane Enrichment Culture	*Oerskovia sp.*	++
HC 21	n-Hexane Enrichment Culture	*Escherichia coli*	+++
HP 41	Fresh Peat	*Corynebacterium* sp.	++
HP 43	Fresh Peat	*Corynebacterium* sp.	+++
HP 67	Fresh Peat	unknown	++
HP 69	Fresh Peat	*Burkholderia* sp.	++
HP 70	Fresh Peat	*Cytophaga* sp.	+

The isolates were organized into a dendogram based on the relative similarity of their fatty acid compositions. The resulting dendogram (not shown) revealed the isolates to be divided into two distinctive groups; the pseudomonad-like bacteria (Gram-negative bacteria) and the *Arthrobacter*-like bacteria (Gram-positive bacteria). The most prevalent, homogeneous genera found were the pseudomonads. These were isolated from each biofilter run and from the enrichment culture. No pseudomonad was isolated from the fresh peat. The next most prevalent group was the irregular, nonsporing, Gram-positive rods such as *Arthrobacter*, *Aureobacterium* and *Cellulomonas*. These were also isolated from each biofilter run, but not from the enrichment culture or fresh peat. Isolates that were only found on the fresh peat were *Corynebacterium* sp., *Cytophaga* sp. and *Burkholderia* sp. Coryneform bacteria have been characterized from biofilters by Bendinger et al. (1992). While a number of different colonies from fresh peat were isolated, extracting fatty acids from these isolates and analysis by gas chromatography proved to be difficult. This is probably because the majority of the species isolated were fungi which are not suited for identification by the MIDI system. The only species isolated unique to the enrichment culture were *Xanthomonas maltophilia* and *Escherichia coli*. The only other species that was found in both the enrichment culture and the biofilters was *Oerskovia* sp., belonging to the nocardioform actinomyctes.

All of the pseudomonad isolates, as well as most of the *Arthrobacter*-like species, grew well in a basal salts medium with *n*-hexane (1% v/v) as sole carbon source (Table 2). All of the species isolated from the enrichment culture demonstrated excellent growth with *n*-hexane, whereas those from the fresh peat demonstrated poor growth (with one exception, an unknown isolate that grew well in the presence of *n*-hexane).

In conclusion, it was demonstrated that a wide diversity of bacterial species capable of growing in the presence of *n*-hexane could be isolated and identified from peat-based biofilters. Even though the enrichment culture was used to inoculate each biofilter run, the heterotrophic bacteria found in the culture were not those found to be dominant on the biofilter peat after a biofiltration run. As well, isolates found on fresh peat were not isolated after the peat had been used in a biofilter run. This suggests that a microbial community capable of degrading *n*-hexane can evolve spontaneously on a biofilter bed material (in this case peat).

Although it was possible to use the technique of fatty acid extraction and profiling to identify the heterotrophic bacteria, the method did not give a complete characterization of the microbial community within the biofilter. The method relies that firstly, the microorganisms can be cultured and secondly can be cultured on the medium required for the fatty acid extractions. Furthermore, some isolates could not be identified as no quantifiable fatty acid profile could be generated. To ensure the identification of as many types of bacteria as possible a multi-method approach should be taken (Ahrens et al. 1997). Other identification methods include biochemical/physiological tests and 16S rRNA sequencing and possibly direct gene probing of the peat samples to avoid having to use culturing techniques.

DMS Biofiltration

Peat-based biofilters

The first DMS biofiltration experiment used only peat as the filter bed medium. Two up-flow biofilters were operated in parallel; one was inoculated with a culture of *Thiobacillus thioparus* ATCC 8185, the second one was inoculated with a DMS enrichment culture from diesel oil-contaminated soil.

Figure 8 shows the biofilter performances over the operating period. Elimination capacities were the same in each biofilter, the maxima achieved ranged from 4.0 to 4.3 g DMS/m^3 bed material/hr. This is equivalent to what was achieved with a peat-based biofilter inoculated with a *T. thioparus* culture (Cho et al. 1991), but less than what has been achieved by other researchers looking at DMS biofiltration (Zhang et al. 1991; Pol et al. 1994; Smet et al. 1996a, b). Table 3 summarizes DMS removals reported in the literature and removals achieved in our lab.

