Acetone Removal Kinetics by an Indoor Biofilter

Alan B. Darlington and Michael A. Dixon
University of Guelph

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ABSTRACT
A biofiltration system was tested to remove low levels of acetone from an indoor space. The biofilters were subjected to a range of air fluxes and concentrations of acetone between 100 and 500 ppbv. Passing low levels of acetone through a canopy of green plants did not improve the quality of the air. However, acetone removal by the biofilters with living moss as a principle substrate, reached a maximum of between 1 and 1.6 µmol s⁻¹ m⁻² with a loading rate of approximately 2 µmol s⁻¹ m⁻². Generally the removal efficiency decreased with increased loading rates over a range of air fluxes (0.05 to 0.2 m s⁻¹) but appear to increase with loading within the slower fluxes. Neither ZERO nor FIRST order kinetics could adequately describe removal. Instead an empirical model that described the natural logarithm of the unloading rate as a function of the natural logarithm of the loading rate and the natural logarithm of the inverse of the air flux fit the data well. The moss coverage appeared to improve acetone removal beyond what would be expected due to an increase biofilter thickness.

INTRODUCTION
North Americans spend in excess of 85% of their time indoors [1]. This high exposure makes the quality of the indoor environment an important public health issue. With more energy efficient buildings, there is a tendency to construct structures as ‘air-tight’ as possible. The sealing of the indoor space not only reduces infiltration of the hotter or cooler outside air but also enables the accumulation of volatile organic compounds (VOCs) which arise from gassing of construction materials and furnishings and activities in the space. Traditionally, indoor air quality is maintained through ventilation which displaces the contaminants with outdoor air. But conditioning this additional air flow in terms of its temperature can greatly increase the energy consumption of the building and hence the building’s operation cost. An alternative approach may be biofiltration of the air recirculating within the space. Biofiltration uses microbial systems to breakdown captured contaminants into their benign constituents (principally biomass, CO₂ and water) and is increasingly used to treat large volumes of industrial air or water contaminated with low concentrations of VOCs.

In these industrial systems, the principal organic source which supports the microbial population is the introduced contaminant. The result of this is a highly specialized microbial population arising either through selection pressures or through inoculation of selected microbe populations into sterilized systems [2].

A VOC biofilter for indoor air would have to differ from these industrial systems largely because the VOC loads associated with the indoor space tend to be at very low levels (i.e. typically less than 200 µg m⁻³) of a broad range of VOCs [3, 4] which given the works of others would make it extremely difficult to develop and maintain highly specialized microbial populations [5]. It may be more appropriate to utilize phyto remediation approaches developed for recovery of contaminated soils [6]. Botanical constituents integrated into these systems, enhance the removal of low level VOCs [7] [8]. More specific for the indoor environment, green plants are included in the system to take advantage of their capacity to sequester the major indoor contaminant CO₂ from the indoor environment [9].

Biofilters which include plants can remove significant amounts of VOCs from an indoor space [10], but before this technology can gain wide acceptance, descriptions of the performance of the system are required. The initial steps are to describe how the air flow rates (filter retention time) and the influent concentration of VOCs influence the VOC removal by the filter. This information will enable the ‘sizing’ of the system for particular applications. Acetone was chosen for these initial studies because its widespread use make it a common indoor VOC contaminate.

METHOD
THE BUILDING – The test biofiltration system was located in the ground floor of Canada Life Assurance headquarters building (Toronto, Ontario). Completed in 1994, the 12 storey office building is composed of approximately 2,000 m² of space above grade and three levels of truck dock, parking and storage below grade. The ‘environmental room’ (the room housing the biofilter) was a 160 m² (640 m³) L-shaped conference space in the southeast corner of the ground floor. The air handling system of the room was not connected to the rest of
building and was essentially standalone. The room averaged 0.2 ± 0.1 air changes per hour under normal functioning conditions.

The room was maintained at 22° during the day and 18° C at night with humidity ranging between 40 and 75% RH. Lighting was natural (c.a. 30% of the southern external walls were glazed), supplemented by high pressure sodium and metal halide lamps located 2.3m above the aquarium. The environmental control system was provided by L. W. Anderson Software Consultant (Leamington, Ont.).

