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The surface emissions trap: A new approach in indoor air purification

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ABSTRACT

A new device for stopping or reducing potentially irritating or harmful emissions from surfaces indoors is described. The device is a surface emissions trap prototype and consists of an adsorbent sheet with a semipermeable barrier surrounded by two thin nonwoven layers. The trap may be applied directly at the source of the emissions e.g. at moisture-affected floors and walls, surfaces contaminated by chemical spills etc. This results in an immediate stop or reduction of the emitting pollutants. The trap has a very low water vapor resistance thus allowing drying of wet surfaces. In laboratory experiments typically 98% reduction of air concentrations of volatile organic compounds and a virtually total reduction of mold particle-associated mycotoxins was observed. The surface emissions trap may represent a convenient and efficient way of restoring indoor environments polluted by microbial and other moisture-associated emissions.

1. Introduction

Water-damage of buildings leading to dampness is common all over the world due to unsatisfactory building methods and maintenance of existing buildings. The problem is expected to increase with the ongoing climate change leading to more rain in the future in many parts of the world (Andersen et al., 2011; Beggs, 2010; Hägerhed-Engman et al., 2009a). Indoor dampness is related to adverse health effects and/or bad smell and has, for example, been estimated to account for 30–50% of all asthma cases in the United States (Fisk et al., 2007; Hägerhed-Engman et al., 2009b; Mendell et al., 2011). The adverse effects and/or bad smell is due to emissions from moist construction parts, e.g. wood, concrete, glue, paint, or gypsum, of the affected building. Such emissions are formed as a result of the effect of water on a particular material (Andersen et al., 2011; Claeson et al., 2007). For example, 2-ethylhexanol and n-butanol may be formed due to alkaline hydrolysis of PVC carpets glued on concrete floor (Sjöberg and Ramnäs, 2007; Uhde and Salthammer, 2007). Moist cellulose or starch containing materials, e.g. wood, paper and gypsum board, provides a suitable milieu for growth of fungi and bacteria (Murtoniemi et al., 2003; Nielsen et al., 2004). Related volatile and semi-volatile microbial products and hazardous microbial particles and constituents, such as mycotoxins or endotoxins, may be emitted from the materials (Mitchell et al., 2007; Täubel et al., 2011). In particular, multidrug resistant strains may be fatal e.g. to hospitalized or immunocompromised individuals (Mulvey and Simor, 2009).

Additional undesired emissions, not necessarily related to water-damage, include e.g. emissions by chemicals used to protect building materials from degradation or in remediation of buildings, odors and organic solvents from drying paint and monomers, or other volatile, semi-volatile or non-volatile organic compounds, such as hormone disruptors, and chemical spills (Choi et al., 2010; Nielsen et al., 2007; Wolkoff et al., 2006).

Air cleaners (air filtration) may be efficient in reducing pollutants in indoor air (Sublett et al., 2010). Indeed, home ventilation rates above 0.5 air changes per hour have been associated with a reduced risk for allergy; at the same time, however, increasing ventilation is not energy efficient (Sundell et al., 2011). In the present study we describe a novel approach for air purification where a cloth is attached at the surface of the contaminated material for adsorbing the emissions. Thus the emissions are stopped at the source, thereby prevented from entering the adjacent surrounding (Larsson and Markowicz, 2011). A prototype cloth, a surface emissions trap (cTrap) developed at Lund University Innovation System (LUIS, Lund, Sweden), was evaluated with regards to its performance in stopping or reducing microbial particles, and volatile organic compounds (VOC), while at the same time allowing the passage of water in the gaseous phase.

2. Materials and methods

2.1. Chemicals

The solvents and reagents were of analytical or HPLC grade. The aqueous solutions were prepared using distilled and deionized water. 1-Butanol, 3-methyl-2-butanol, 3-methylbutanol, dimethyl disulfide, hexanal, 2-heptanone, styrene, anisole, alpha-pinene, 1-octen-3-ol,

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benzaldehyde, 2-ethyl-1-hexanol, 2-methyl-1-propanol, 2-methylfuran, 1-methoxy-2-propanol, dichloromethane, ethanol, 1-propanol, ammonium acetate, sodium acetate and sterigmatocystin, were purchased from Sigma Aldrich (Schnelldorf, Germany). N-octanol was purchased from Cambridge Isotopes Laboratories, Inc. (Andover, USA), acetone and methanol from Scharlau Chemie S.A. (Barcelona, Spain), ethyl acetate and toluene from Lab Scan (Dublin, Ireland). Benzene was purchased from Acros Organics (Geel, Belgium) and reserpine from Varian, Inc. (Walnut Creek, CA). Stachybotrylactam was purchased from Biopure, (Tulln, Austria), and roquefortine C from Sorbent AB/Romer Labs (Stockholm, Sweden).