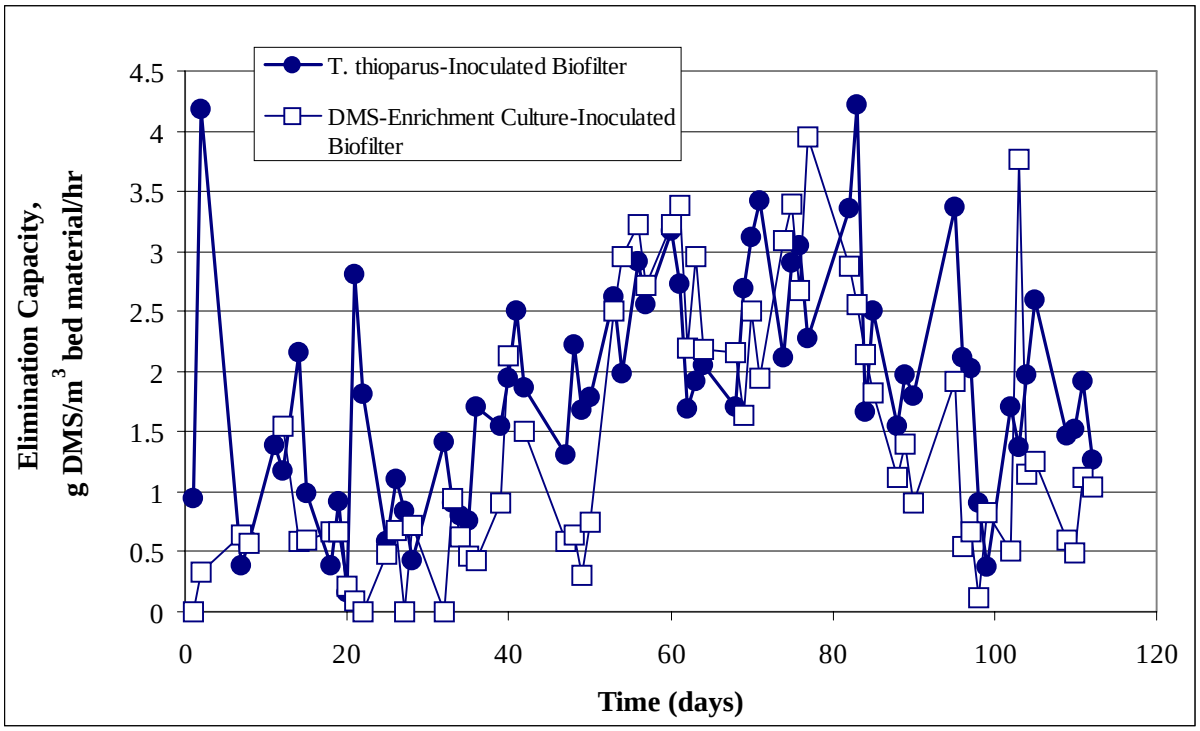

Figure 7. DMS removal performances of peat-based biofilters inoculated with two different types of bacterial culture.

Table 3. Maximum DMS elimination capacities reported in the literature as compared to values achieved in our laboratory.

Biofilter Bed Medium	Inoculum	Maximum Elimination Capacity, g DMS/m^3 bed material/hr	Reference
Peat	*Thiobacillus thioparus* DW44	4.2	Cho et al. 1991
Peat	*Hyphomicrobium* I55	4.6	Zhang et al. 1991
Polyurethane	*Hyphomicrobium* VS	13.75	Pol et al. 1994
Bark	*Hyphomicrobium* MS3	1.25	Smet et al. 1996a
Compost	*Hyphomicrobium* MS3	28.3	Smet et al. 1996a
Compost/Dolomite	*Hyphomicrobium* MS3	70	Smet and Van Langenhove 1998
Peat	*T. thioparus* ATCC 8185	4.3	This paper
Aspen Chips/Peat	*T. thioparus* ATCC 8185	4.1	This paper
Peat/Perlite	*T. thioparus* ATCC 8185	12.95	This paper
Peat/Perlite	Unknown culture	19.21	This paper