THE BIOFILTRATION SYSTEM – There were three major functional components of the system: a bioscrubber through which room air was drawn, a region of hydroponically grown higher plants and an aquarium. The bioscrubber was composed of five parallel fibreglass air plenums (1.2 x 2 x 0.2 m) faced with porous, constantly wetted lava rock (designed by Genetron Systems Inc., Downsview, Ont. Canada). Approximately 70 to 80% of the external rock vertical face of three modules was covered with mosses (Plagiomnium cuspidatum and Taxiphyllum deplanatum) and constantly wetted. One module was wetted but devoid of moss. The external faces of the wet bioscrubbers were covered with geotextile cloth which was used to support the moss (when present). The fifth panel was dry (not wetted) and devoid of both moss and the geotextile cloth. The system was not inoculated with specific microbes.

For the biofiltration of certain VOCs such as halogenated material, the ‘bioscrubber’ captured the VOC out of the air and into the water column. Once in the water, VOC can be degraded in either the hydroponic or aquatic components which function as ‘bioreactors’. However, for readily degraded VOCs such as formaldehyde and toluene [10] and acetone, the degradation occurs in the scrubbing unit and does not accumulate in the water column (results for acetone not presented). Thus it was reasonable to consider each separate ‘bioscrubber’ as independent ‘biofilters’.

Air from the room was drawn through a 0.27 m² subsection of each biofilter by a variable speed centrifugal fan then mixed with the return air from the room, conditioned in terms of its humidity and temperature and supplied back to the room. The air fluxes through each biofilter were controlled with valves located between the biofilters and HVAC. The rates of air flow through the biofilter were monitored by ‘hot-wire’ type anemometers located in the air ducts.

Prior to entering the modules, air first passed through a 1 m wide region of hydroponically grown plants in front of the bioscrubbers. The principal plant species in this region were Dracaena godseffiana, Adiantum radidianum, Hedera helix, Spaphiphyllym maunahoa, Rhododendron obtusum, Marraya sp., Vriesea splendidens and Dieffenbachia picta. At the base of the entire plant community, was a 3,500 litre aquarium containing a variety of aquatic (such as Elodea sp., Cabomba sp. and Vallisneria sp.) and semi-aquatic plants (such as Cyperus spp., Myriophyllum prosperinacoides and Lysimachia sp.). Aquarium water was circulated through the hydroponics and flowed down the surface of the bioscrubbers. Condensate from the HVAC was returned to the aquatic system. There was little or no loss of liquid water from the system over the duration of the experiment although c.a. 20 liters of water was required per day to compensate for the loss of water vapor.

The aquatic system was maintained at 25° C with a pH of 6.7 ± 0.1 and salinity did not exceed 0.1 mS. The entire system was maintained in a low nutrient state with little nutrient addition after the initial startup (24 months earlier). Despite the concentrations of macro-nutrients in the water column being low (µM levels), the analysis of the plant community indicated no mineral deficiencies in the system. A nutritional budget suggested a very rapid turnover of nutrients within the system was more responsible for the low aquatic concentrations than any real deficiency (C. Wong, unpublished).

ANALYTICAL METHODS – An SRI 310 gas chromatograph equipped with a 30 m RESTEK MXT-volatiles column with 0.53 mm ID and a photo ionization detector (PID) was used to detect the amount of acetone in the air stream. Operating conditions were oven, 40° C; detector, 200° C; carrier gas (He) flow rate of 50 ml min⁻¹. The detector was operated in HIGH GAIN mode. Under these conditions the retention time for acetone was 2.0 minutes. GC data logging and control was on a peripheral computer using PEAKSIMPLE FOR WINDOWS (32 bit) version 1.69. Calibration of the GC was performed at the start and completion of the experiment. Briefly a volume of liquid acetone was added to a 1 liter ‘stock’ bottle of clean air (filtered through a particle filter and activated charcoal) to give 1000 ppbv. Volumes of this stock were added to 1 liter of clean air to give 7 concentrations between 0 and 1000 ppbv (parts per billion volume/volume) Samples were injected into the GC using the same Valco valve used for routine sampling (described below). At least 100 ml of sample was rinsed through the valve prior to injection.