2.2. Methods

2.2.1. Reducing VOC emissions

A series of experiments were performed to study the efficiency of the cTrap to eliminate or reduce VOC emissions. All experiments were performed at room temperature.

An aqueous solution containing 8 different VOC and another aqueous solution containing 12 other VOC were used. The specific compounds were selected as model emission substances because they are commonly found in indoor air of water-damaged buildings, they may be of microbial and/or non-microbial origin, and they represent different chemical classes of compounds to illustrate the versatility in the performance of the cTrap. Solution 1 contained acetone (13.8 μM), 2-methyl-1-propanol (14.8 μM), benzene (12.8 μM), ethyl acetate (11.3 μM), 2-methylfuran (13.4 μM), 1-propanol (18.3 μM), 1-methoxy-2-propanol (13.3 μM), and ethanol (13 μM). Solution 2 contained 1-butanol (42 μM), 3-methyl-2-butanol (82 μM), 3-methylbutanol (13 μM), dimethyl disulfide (17 μM), hexanal (42 μM), 2-heptanone (36 μM), styrene (43 μM), anisole (37 μM), alpha-pinene (5 μM), 1-octen-3-ol (26 μM), benzaldehyde (64 μM), and 2-ethyl-1-hexanol (27 μM). Of each solution, a 20-ml aliquot was transferred to a plastic box (300×200×H6.5 mm, 2.6-L) which was then closed with a lid which had a 14.5-cm long and 1-cm wide rectangular slit. In subsequent experiments, the slit was either covered using 71 cm^2 of the cTrap, firmly attached to the lid by an adhesive tape (VOC free), or left open. The boxes were stored at separate locations for up to 24 h (Solution 1) or 72 h (Solution 2). At regular time intervals one box at a time was placed in a wooden closet following active air sampling. The closet (75×40×35.5 cm) had a 1-cm diameter hole to allow for sampling of VOC through a tube (see below). The empty closet did not contain any detectable amounts of any of the test VOC upon air sampling. Immediately after the experiments (after 24 and 72 h, respectively), additional air samplings were performed with the lids kept open.

In another experiment 50 ml of Solution 2 was sprayed on 2 m^2 of a concrete floor in a small (7.5 m^3) room and then immediately covered with the cTrap. After 15 min air sampling was performed. Thereafter the cTrap was removed following an additional air sampling. The air exchange rate in the room was 0.62 air changes per hour as measured by an active instrument for monitoring nitrogen oxide (Etheridge and Sandberg, 1996).

A strain of *Aspergillus versicolor* (IBT 16000) (kindly provided by Ulf Trane, Technical University of Denmark) was cultivated on two Petri dishes (9 cm diameter) containing malt extract agar (MEA) for 7 days at 25 °C, until confluent growth was observed on both plates. One plate was covered with a 57-cm^2 disk of cTrap which was firmly attached to the plate with an adhesive tape, while the other plate was left uncovered. Thereafter the plates were transferred into separate glass containers (5.8-L volume) which were then sealed with glass lids and stored in the dark following passive air samplings for 72 h.

2.2.2. Extraction of trapped VOC

A series of experiments was performed to analyze the VOC adsorbed on the cTrap. 20 ml of Solution 2 was transferred to a plastic box (300×200×H6.5 mm, 2.6-L) with a lid with a 17-cm long and 8-cm wide rectangular slit, covered with 304 cm^2 (18.4 g) of the cTrap, and stored for 24 h. Thereafter, 1 cm^2 (60.5 mg) of the cTrap was extracted with dichloromethane, diluted, and analyzed by GC-MS. Analysis of cTrap exposed to water vapor only was performed as a control. A standard curve was obtained by injecting 0.146–1.825 ng of toluene using 2.4 ng of N-octanol as an internal standard.

