THE BIOFILTRATION OF INDOOR AIR I: A NOVEL REACTOR FOR A NOVEL WASTE GAS STREAM

David Llewellyn[1], Alan Darlington, Michael Dixon and Jeff Mallany

ABSTRACT

Indoor air quality (IAQ) is becoming a major health concern as modern buildings are being increasingly sealed from the outdoors; allowing pollutants such as VOCs to accumulate indoors. Biofiltration has been proposed as an alternative to ventilation for maintaining IAQ. Indoor air is very different than waste gas streams treated in conventional biofilters. An indoor air biofilter must handle very large volumes of air containing a large consortium of VOCs present at trace concentrations. Ecologically complex, plant-based biofilters have been designed to treat VOC-contaminated indoor air. Prototypes have been shown to improve IAQ through the elimination of target VOCs.

INTRODUCTION

North Americans spend over 90% of their time indoors (1). Thus, the quality of the indoor environment can have tremendous health implications. Indoor air quality (IAQ) issues keep increasing as modern buildings are designed to reduce both passive leakage and active ventilation (2). The resulting decrease in the air exchange between indoors and outdoors reduces energy costs of conditioning the building's air. The savings can be substantial in extreme climates where the outside conditions may be drastically different from the desired indoor climate. However, sealing buildings can also lead to the accumulation of airborne pollutants in the which may adversely affect occupant health. In fact, the Environment Protection Agency (3) cites IAQ as one of the top 5 public health concerns.

The levels of indoor contaminants are the result of many factors such as building structure, geographic location and occupant activities (for a review see 4). The major contaminants are volatile organic compounds (VOCs), inorganic gases, bioaerosols and particulates. Our current research interest focuses on the VOCs (and addresses their susceptibility to biological degradation).

There are a tremendous number of VOC sources indoors. Contaminants may arise from the off-gassing of building materials and textiles, cleaning solvents, adhesives, paint, electronics, dry-cleaned clothing, smoking and even the occupants themselves (3, 4). In addition, these sources vary widely according to their emission characteristics (emission strength and duration). For example, some contaminants arise from one-time sources such a cleaning solvent spill, others come from intermittent activities such as photocopying and others may be emitted long-term such as from new carpeting (5). Thus, indoor air streams characteristically contain large consortia of VOCs, ranging widely in spatial and temporal concentrations (Table 1).

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[1]Division of Horticultural Science, Department of Plant Agriculture, University of Guelph, Guelph, Ontario, Canada, N1G 2W1, dllewell@uoguelph.ca

Many common indoor VOCs have been linked to acute and chronic health conditions. However, no single compound is typically present in concentrations high enough to influence occupant health. Rather, it is the combined concentration of the broad range of VOCs, each present at trace concentrations, that may affect occupant health. Short-term symptoms include dizziness, fatigue, mucous membrane irritation, shortness of breath, headaches and irritability. Long-term exposure has been linked to asthma, organ and tissue damage, birth defects and cancer (3).

Compound	mean concentration (F$g m^{-3}$)	Compound	mean concentration (F$g m^{-3}$)
1,1,1-Trichloroethane	1.55	n-Decane	3.45
Trichloroethylene	0.97	n-Undecane	2.22
Tetrachloroethane	0.46	n-Dodecane	1.45
Chlorobenzene	0.02	n-Tridecane	0.82
1,4-Dichlorobenzene	0.65	n-Tetradecane	1.83
2,4-Dichlorobenzene	0.03	n-Pentadecabe	1.73
1,2,4-Trichlorobenzene	0.21	n-Hexadecane	1.08
Benzene	4.9	Methylcyclohexane	1.17
Toluene	21.27	n-Propylcyclohexane	0.67
Ethylbenzene	3.2	Alpha-pinene	9.32
1,4-Xylene	7.42	Delta-3-carene	2.76
1,2-Xylene	2.37	Limonene	14.2
Styrene	0.75	Camphor	0.3
Propylbenzene	0.84	Hexanal	6.6
1,3,5-Trimethylbenzene	0.86	Octanal	4.63
1,3,5-Triethylbenzene	0.02	Nonal	3.57
Napthalene	0.44	2-Furancarboxaldehyde	1.56
1-Methylnapthalene	0.08	Benzylaldehyde	2.09
Biphenyl	0.16	1-Pentanol	2.56
n-Heptane	1.67	Phenol	0.88
n-Octane	1.35	Acetic acid	2.56
n-Nonane	3.01	TVOC	123.22

Table 1 An example of typical indoor VOC consortia (taken from 6)

INDOOR AIR BIOFILTRATION

Biofiltration of indoor air, as an alternative to ventilation, is a truly novel application of conventional biofiltration. However, there are a number of significant technical challenges to overcome to make indoor air biofiltration viable.