During the experiments, the acetone levels of seven different locations were constantly monitored. These sites were the air exiting each of the 5 biofilters (the effluents); the air entering the biofilters (the influent) and a reference space elsewhere in the building. Air samples were moved via tubing to a central sampling site relay system and then through a 10 port VICI E36 injection valve with a 1 ml injection loop (Valco Instrument Co. Inc.) of the GC by a MagneTek vacuum pump at a rate of ca 300 ml min⁻¹. All tubing was either degreased flexible copper or Teflon tubing (1/8” ID) using gas-tight Swaglock fittings. A Peter Paul Electronic three-way 24VDC solenoid was installed between the Valco injection valve and the vacuum pump. This valve drew air through the tubing (and injector) to the pump for 2.75 minutes (flushing volume c.a. 800 ml) and 45 seconds prior to sample injection, the valve was switched to stop the flow through the injection system.
This enabled line pressure to reach near atmospheric levels prior to injection into the GC (there was a slight 1 kPa pressure drop across the biofilter due to HVAC activity). Site selection relay system was composed of customized 3 to 8 signal multiplexer and 7 Ascot 24VAC solenoid valves. On-board GC relay system (controlled by EVENTS subroutine of PEAKSIMPLE) controlled three-way valve activity and selection of sampling site. The sampling protocol was assembled under the AUTOSAMPLE routine of PEAKSIMPLE and structured in a manner that all effluent readings were never more than one sampling cycle (3.5 minutes) from an influent measurement.

CONTROL OF INFLUENT ACETONE LEVELS – To estimate the relationship between loading rates and removal efficiency of the biofilter, the system was exposed to a range of acetone concentrations on a diurnal basis. This had the added benefit of enabling the experimentation to occur concurrently with the use of the room as a meeting space by the building occupants, avoiding any human exposure to the VOC tested. To control influent, the gas chromatography was interfaced with a peripheral VOC release system composed of customized software operating on a PC; a LPT power switching system and up to four VOC releasers. Each releaser was composed of a low pressure air pump, an air flow regulator and an impinger filled with the selected VOC connected to the supply air duct of the room's HVAC system (see Figure 1). Briefly, when the influent (room air) was sampled by the GC, its governing computer 'printed' the results to the peripheral computer (via a RS232 connection). The peripheral compared actual VOC levels with a desired level based upon a user defined diurnal profile (starting at 0 ppbv at 18:00 rising to c.a. 500 ppbv at mid-night and back to 0 by 06:00). If the actual level was below the desired amounts, the peripheral activated the appropriate air pump and a specific amount of air was bubbled through the solvent in the impinger. The resulting air saturated with the desired VOC was released into the supply air of the room's HVAC system which dispersed the VOC throughout the room. VOC levels of the site could not be actively lowered, but occurred as a result of biofiltration or leakage. Although up to four different VOCs could be concurrently and independently controlled using this system, for this experiment only acetone was used. Several safety features were built into the system, both in terms of hardware and software. Hardware was configured in a manner to ensure fail safe operation (power failure left everything in an OFF position). Software would close everything if control was not adequate (unable to reach desired levels) or if influent or levels in a neighboring room exceeded some predetermined safety level. Typically, between 2 and 4 ml of the solvent per day, were required.

During the experiment, the flow rates (or filter residence times) of the air stream through each of the separate biofilters were varied daily. Four different air fluxes of 0.05, 0.1, 0.15 and 0.2 m s$^{-1}$ were tested (roughly equivalent to 9 to 35 ft$^3$ of air per ft$^2$ of biofilter per minute). Several of the biofilters could not obtain the fastest flux. Each speed was run for two separate 24 hour periods through each panel. The amount of moss present on each biofilter (thickness of the moss and support media) was estimated, based on 20 subsamples per panel. For the dry biofilter devoid of moss, retention time was based on the 1m section of hydroponic foliage plants in front of the biofilter.
DATA ANALYSIS – To normalize the data for the different air fluxes, the influent and effluent VOC levels were expressed as loading rates (the amount of material entering into biofilter per unit surface area of biofilter per unit time, \(\mu\text{mol VOC m}^{-2}\text{biofilter s}^{-1}\)). This was accomplished by merging the data collected from the air flux sensors with the GC data.