The adsorption capacity of the cTrap for 2-ethyl-1-hexanol and 1-octen-3-ol was determined. Two different solutions consisting of 20-ml aliquots of 2-ethyl-1-hexanol (1.08 mM) and 1-octen-3-ol (1.33 mM), respectively, were added to several 250-ml glass beakers which were covered by 23.5 cm^2 discs of the cTrap, fixed by using an adhesive tape, and stored. Every second day the solutions were replaced with new 20-ml solutions, and 1 cm^2 of the cTrap from one of the beakers was extracted and analyzed by GC-MS as described above. The tests continued until the cTrap was saturated as judged by the GC-MS results. Standard curves were constructed by injecting 0.66–13.2 ng of 2-ethyl-1-hexanol, 0.35–17.5 ng of 1-octen-3-ol, and 2.4 ng of N-octanol (internal standard).

2.2.3. Air sampling and analysis of VOC

Active air samplings, using an AirCheck XR5000 sample pump (SKC Inc.), were performed during 30 min through a cartridge containing either Tenax (IVL, Stockholm, Sweden) (Solution 1, sampling at 100 ml/min following thermal desorption and gas chromatography–mass spectrometry (GC-MS) analysis at IVL, Stockholm) or activated charcoal (Anasorb 747, SKC Inc., USA) (Solution 2, sampling at 250 ml/min following extraction with dichloromethane and analyzed by GC-MS at our laboratory, see below). Passive samplings were performed by exposing Tenax cartridges to the VOC for 72 h according to the instructions of the manufacturer.

The Solution 2 samples were analyzed using a Varian model 3800 gas chromatograph equipped with a combiPAL autosampler (CTC Analytics AG, Zwingen, Switzerland) and a silica capillary column (VF5ms, 60 m×0.25 mm ID, 1 μm film thickness, Agilent Technologies) coupled to a 1200 L triple quadrupole MSMS detector (Varian INC. Walnut Creek, CA, USA). Helium was used as a carrier gas at a column flow 1.0 ml/min. The column temperature was programmed from 50 °C to 200 °C at 7 °C/min where it was held for 4 min. The injector temperature was 200 °C, the transfer line temperature 280 °C, the ion source temperature 200 °C, the electron energy 70 eV, and the filament current 50 μA. 1-μl injections in the splitless mode were used. Samples were analyzed either in selected-ion monitoring (SIM) or SCAN mode.

2.2.4. Mycotoxins emissions

A powder mixture (approximately 1.5 g) of freeze-dried cultures of *Stachybotrys chartarum* and *Penicillum expansum* (from Allergon, Ängelholm, Sweden) and *A. versicolor* IBT 16000, was transferred to a 600-ml plastic container with a plastic sieve attached 4 cm from the bottom. A 57 cm^2 piece of cTrap disk was placed on the sieve and fixed to the container walls with an adhesive tape. Then the container was closed by a lid. An aerosol of the mixture was achieved by a magnetic stirrer (500 rpm). After 16, 22 and 40 h the upper surface of the cTrap and the container walls above the sieve were cleaned with sterile Q tips which had been prewetted in methanol before use. The tips were placed in test tubes and washed with methanol, diluted, and analyzed by HPLC-MSMS. The experiment was also performed without applying the cTrap for comparison.

High-performance liquid chromatography/tandem mass spectrometry (ProStarHPLC/1200 L triple-quadrupole MSMS, Varian INC., Walnut Creek, CA) in positive ion electrospray mode was used. The analyses were performed with gradient elutions using water and methanol supplemented with 10 mM ammonium acetate and 20 μM sodium acetate at a flow rate of 0.2 ml/min. 20 μl of sample solution was injected using an autosampler (Varian, ProStar410) into a RP-18 Polaris 5 μm C18-A 150×2.0 mm column. Further details are provided elsewhere (Bloom et al., 2007). Standard curves were obtained by injecting 0.08–7.2 ng of roquefortine C and 0.08–4 ng of stachybotrylactam

with 1.2 ng of reserpine as an internal standard, and 8–240 pg of sterigmatocystin with 400 pg of reserpine as the internal standard.