Conventional biofilters take an ‘end of the pipe’ approach to contaminant treatment, in that effluent streams are vented into the external environment after treatment. The main concern is to reduce effluent concentrations to acceptable levels. In contrast, an indoor air biofilter must treat a recirculating air stream. Removal efficiency loses importance to the biofilter’s overall impact on the indoor air stream (ie. elimination capacity). Furthermore, effluent quality is governed by additional parameters such as

temperature, humidity and bioaerosols. These parameters must also be within acceptable levels to maintain occupant comfort.

In conventional biofilters, the waste gas streams are generally well defined in terms of contaminant composition and concentrations. These provide design parameters for optimum biofilter configuration. In contrast, the indoor air stream comprises a complex mixture of VOCs at variable concentrations. Thus, an indoor biofilter must be capable of degrading a broad range of VOCs and adapting to a dynamic air stream. Microbial species diversity is likely a key parameter. To maximize diversity, an indoor biofilter must provide many different microbial ecological niches.

Conventional biofilters generally treat contaminant concentrations in the order of 10^{-3} to 10 g m^{-3}. This range enables adequate biofilm concentrations for efficient degradation. Concentrations below this range may be too dilute to effect an adequate biodegradation response (7). However, an indoor air biofilter must be able to treat trace levels of VOCs. In fact, single component concentrations are typically 10^{-7} to 10^{-4} g m^{-3} while total VOCs (tVOC) range from 10^{-5} to 10^{-3} g m^{-3} (Table 1). With the low solubility of many of the common indoor VOCs, biofilm concentrations may be below threshold levels for microbial degradation.

The extremely low concentrations may be somewhat offset by the very large volumes of air to be treated. Considering that standard ventilation rates range from 2 to 15 air changes per hour (8), an indoor air biofilter will have to handle large air volumes. The practical solution, without impacting on floorspace constraints, is to run air through the biofilter at a rapid rate. The advantage is that loading rates may be comparable to conventional biofilters.

PROTOTYPES

Prototype biofilters were developed to test their impact on indoor air with the above considerations in mind (see figure 1 for a schematic). Dubbed the Canada Life Environmental Room (CLER), the first reactor is incorporated into the air handling system in a 160 m^2 conference room in the Canada Life Assurance Building (Toronto, Ontario, Canada). The room is sealed from the rest of the building and has a dedicated air handling system. The reactor is divided into 3 sections: an aquarium, a terrestrial hydroponic system and a bioscrubber. The aquarium (3.5 m^3) and maintains a diverse population of aquatic plants and fish. The terrestrial section is comprised of 20 m^2 of domesticated plants. The bioscrubber is a 10 m^2 section of wall comprised of porous lava rock colonized by 2 native mosses (*Plagiomnium cuspidatum* and *Taxiphyllum deplanatum*). The air stream is actively drawn through the bioscrubber and returned to the room. The moss acts as a biofilter packing medium, allowing the formation of a biofilm community. The bioscrubber is constantly wetted by a recirculating gravity trickling system that sources water from the terrestrial and aquatic zones (closed loop with little liquid loss). As contaminants pass through the moss, they transfer into the liquid phase where they may be degraded within the bioscrubber or circulated and degraded in the terrestrial and aquatic zones.

A smaller scale, modular prototype has been developed at the Northern Centre for Advanced Technology (Sudbury, Ontario, Canada) (NORCAT). It maintains the same operating principles as CLER except that it can be retrofitted into an existing building space. Another key difference is that the modular biofilter is populated entirely with boreal plants (from northern Ontario). With careful plant selection, this prototype showed that local, native plants could be used to populate an indoor biofilter; proving its usefulness in far north applications.