There could have been several factors that contributed to the poor performances of the peat-based biofilters. Firstly there were problems in controlling the pH of the peat. The pH started off at around 7.0 but decreased to below 5.0 within 30 days. Attempts at adjusting the pH with the additions of base only created temporary slight increases in pH levels (slight increases) and had no effect on the removals. Periodic trickling of a phosphate buffer onto the top of the filter bed produced no obvious effects on the removal rates either.

Secondly, a nutrient solution was trickled onto the top of the biofilter beds, at first continuous, but later semi-continuous, in order to ensure the microorganisms were not nutrient limited, and so increase DMS removal rates. But as this caused no apparent effects on removal and only lead to an increase in the peat moisture content, the nutrient solution addition was halted on the 30^{th} day and a slow-release fertilizer was mixed into the bed medium instead. However, this caused only a slight increase in the elimination capacities from below 1.0 to 2.0 g DMS/m^3 bed material/hr.

Despite these possible factors, the relatively poor removal was most likely a result of the high moisture content of the peat. A combination of using an up-flow configuration, semi-continuous addition of a phosphate buffer, humidification of the air stream, and peat's affinity to retain water led to moisture contents above 80%. As has been stated earlier, these high moisture contents may have lowered the surface area to volume ratio of the peat, and impeded DMS diffusion into the biofilm layer.

Wood chips/peat-based biofilters

Encouraged by the good moisture control of the wood chips/peat mixture used in the n-hexane biofilter experiments, we decided to use a similar filter bed composition to treat DMS. A mixture of aspen chips and peat in a ratio of 70:30% was, therefore, used.

In order to differentiate between biological removal of DMS and background adsorption onto the bed medium, a sterile control biofilter was run. In addition to this, two inoculated biofilters were operated and were inoculated with either a culture of *T. thioparus* ATCC 8185 or with a culture of *Hyphomicrobium* sp. The biofilters were operated in an up-flow manner. The pH of the bed medium was adjusted to above 11.0, however, the pH had dropped to around 7.0 within two weeks, and after the addition of hydrochloric acid, and stayed around this value throughout the duration of the experiment.

The moisture content of the bed medium was indeed lower than the peat from the previous biofilter experiment. The moisture content started off at approximately 72% and increased to 78% at the end of the experiment.

Despite the improved pH and moisture control, poor removal rates continued to occur (Figure 9). It is not known why such low removals were achieved. Microbial enumeration of the filter bed medium revealed colony counts in the range of 10^7 to 10^8 cfu/g for heterotrophic and thiobacilli species. This is an increase in bacterial numbers from 10^3 to 10^5 cfu/g at the start of the experiment. Biofilters were routinely inoculated as well. Even the sterile control biofilter had bacterial numbers of 10^7 cfu/g at the end of the experiment indicating that perhaps bacteria were introduced to the biofilter from the air stream or some bacteria had survived the sterilization procedure.