2.2.5. Water vapor permeability

A method frequently used to measure vapor permeability of textiles was used (Svennberg and Wadsö, 2002). In this method several layers of small pieces of the material are placed between two relative humidities in a way that decreases the boundary resistances. In the present case a saturated solution of KCl (85% RH) was used on one side, while the other side was in contact with a climate room at 55% RH.

3. Results

3.1. VOC emissions

The air concentrations (in the closet) of the VOC immediately after the solutions had been transferred to the plastic boxes (before applying the cTrap, thus with open slits) were between 10 and 878 μg/m^3 (sum 5.6 mg/m^3) (toluene equivalents, Tables 1 and 2). Closing the slits by the cTrap resulted in a decrease of the VOC concentrations of up to 100% (Tables 1 and 2). Air concentrations of the individual VOC following opening the lids after the experiments were 3.0–67 μg/m^3 (Solution 1) and 24.5–83.2 μg/m^3 (Solution 2).

The air concentrations of the chemicals in Solution 2 emitted from the contaminated floor varied between 30.8 and 68 μg/m^3 (sum 560 μg/m^3, toluene equivalents). The concentrations were reduced by from 92.1% (styrene) up to 98.6% (benzaldehyde) by the cTrap; the average emission reduction for the 12 analyzed compounds was 95.2%. These results imply that the cTrap blocks also emissions from surface areas much larger than of the slit (see above).

Five compounds, i.e. 1-octen-3-ol (17 μg/m^3), 2-methylfuran (2.9 μg/m^3), 2-methyl-1-propanol (2.6 μg/m^3), styrene (82 μg/m^3), and 2-methyl-1-butanol (4.2 μg/m^3) (toluene equivalents), were identified above the uncovered plate with growth of *A. versicolor*. Covering the container with cTrap gave a concentration reduction of 88% for 1-octen-3-ol and 98% for styrene; the remaining compounds were reduced by 100% (amounts below the detection limit). The experiment shows that the cTrap adsorbs efficiently microbial VOC during growth.

3.2. Extraction of the trapped VOC

The amounts of VOC extracted from the cTrap which had been exposed to Solution 2 for 24 h ranged from 10 to 145.5 μg/g (toluene equivalents) (Table 2). A total of 953 μg of VOC were adsorbed comprising 32.7% of the total amounts used in the experiment. No VOC were detected in samples extracted from cTrap which was unused or had been exposed to water vapor only. The adsorption capacity for 2-ethyl-1-hexanol was 27.1 ± 6.02% (n = 5) and for 1-octen-3-ol 14.0 ± 16.3% (n = 5) mg/g cTrap (13.5 ± 6.02% and 7.0 ± 16.3% g/m^2, respectively).

Table 1
Air concentrations (μg/m^3) of VOC unexposed to cTrap, and reductions of air concentrations of VOC by cTrap. A 100% reduction denotes that the amounts were below the detection limit.

Compound	Air concentration	% Reduction	
		0.5 h	24 h
Acetone	57	91.8	93.9
2-Methylfuran	101	99.8	100
Ethyl acetate	98	100	99.6
Benzene	111	99.5	99.5
1-Propanol	28	100	100
2-Methyl-1-propanol	60	99.3	99.7
1-Methoxy-2-propanol	10	96.0	89.0
Ethanol	12	95.8	91.7

Table 2
Air concentrations (μg/m^3) of VOC unexposed to cTrap, reductions of air concentrations of VOC by cTrap (a 100% reduction denotes that the amounts were below the detection limit), and concentrations (μg/g) of VOC extracted from cTrap after 24 h exposure.

Compound	Air concentration	% Reduction				Extracted after 24 h
		0.5 h	24 h	48 h	72 h	
1-Butanol	348	99.0	99.6	99.7	99.8	77.5
3-Methyl-2-butanol	391	99.5	99.6	99.4	99.8	92.1
3-Methylbutanol	428	100	99.9	100	100	105.5
Dimethyl disulfide	349	99.7	99.9	99.9	100	10
Hexanal	282	99.7	99.6	99.7	99.7	9.3
2-Heptanone	830	100	100	100	100	90.8
Styrene	294	99.9	100	99.9	100	58.2
Anisole	435	99.9	100	99.9	100	88.1
Alpha-pinene	82	98.8	97.7	99.0	98.9	29
1-Octen-3-ol	878	100	99.6	99.9	99.9	124.7
Benzaldehyde	259	99.9	99.9	99.9	99.9	145.5
2-Ethyl-1-hexanol	556	99.9	100	99.9	99.9	122.2