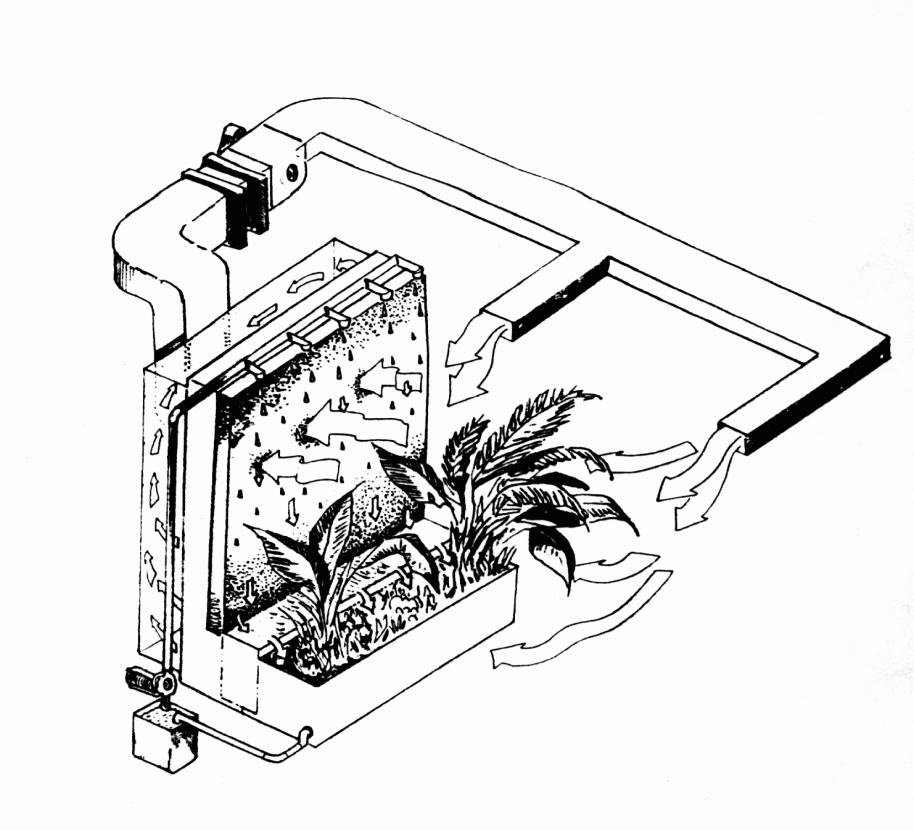

Figure 1 Schematic of an indoor air biofilter (courtesy of Canada Life Assurance Company, Toronto)

GREEN PLANTS IN A BIOFILTER?

The prototypes were designed as complex ecosystems which infers operational stability and, contrary to conventional biofiltration, ecosystem diversity which may promote the degradation of a broader range of contaminants. Not only were green plants the basis of the terrestrial system, they also acted as the packing medium on the bioscrubber. Living mosses are an ideal media for an indoor biofilter:

1. Moss colony architecture and high surface area to volume ratios provide excellent bed characteristics. The high porosity allows for even air flow while high surface area provides for good biofilm contact even with very shallow bed depths (ie < 0.05m).

2. Many conventional, organically-based packings have a limited life span. While supporting contaminant degradation, they are being degraded themselves. Living moss is a bioregenerative packing medium, replacing decayed material. In addition, decaying biomass and plant exudates provide alternative carbon sources to maintain biofilm activity.

3. Mosses can alter the composition of its associated microbial population. Careful selection of moss species may promote desirable VOC-degraders. However, many mosses also produce antibiotic compounds and may actually inhibit biofilm growth (9).

4. Mosses evolve oxygen in the presence of light through photosynthesis. Under oxygen-limiting conditions the mosses may promote aerobic microbial metabolism by charging the biofilm with oxygen from the inside

5. Mosses form in dense, porous mats and are well adapted to growing on vertical surfaces under indoor conditions.

6. Mosses have been associated with organic compound accumulation in native habitats. In fact, mosses are commonly used for pollution monitoring. In addition, mosses have been linked to VOC degradation in contaminated ecosystems. For example: the aquatic moss, *Eurychinum riparoides* has been shown to degrade phenols in industrial wastewater (10).

The inclusion of green plants in the terrestrial system also incorporates the advantages of phytoremediation into a biofilter:

1. The rhizosphere contains higher microbial populations than bare soil. Hence, plants may be able to enhance degrader populations. Plant transpiration also draws air onto the rootzone (to displace water uptake), thus directly exposing rhizosphere microbes to contaminants.

2. Plants may be able to break down VOCs. Plants grown in cell culture could metabolize formaldehyde into cellular components(11). However, houseplants have limited impact on indoor VOCs due to boundary layer resistance. The incorporation of a biofilter into the air handling system will greatly reduce this resistance.