Because of the sampling lag (3.5 minutes were required to run a sample) instantaneous comparisons of actual influent and effluent levels were not possible. Prior to the experiment, two methods of compensating for this were tested using three other VOCs (toluene, ethyl-benzene and o-xylene). First, instantaneous effluent was compared to the single most current influent reading (either 3.5 minutes immediately before or after sampling effluent) or compared to a calculated instantaneous influent based on a weighted average of the two influent readings closest to the effluent reading. A brief experiment was conducted based on the following repeated 3 step AUTOSAMPLE routine INFLUENT; infl.(a); infl.(b). Here infl.(a) and (b) are influent samples which are not used for control. The influent concentration started at below detection and was increased to 60 ppbv and then allowed to drop back down to background levels. The actual infl.(a) and (b) concentrations were compared to a weighted average INFLUENT and to the most recent INFLUENT. From this experiment, the weighted influent more reliably predicted the actual levels than using the most recent approach (actual - predicted = 0.12±0.83 and 0.20 ±1.15 ppbv respectively, \(n = 73\)). The weighted average influent was used in all subsequent analyses.

Data analyses were conducted using SAS 6.12 (SAS Institute Inc. Cary, NC). Analytical procedures relied on the following procedures GLM, REG and RSREG.

RESULTS

BIOFILTER START-UP – Acclimation was carried out for a 1 week period by subjecting all biofilters to the diurnal exposure under uniform flux rates (0.15 m s\(^{-1}\)). After the initial diurnal cycle, removal efficiencies did not vary for the remainder of the acclimation period (results not presented). This time period is comparable to the acclimation to acetone seen in other systems [11]. To test if an additional acclimation period was required when the fluxes were changed, the biofilters were subjected to three diurnal cyclings under fluxes of 0.05 or 0.15 m s\(^{-1}\). Fluxes were then changed to 0.15 and 0.05 m s\(^{-1}\) respectively, for an additional three days and removal monitored. These results (not presented) indicated that as for other systems [12], once the system had been acclimated to the VOC, there was no apparent additional acclimation period required when the flux was altered.

The role of sorption of acetone was examined through the comparison of the removal efficiencies under either increasing and decreasing influent concentrations. If sorption plays a substantial role in the removal of the VOC then the system will remove less of the material with prolonged exposure (as the sorbent becomes saturated). During the phase of increasing influent levels, the system would ‘appear’ to be more effective than during the return to background levels. This not was the case during this experiment (results not presented). As noted by others [11], acetone appeared to have a low affinity for organic and inorganic materials.

ACETONE AND THE PLANT CANOPY – Our earlier work using a ‘grab-sample method’ suggested the plant canopy can remove significant amounts of the VOCs formaldehyde and toluene, while having limited ability to remove TCE [10]. Such removal may be through metabolism [13] or through sorption [14]. In the current study, the acetone removal by the plant canopy was examined through the correlation of the loading and unloading rates for all biofiltration units. Loading rates were used instead of actual concentrations since loading rates normalized the data for the different air fluxes and gave a higher degree of correlation across the range of fluxes (results not presented). The results of biofilter composed only of the plant canopy and a typical ‘complete’ biofilter (including both the canopy and the wet moss layer) are presented in Figure 2. Although, the relationship was the strongest for the canopy alone \((r^2 =0.93)\), the intercept and the slope of the correlation for this unit were not significantly different from ZERO and ONE respectively. For
the wet biofilters, both the slope and the intercept were significantly different from ONE or ZERO indicating removal. Considering when the canopy was subjected to only the slowest flux (0.05 m s\(^{-1}\)) (and therefore should show the highest degree of removal), the average removal efficiency was 0.4 ± 18.3% while the other units at that same flux had removal efficiencies between 45 and 80% with similar error terms. It was therefore concluded that passing an air stream through the plant canopy did not remove acetone from the air stream. This biofilter was excluded from subsequent analyses.