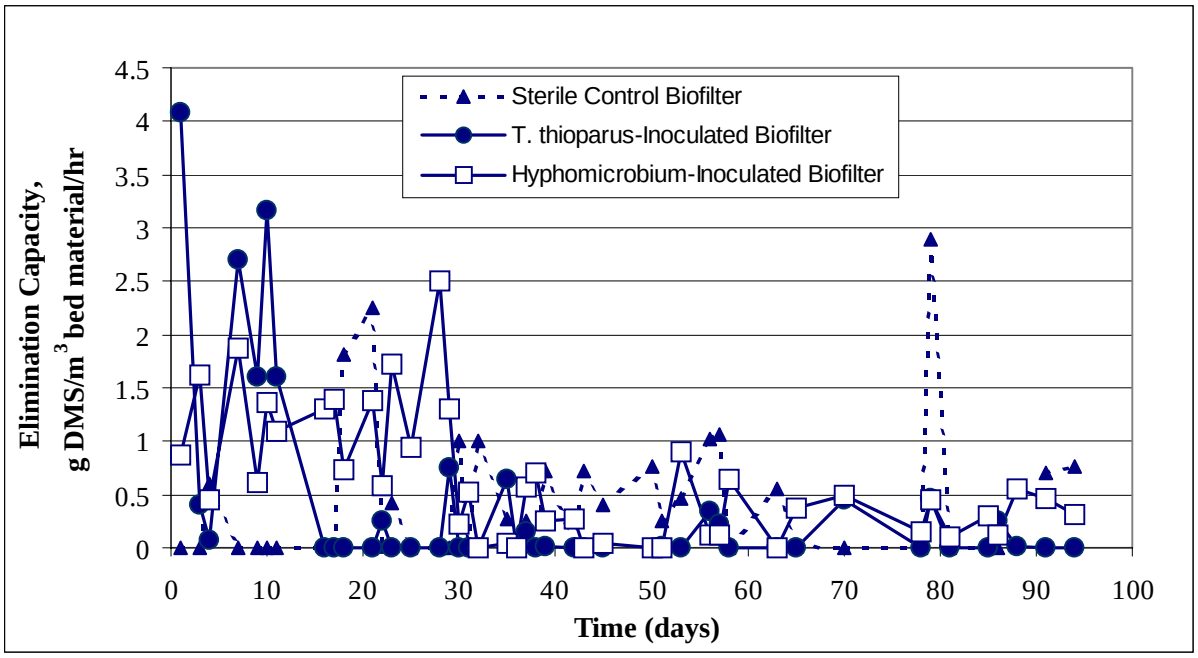

Figure 9. DMS removal performances of aspen chips/peat-based biofilters either sterilized or inoculated with two different types of bacterial culture.

Perhaps the wood/peat mixture did not have a high surface area to volume ratio, and poor adsorption contact of the DMS to the wood chips/biofilm occurred. Smet et al. (1996b) reported

similar low removals (1.25 g DMS/m^3 bed material/hr, see Table 3) when bark was used as a biofilter bed medium.

Peat/perlite-based biofilters

Perlite has been used in biofiltration systems as an amendment to the primary filter bed medium and provides loft, improved porosity, homogenizes gas flow, prevents cracking and reduces channeling and pressure drops (Swanson and Loehr 1997). We decided to mix perlite with peat to determine whether this would improve the porosity and moisture content of the filter bed medium. Perlite was mixed in with peat in a ratio of 1:4 and the pH adjusted to 7.0 with base and buffered with calcium hydroxide. One biofilter received sterilized filter bed material and acted as the control to measure background adsorption of DMS. The other biofilter was inoculated with a culture of *T. thioparus* ATCC 8185.

Enhanced elimination capacities over the previous DMS experiments were achieved as shown in Figure 10. There was a clear lag period of about 20 days before DMS removal increased above 2.0 g DMS/m^3 bed material/hr. Unlike the previous experiments, the elimination capacities remained above 2.0 and increased to around 4 g DMS/m^3 bed material/hr, however, this only represented a removal of 40%. Removals of close to 100% could be achieved when the bed filter medium was removed, the pH adjusted to 7.0 and repacked (see Figure 10, arrows indicate times when the bed medium was repacked, note that on day 99 no pH adjustment was done).