3.3. Mycotoxins emissions

Mycotoxins were demonstrated in the Q tip methanolic extracts from the experiments with uncovered sieve. Thus, after 16, 22, and 40 h of stirring stachybotrylactam (59, 57.7, and 17.6 μg respectively), roquefortin C (1.4, 1.7, and 1.8 μg, respectively) and sterigmatocystin (21, 18, and 39 ng, respectively) were identified. By contrast, no mycotoxins were detected in any of the extracts when the sieve had been covered with the cTrap (Fig. 1).

3.4. Water vapor permeability

The water vapor resistance (Z) was established as 200 s/m, a very low value indicating that a moist surface covered with cTrap will not be prevented from drying.

4. Discussion

The rationale of the development of the cTrap was the prospect of being able to stop harmful emissions from contaminated building materials in a quick and convenient way. For example, when a building has been subjected to water-damage leading to mold growth the tenants may be temporarily evacuated and accommodated at hotels etc. until remediation can commence, which is very costly and trying for the evacuees. In such a case the cTrap may represent an attractive temporary solution. Since the cTrap stops efficiently both microbial particles, containing e.g. mycotoxins, and microbial VOC, emitted from a narrow slit (simulating leakage through a skirting board), as well as from a larger surface (2 m^2 was used), the tenants may stay in their home until remediation. Notably, the total VOC concentrations used in the experiments, viz 5.6 mg/m^3, are higher by at least one order of magnitude than the concentrations typically found in water-damaged buildings (Korpi et al., 2009). Since the cTrap shows a very low water vapor resistance, similar as e.g. felted wool fabric (Svennberg, 2006), it will not prevent the affected building material surfaces from drying, and condensation will be avoided. For example, the cTrap may be adapted at a surface with active mold growth for stopping emissions. After the surface has been dried and the emissions reduced accordingly, the adsorbed VOC may be physically removed from the building, together with the cTrap, and sent for destruction. We showed that adsorbed VOC can be extracted from the cTrap and analyzed by GC-MS, which also means that it can be used for identifying the source of the emissions. This also means that in order to take full advantage of the cTrap it is necessary to know from which surfaces the emissions escape.

Emissions due to 2-ethyl-1-hexanol and n-butanol are common in buildings where water is allowed to diffuse from the soil through a concrete floor resulting in alkaline hydrolysis of compounds present in the