3. Plants may also accumulate airborne contaminants (12). Organics can either adsorb to plant cuticle (13) or be accumulated internally (14, 15). Hence, plants may act as a contaminant sink or they may impart some buffering capacity to the biofilter for fluctuating pollutant concentrations.

4. Green plants are a sink for CO_2 which is considered an indoor pollutant (5). Through photosynthesis, they combine carbon dioxide and water into biomass and evolve oxygen.

5. Green plants have been included for aesthetic purposes. Maintaining an indoor ‘green’ area may increase employee productivity and lower absenteeism

RESEARCH

Considerable research energy has gone into these pilot and additional lab-scale prototypes. A custom gas chromatography system has allowed for real-time analysis of contaminant removal parameters over replicate biofilters simultaneously. In addition, a peripheral feedback control system allowed for the artificial ‘challenging’ of the biofilters with target contaminants.

Initial studies examined the impact of incorporating large amounts of biomass indoors while

operating the biofilters in a pristine state (ie. unchallenged). Of interest were airborne spore loads and tVOC levels (when compared to other reference sites). The biofilters did not lower air quality through spore production (16, 17). They were then challenged with VOCs including: toluene, ethylbenzene, xylenes, formaldehyde, trichloroethylene, tetrachloroethylene, dichloromethane, acetone and methylethylketone (MEK). Typical single-component concentrations ranged from 20 to 200 ppbv. The effects of various environmental parameters such as flow rate, temperature, moisture content and lighting were examined in detail.

Figure 2 is an example of the data collected during lab-scale biofiltration experiments. The biofilter was exposed to a diurnally fluctuating MEK load (concentrations ranging from 10 to 80 ppbv, flow rates of 0.05 m s^{-1}). The biofilter began acclimating to MEK after the first day, reaching a maximum of about 50% removal after 5 days. This illustrates the biofilter's ability to consume trace levels of target contaminants and these results are typical of most VOCs used to challenge the biofilters.

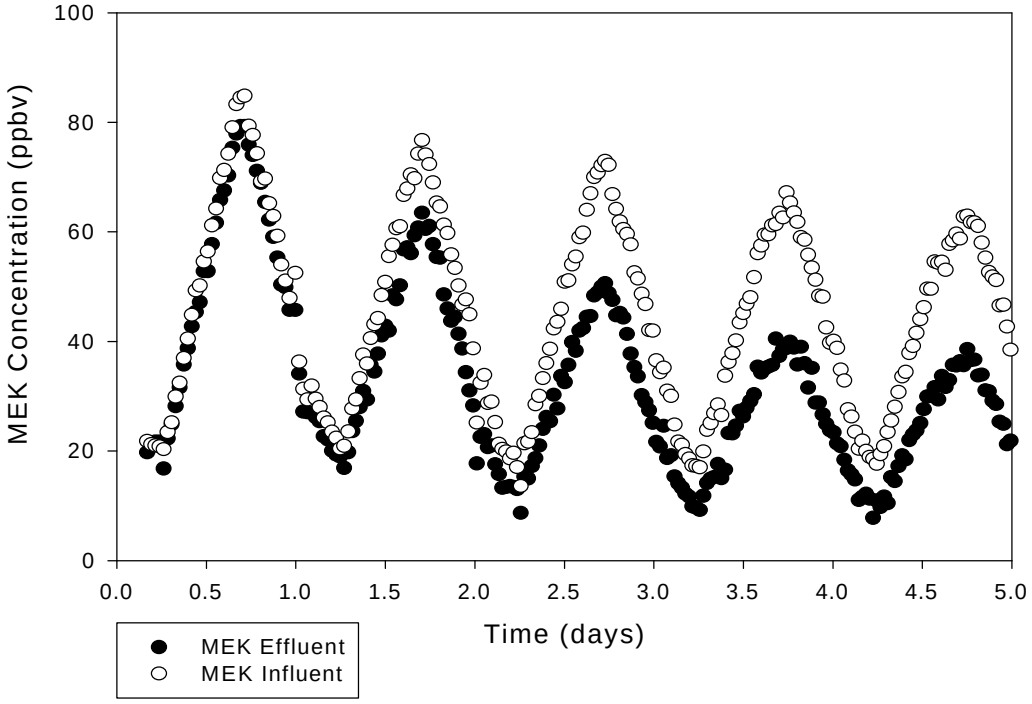

Figure 2 Acclimation of an indoor biofilter to diurnally fluctuating methylethylketone concentrations. Acclimation began shortly after start-up (ie. <1 day) and reached near steady-state removal efficiency of about 50% in 5 days.

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