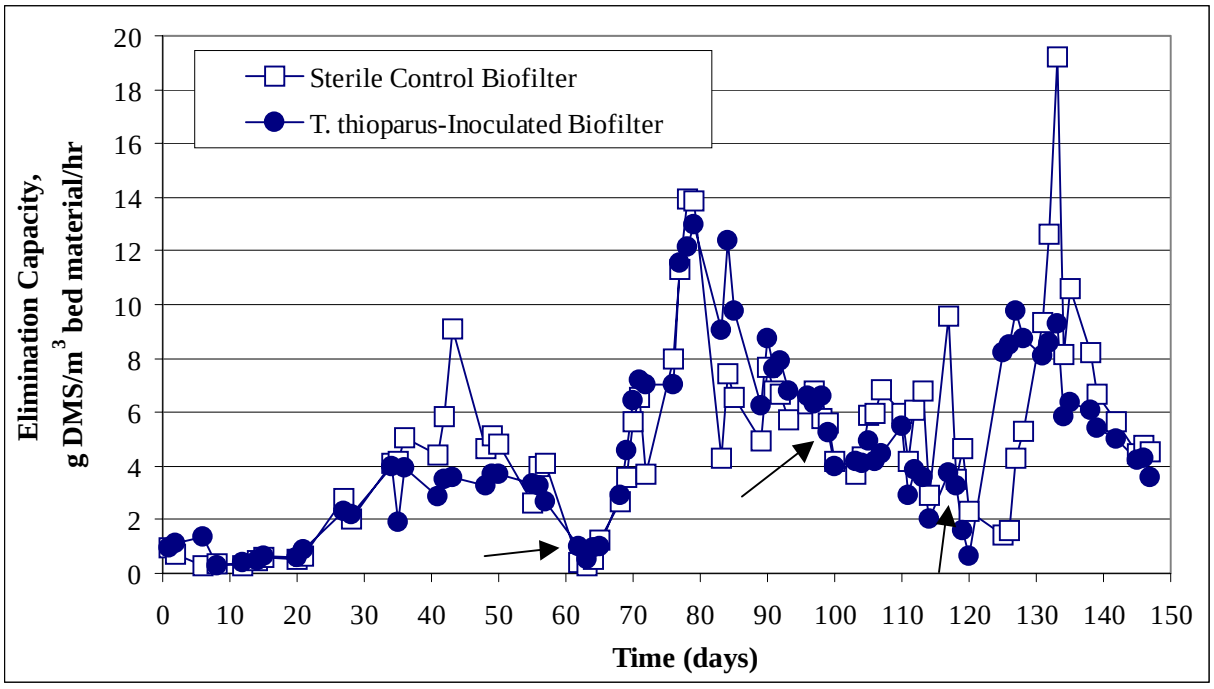

Figure 10. DMS removal performances of peat/perlite-based biofilters either sterilized or inoculated with *T. thioparus* ATCC 8185. Arrows indicate times when biofilter bed media were repacked (days 62, 99 and 118).

Table 4 and Figure 11 investigate the effect of pH on removal rates more closely. The different time periods in Table 4 represent the times between repacking of the biofilter medium and pH adjustment. The lag period is not shown. As can be seen from the table and graph, the pH of bed material positively affected the DMS removal rate. The optimum pH for *T. thioparus* growth is 6.5 (Staley et al. 1989). Due to peat's acidic nature and the production of acid during DMS metabolism, the pH of the bed material dropped down to 3.0-4.0. The first time the filter bed was repacked and base added, removals of up to 100% were achieved within 15 days. Removals decreased until the bed material was repacked and pH increased. Just repacking the peat with no pH adjustments (pH was approximately 5.0), had only a minor effect on increased DMS removal (see Figure 10, days 99-118). Smet *et al*. (1996b) reported that maintaining the proper pH of their filter bed medium by the additions of a phosphate buffer had marginal effects on DMS removal, whereas the addition of calcium carbonate provided good buffering capacity, and high DMS removal rates could be maintained over a long period of time.

Table 4. Maximum elimination capacities achieved after repacking biofilter bed medium.

	Elimination Capacity at Time of Bed Repacking (g DMS/m^3 bed material/hr)		**Maximum Elimination Capacity Achieved in Time period (g DMS/m^3 bed material/hr)**	
Time Period (days)	**Sterile Control Biofilter**	**T. thioparus-Inoculated Biofilter**	**Sterile Control Biofilter**	**T. thioparus-Inoculated Biofilter**
20-62	0.56 (day 20)	0.60 (day 20)	9.12	3.69
62-99	0.40	1.00	13.88	12.95
99[a] -118	5.60	5.26	9.58	3.84
118-147	3.49	3.30	19.21	9.74

[a]pH of bed medium was not adjusted.