**ACETONE AND WET BIOFILTERS** – The relationship between loading rates and removal rates and removal efficiency for the wet biofilter without a moss layer and one of three wet moss covered biofilters are presented in Figures 3 and 4. For both ‘types’ of biofilter, over the range of fluxes, there was a decrease in removal efficiency with increased loading rates. However, at the slower and moderate fluxes, there was increased efficiency with increased load rates. This was more pronounced in the moss covered biofilters. Typically, efficiency decreases with increasing influent concentration [15]. Sorial and coworkers [12] subjected a biofilter to a range of concentrations (between 50 and 175 ppmv toluene) under one flux and found decreasing removal rates with increasing contaminant levels (the nature of the relationship was not determined). The results of this study may reflect a threshold for acetone metabolism as described by Alexander [5]. However, given the nature of the degrading environment, it is likely that the microbial population contained one or more oligotrophs and therefore thresholds would not be likely[5].

For all units, total removal increased with loading rate up to c.a. 1.5 \(\mu\)mol m\(^{-2}\) s\(^{-1}\) (Figure 4). The maximal removal rates for the moss covered biofilter ranged between 1 and 1.6 \(\mu\)mol m\(^{-2}\) s\(^{-1}\). Given the thickness of the biofilters, these removal rates are equivalent to between 9 and 14 g h\(^{-1}\) m\(^{-3}\). The biofilter devoid of moss had a maximal removal rate of 0.75 \(\mu\)mol m\(^{-2}\) s\(^{-1}\) (6 g h\(^{-1}\) m\(^{-3}\)). These estimates are considerably below those reported for ‘industrial’ biofilters of approximately 80 g h\(^{-1}\) m\(^{-3}\) which were inoculated with specific acetone degrading microbes and loaded with the VOC at rates up to 150 g h\(^{-1}\) m\(^{-3}\) [16]. In the presented study, the variation in both removal efficiency and amount removed increased with increased flux which may have been due to reduced contact of the contaminant to the microbial populations or may have been due to channeling of the influent air stream through the biofilter ‘short circuiting’ its effectiveness. This channeling has been commented on by other researchers [12].

![Figure 4](image-url)

**Figure 4.** The removal efficiency of wet bioscrubbers over a range of air fluxes (a) with or (b) without a living moss layer covering the surface. Removal efficiencies were determined as the ratio of the amount of acetone removed to the amount entering the bioscrubber. Concentrations below 100 ppbv were considered ‘below the detection limit’ and not included.

The role of moss in the system is not clear. Generally there was more variation in the biofilter devoid of moss, suggesting that the moss covered system may have had improved contact. However, the ability to actively break down other organic pollutants such as phenols by mosses [17]) and other VOCs by green plants [13] has been reported. While acetone is generated by plants [18], there are no indications that they can metabolism the VOC as seen in the lack of removal when passed through the plant canopy. It is possible, but not likely, that the moss specifically may be actively degrading the acetone. A more likely alternative was that the moss was enhancing the metabolism of the acetone by creating a micro-
environment which was superior in terms of microbial growth and activity as has been recorded surrounding the roots of higher plants [7]. In this case, the moss was facilitating the breakdown. Efforts are currently underway to distinguish the relative roles of the moss and the bacteria.

MACROKINETICS OF ACETONE REMOVAL – Removal kinetics by a biofilter have been described, [5,19]. The determination of whether a particular system is First order, Zero order (reaction limited) or Zero order (diffusion limited) can offer insights into the performance of the system. Considering the moss covered biofilters, there was a good correlation between the average removal efficiency of each flux and the natural logarithm of the inverse of flux (r² = 0.53) (Figure 5). Since retention time is the product of the inverse of flux and the thickness of the biofilter (a constant for each unit), this correlation indicated first order kinetics [5]. These are similar to the results of Sorial and coworkers [12] where reducing retention time in a 1.2 x 0.146 m biofilter from 12 to 2 minutes reduced toluene removal efficiency from c.a. 100% to 75% under identical loading rates. The relationship was not quantified but the removal efficiency appeared to be related to the inverse of the retention time which may suggest FIRST order kinetics. However when the entire data set (for the moss covered biofilters) was considered, the correlation fell to less than 0.1, raising doubts about the appropriateness of this model. When Zero order kinetics were assumed, the data exhibited some correlation with its predictions of a diffusion limited model (r² = 0.24) and an apparent K value of 0.272 ± 0.041. For other VOCs such as toluene, at low concentrations, the resistance of contaminant movement out of the air stream and into the biofilm limits biofilter effectiveness while at higher levels the removal is more limited by biological degradation [20]. However, acetone is far more soluble in water than toluene and therefore diffusion would not be as likely to be limiting. In other studies, under much higher influent concentrations of acetone, the reaction was not limited by acetone diffusion but rather limited by oxygen availability within the biofilm [16]. The role of diffusion in the current system is difficult to infer. The surface was under constant flow of water and the very thick water layer could offer considerable resistance to oxygen and acetone diffusion. However, since both aerobic and anaerobic acetone degraders exist [21], the importance of oxygen is further complicated. Recent studies have indicated that BTEX biofiltration efficiencies can be improved by decreasing the water content of the moss (Llewellyn, unpublished data).