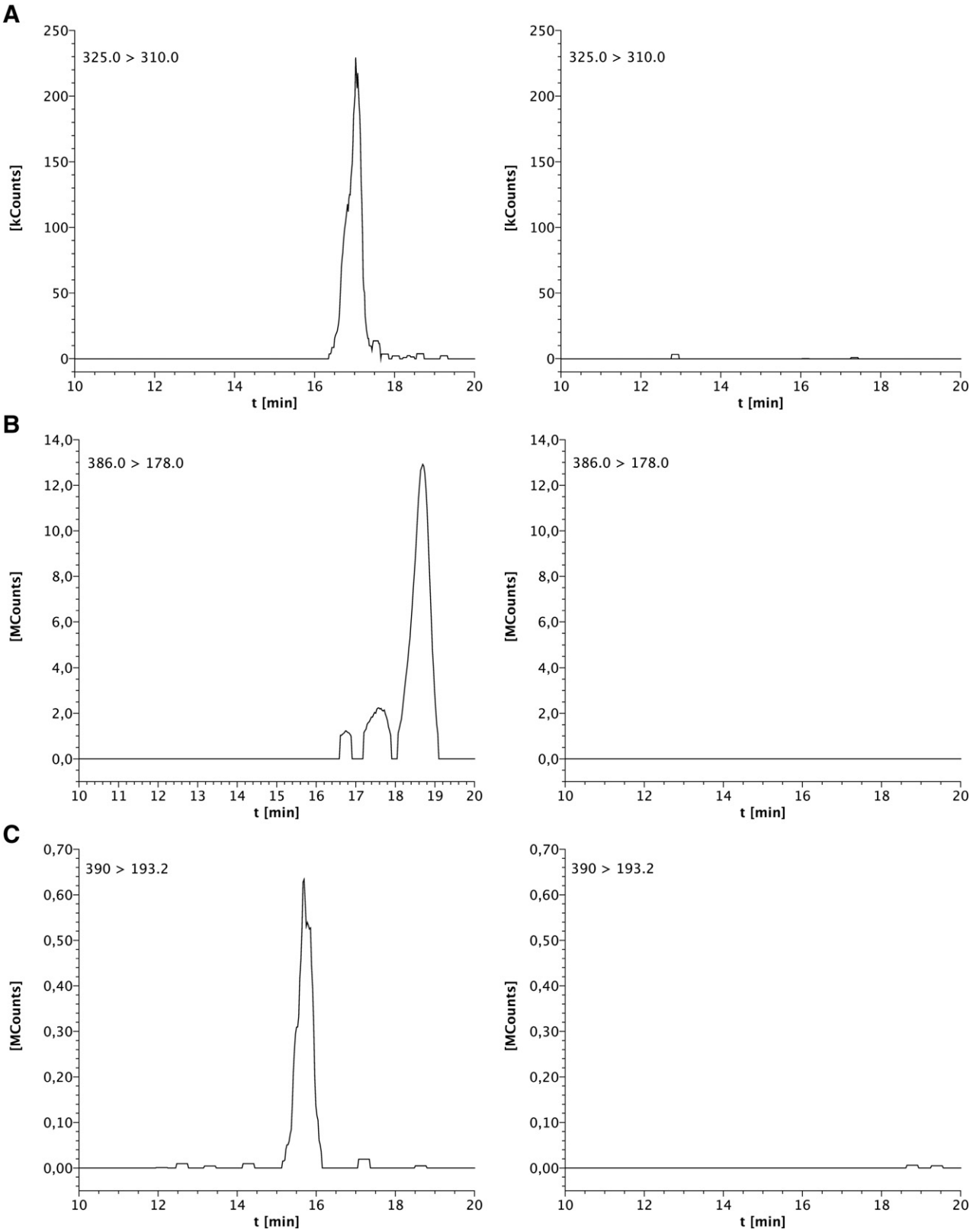

Fig. 1. MSMS chromatograms of mycotoxins in an aerosol mixture of molds found after 40 h of sampling representing sterigmatocystein from *Aspergillus versicolor* (A), stachybotrylactam from *Stachybotrys chartarum* (B), and roquefortin C from *Penicillum expansum* (C). Chromatograms represent the presence (right) and absence (left) of the cTrap, respectively.

glue and PVC carpets. Such emissions are also adsorbed efficiently (>99%); the cTrap's adsorption capacity for 2-ethyl-1-hexanol was estimated as 27.1 mg/g (13.5 g/m^2). Further research is required for evaluating whether use of cTrap can provide a viable alternative to more costly and time-consuming measures, e.g. floor ventilation or physical removal of the contaminated concrete.

Of the five different VOC identified from the culture of *A. versicolor*, viz 1-octen-3-ol (17 μg/m^3), 2-methylfuran (2.9 μg/m^3), 2-methyl-1-propanol (2.6 μg/m^3), styrene (82 μg/m^3), and 2-methyl-1-butanol (4.2 μg/m^3), the cTrap showed least efficiency for 1-octen-3-ol and styrene (88% and 98% reduction, respectively). The adsorption capacity for 1-octene-3-ol, a metabolite frequently viewed as being a representative microbial VOC, was 14 mg/g (7 g/m^2), thus lower by approximately 50% in comparison with 2-ethyl-1-hexanol. It is well-known that adsorbents have different adsorption capacities for different VOC depending upon their chemical and physical properties.

5. Conclusions

We report a novel concept for stopping or reducing unwanted emissions from building materials indoors by using a surface emissions trap. The trap stops the emissions at the source thus preventing them from entering the living spaces. In the present study the trap proved to be very efficient in stopping mold-associated emissions, both particular and gaseous, as well as other moisture-related chemical emissions. We are currently exploring the performance of the cTrap in buildings affected by moisture resulting in potentially irritating or harmful emissions indoors.

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