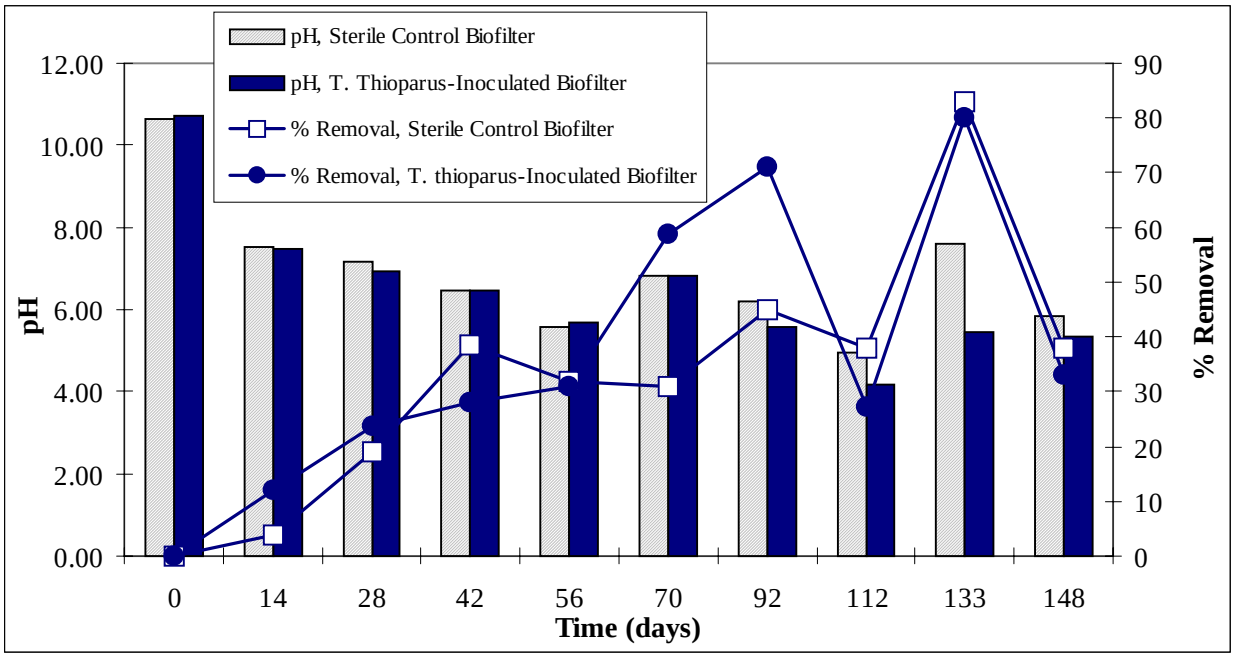

Figure 11. Average pH of biofilter bed medium over course of experiment and the corresponding DMS removal (expressed as a percentage). pH adjustments to the bed medium were done on days 62, 99, and 118.

As can be seen from the data, the sterile control biofilter did not remain sterile for very long, as DMS removals were much higher than expected if only background adsorption occurred. As well, this biofilter responded in a similar manner as the inoculated biofliter to the pH adjustments. Bacterial enumeration showed an increase from no counts at the start of the experiment to 10^7 cfu/g heterotrophic bacteria and 10^5 cfu/g thiobacilli sp. The sterile control could have become colonized by bacteria from the air stream or by bacteria that had perhaps survived the sterilization procedure. The fact that the same elimination capacities could be achieved with a biofilter not inoculated with a specific culture as to one that is, puts into question the effectiveness of direct inoculation. The data presented here would suggest that perhaps inoculation with *T. thioparus* is not needed.

Table 3 compares DMS elimination capacities we achieved to those reported in the literature. As can clearly be seen, the mixture of peat and perlite proved to be a good bed medium for DMS removal, and removal values compare to those achieved by others. Good moisture control could be achieved with this mixed filter bed medium. The increase in moisture content in the sterile control biofilter only increased by 6.5% and remained below 80%, whereas the moisture content in the inoculated biofilter increased by 2% and was around 80% at the end of the run.