Extreme care must be taken in attempting to infer kinetics derived from industrial type biofiltration systems which use much higher VOC levels. Alexander [5] warned that the behavior of biological systems exposed to low levels of pollutants may not be similar to when it is exposed to higher levels. Also key assumptions such as biofilm thickness being small relative to the diameter of the support media were not true (the relative water content of the moss was estimated to exceed 500%). Because of these reasons, rather than extrapolating mechanistic models derived from ‘industrial’ biofilters, an empirical approach to the modelling may be beneficial.

![Figure 5](image)

Figure 5. The removal efficiency of wet, moss covered bioscrubbers as a function of flux (m s⁻¹). For each 24 hour run three bioscrubbers were subjected to influent acetone concentrations between 100 and 500 ppbv and an average removal efficiency determined. These averages are plotted below against the natural logarithm of the inverse of air flux (hence a factor the log of retention time in the filter). Vertical lines associated with each mean represent the standard error of the mean for each estimate. Horizontal bars representing the standard error of the mean for each flux estimate are also included but are smaller than the associated symbol.

To this end, linear, cross-product and quadratic models were tested with the raw data and natural logarithms of either the influent and effluent concentrations or the loading/unloading rates along with either the raw data, natural logarithm or inverse of air flux rates (the inverse of flux rates was directly related to retention times in the biofilter). Each biofilter was considered separately. Because influent concentrations were not applied as discrete levels (i.e. in a step-wise manner), analytical methods to determine lack of fit could not be applied and instead an appropriate model was selected based upon the overall F test of the model and based upon predicted versus residual scatter plots (not presented). From these results, a multiple linear regression model based on natural logarithms of the load rate and the inverse of the flux rate was fitted. The resulting best model for each individual biofilter described the logarithm of the unloading rate with a linear and quadratic term for the logarithm of loading rate and a linear term for the logarithm of the inverse of the air flux with no cross product term. The relevant terms for each of the different biofilters are presented in Table I.
Table 1. The determined best model to describe the removal of acetone for five bioscrubbers with a range of compositions. The model describes the natural logarithm of the unloading rate (product of concentration and flux in µmol m⁻² s⁻¹) as a function of the natural logarithm of the loading rate, and the natural logarithm of the inverse of air flux (m s⁻¹). Bioscrubbers were subjected to acetone concentrations between 4 and 20 µmol m⁻³ (100 and 500 ppbv) and fluxes between 0.05 and 0.20 m s⁻¹.

### Bioscrubber and characteristics

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<td>0.91</td>
<td>0.96</td>
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<td>C.V.</td>
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<td>-101.96</td>
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<tr>
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<td>2.801</td>
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<td>0.583 (0.045)</td>
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<td>-1.074 (0.074)</td>
<td>-0.830 (0.048)</td>
<td>-0.941 (0.044)</td>
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<td>(Ln of Loading rate)²</td>
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<td>0.189 (0.043)</td>
<td>0.153 (0.061)</td>
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To extrapolate the model to a general case for wet, moss covered indoor air biofilters, the model was expanded to include a term for the thickness of the moss and support material. The thickness of the moss and support layers were 0.0264, 0.0223 and 0.0264m, compared to 0.0126m for the similar unit without the moss (each estimate was based upon 20 subsamples per unit). Examining possible interactions with the above determined terms, the actual thickness was superior to both its inverse and logarithm transformation (r² = 0.93, 0.85 and 0.90 respectively). Based upon the TYPE III sums of squares under PROC GLM of SAS non-significant terms (P > 0.15) were removed from the model. The inclusion of thickness changed the nature of the model and led to the quadratic term becoming nonsignificant and the flux term replaced by a logarithm of the inverse of flux by thickness cross-product term. The results are presented Table II.

Table 2. The estimates and their errors (in brackets) and their F values df (1, 334) for determined best model to describe the removal of acetone for three wet bioscrubbers with moss (r² = 0.93). The model describes the natural logarithm of the unloading rate (product of concentration and flux in µmol m⁻² s⁻¹) as a function of the natural logarithm of the loading rate, the natural logarithm of the inverse of air flux (m s⁻¹) and the path length through the biofilter (thickness of moss and support media, m). Bioscrubbers were subject to acetone concentrations between 4 and 20 µmol m⁻³ (100 and 500 ppbv) and air fluxes between 0.05 and 0.20 m s⁻¹.

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<td>Thickness*Ln(1/flux)</td>
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The unit devoid of moss was then included in the data set using the average thickness of the support media as the thickness term and the data re-analyzed. The inclusion of the fourth unit substantially reduced the ability of the model to describe removal. Although the number of data points used increased from 360 to 540, the r² dropped from 0.93 to 0.82. This further suggested that inclusion of moss on the wet biofilters substantially changed the nature of the biofilter and that the increase in removal associated with the moss covered units was due to more than an increase in biofilter thickness.

A likely reason for the enhanced acetone removal associated with the moss is that it supports a more diverse microbial population. Microbial diversity is dependent in part on the diversity of organic material available in the environment as a food source [8]. VOCs which can form part of this food source either can originate from biogenic, geochemical or anthrogenic sources. Biogenic sources are largely botanical in origin either as a by-product of degradation of plant material or directly from plant metabolism. Plant-derived organics enable higher populations of VOC degraders than would be expected based on availability of the anthrogenic contaminant through offering alternative food sources [8] [22] or through the release of materials such as phenols, which contribute to the selective growth and long-term survival of degrading populations while potentially inhibiting other competing microbes [23]. More appropriate for this study, acetone is released by some actively growing healthy plants [18] and through the degradation of botanical material under certain conditions [24] which could further encourage acetone degrading microbes and improve the performance of the system.
CONCLUSIONS

Passing air contaminated with low levels of acetone through a dry canopy of green higher plants does not improve the quality of the air. There was no removal of the VOC by the plant canopy. However, biofilters which used living moss as a principle substrate removed acetone from indoor air containing low levels of the contaminant (c.a. 100 to 500 ppbv). The amount removed by the biofilters reached a maximum of between 1 and 1.6 µmol s⁻¹ m⁻² with a loading rate of approximately 2 µmol s⁻¹ m⁻². Generally the removal efficiency decreased with increased loading rates over a range of air fluxes but appeared to increase with loading within the slower fluxes. The removal kinetics could not be adequately explained using ZERO or FIRST order kinetics, but an empirical model was determined which described the natural logarithm of the unloading rate as a function of the natural logarithm of the loading rate and the natural logarithm of the inverse of the air flux. The moss coverage appeared to improve acetone beyond what would be expected due to an increase in biofilter thickness.

ACKNOWLEDGMENTS

This research was supported by the Centre for Research in Earth and Space Technology (CRESTech), the Ontario Ministry for Agriculture and Rural Affairs (OMAFRA), The Canada Life Assurance Co. and their subsidiary, Adason Properties Ltd.

REFERENCES


CONTACT

Alan Darlington and Michael Dixon are faculty members in the Division of Horticultural Science, Department of Plant Agriculture at the University of Guelph, Guelph, Ontario, Canada N1G 2W1. The authors can be reached via email at ABD@evbhort.uoguelph.ca and Mdixon@evbhort.uoguelph.ca. The Canada Life Environmental Room Project has a web page at www.uoguelph.ca/hortsci/cler/enviroweb.