CONCLUSIONS

The first half of this research project investigated the use of surfactants to enhance the biofiltration of hydrophobic, gaseous compounds with *n*-hexane serving as model hydrophobic compound. Although the use of detergents or surfactants has been successful in dispersing, emulsifying and enhancing the biodegradation of spilled crude oil in aqueous environments (Atlas and Bartha 1992), a previous study (Budwill and Coleman 1996) demonstrated that the use of a surfactant (Tween 80) in a biofilter appeared to have caused a reduction in *n*-hexane degradation. It appeared that Tween 80-degrading microorganisms were selected for, and the biomass increased to the point of plugging the biofilter column. Silicone oil was, therefore, decided to be used in this project because of its relative recalcitrance (Ascon-Cabrera and Lebault 1993).

We observed enhanced removal of *n*-hexane in silicone oil-treated peat-based biofilters to that of untreated biofilters. However, the differences in removal rates were not very significant. This and the cost of silicone oil would make its use in a full-scale biofilter prohibitory.

We speculate that one of factors caused by the use of silicone oil to enhance hydrophobic compound removal was the reduction in moisture content of the peat. A thinner water layer surrounding the peat would increase diffusion of the hydrophobic compound from the gas to the liquid phase and thus increase its chances of being degraded. Controlling the moisture content was difficult with peat due to its ability to absorb and retain water. Although the use of wood chips as biofilter bed medium lowered and maintained the moisture content to a desirable level, removal rates of *n*-hexane and DMS were much more reduced as compared to peat-based biofilters. The wood chips were contaminated by fungi, which were, most likely, using the wood as carbon sources. Thus, compounds and nutrients from the wood chips were being used preferentially over *n*-hexane and DMS. A mixture of peat and perlite provided good moisture control as perlite provided loft and increased porosity. This combination, and adjusting the pH of the bed medium to around neutrality, enhanced the removal of DMS. We observed the best DMS removal rates using peat and perlite and are investigating this combination as filter bed medium further.

MANAGEMENT IMPLICATIONS

This project has demonstrated that the reduction of odourous, gaseous emissions produced by forest products manufacturing by biofiltration technology is feasible. Although we were not able to test a biofilter on-site at a pulp mill (for example), we can make predictions and recommendations for a future on-site test run, based on literature reports (Devinney et al. 1999), on personal experience (Coleman and Dombroski 1995b), as well as on results reported in this paper.

Firstly, the design of the biofilter would have to be based on a site-to-site case, depending on the waste gas emission composition, volume, and moisture and pH content. A single biofilter may not be able to remove all components of a waste gas, especially if there are hydrophilic and hydrophobic contaminants present. In such a case we envision two biofilters operating in sequence. The first would treat readily degraded compounds, such as hydrogen sulphide at a low pH. The second biofilter would then treat the poorly degraded compounds, such as dimethyl sulphide. This biofilter would be designed to provide optimum conditions for removal. As this report indicated, these conditions should include pH buffering and moisture control.

Secondly, the composition of the bed medium plays an important role in the removal of hydrophobic compounds. Although waste wood chips are readily available at a wood-products manufacturing plant, and thus would be an inexpensive bed material for an on-site biofilter, its effectiveness in the removal of gaseous, hydrophobic compounds is questionable as this project demonstrated.

Finally, we would like to re-emphasize the importance of controlling the moisture and pH content of the biofilter bed. Most biofilters fail due to the 1.) bed drying out or 2.) bed compacting due to high moisture contents (Devinney et al. 1999). Moisture content is a critical factor in the biofiltration of hydrophobic compounds. Maintaining the pH at the biofilter microorganisms' optimum level would ensure microbial activity and viability. One of the advantages of biofiltration technology is its low operating costs. Proper maintenance of the moisture content of the biofilter would, however, increase the operating costs. But, in the long term, the biofilter failure rate would be reduced and so provide a cost savings.

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