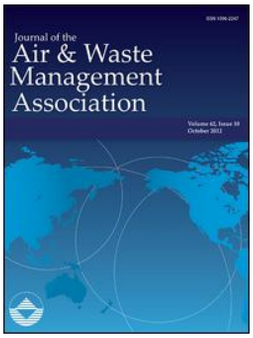

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Evaluation of an Air Sampling Technique for Assessing Low-Level Volatile Organic Compounds in Indoor Environments

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ABSTRACT

Measuring trace levels of volatile organic compounds (VOCs) in indoor environments is important for the characterization of occupant exposures. The ability to quickly collect air samples at relatively low costs per sample can increase the number of samples that can be collected and thus improve the overall assessment of potential exposures. The specific goal of this paper is to evaluate the accuracy and precision of evacuated glass bottle air samplers (Entech Bottle-Vacs) to collect representative VOC samples at part-per-billion concentrations in indoor environments. Laboratory generated data are also included to validate the precision and accuracy of the method. Multiple Bottle-Vacs in 10 residences in northern New York over 18 different sampling periods were used to collect whole-air VOC samples. Percent relative standard deviations ranged from 1.2 to 20.3% with a median of 8.8% for the 21 compounds analyzed in each Bottle-Vac. Two sampling techniques were used: around the valve (ATV) and through the valve (TTV). Linear regressions of ATV and TTV sample collection into the Bottle-Vacs show that these two sampling techniques are reproducible. Paired *t* test results show that ATV sampling is more reproducible than TTV; ATV paired samples were statistically the same 100% of the time whereas TTV paired samples were statistically the same 76.9% of the time. ATV sampling of low-level VOCs in indoor built environments is a reproducible chemical sampling technique that could be used by building occupants as a quick and inexpensive means of area sampling.

IMPLICATIONS

By assessing the reproducibility of Entech Bottle-Vacs as passive, whole-air, grab sampling devices, confidence is gained in their field sampling efficacy. These evacuated glass bottles were used to collect microbial-generated VOCs in multiple northern New York residences. The sampling device uses no sampling pumps or chemical solvents and may be reused after appropriate cleaning. The Bottle-Vacs' ease of use, ability to be reused, and accurate results allow for an increased number of samples to be collected using less resources, benefiting the researcher and indoor air quality practitioner.

INTRODUCTION

Exposure assessments in indoor air environments necessitate sampling systems that can provide reliable determinations of airborne contaminant concentrations. Building occupants are continually exposed to low-levels of volatile organic compounds (VOCs) from various sources such as microbial growth, air fresheners, building material off-gassing, and cooking activities.[1–3]

A continuing exposure assessment challenge is accurately assessing low-level VOCs in indoor environments. With the advent of more sophisticated analytical instrumentation, smaller volumes of air are needed to measure low concentrations of VOCs in indoor or outdoor environments. The development of a more robust air sampling system that allows for the accurate measurement of low part-per-billion to part-per-trillion-by-volume concentrations would be useful in various microenvironments.[4–7] The Bottle-Vac sampling system was developed by Entech Instruments, Inc. between 2005 and 2007 to provide a low-cost sampling technique for VOCs in indoor environments. The Bottle-Vac, shown in Figure 1, is a glass bottle with a specially designed Micro-QT (Entech Instruments, Simi Valley, CA) valve used to collect VOCs over short time periods (seconds to minutes).

This study was part of a larger study to investigate the use of passive chemical sampling to assess mold-generated VOCs in contaminated indoor environments. Microbial VOCs (MVOCs) are a group of compounds emitted by mold as secondary metabolic byproducts. They consist of a wide range of compound classes such as alcohols, ketones, esters, ethers, and alkanes and therefore provide a broad range of compounds to validate the Bottle-Vac sampling technique. Multibed sorbent tubes and solid-phase microextraction have successfully been used in the laboratory to sample MVOCs.[8–11] However, whole-air grab samples or time-weighted average samples using an external[12] or internal[13] flow controller to collect

Figure 1. Bottle-Vac sampler.

contaminants in an evacuated container may be a more effective means of collecting representative VOC samples in indoor built environments.

Analysis of the Bottle-Vacs is performed using a modified version of U.S. Environmental Protection Agency (EPA) Method TO-15.[14] Bottle-Vacs are an economical gas-phase sampling device that can increase laboratory productivity by minimizing sample preparation times. Bottle-Vac sampling, like evacuated stainless steel canisters, have several advantages over common sorbent methods such as Tenax or multibed sorbent tubes: (1) they collect a whole-air sample that is not dependent on an external sampling pump, (2) there is no analyte interaction with the adsorbents during collection of the air sample, (3) they have improved sample stability, (4) there is no effect from air currents, and (5) there are no temperature effects at normal sampling temperatures. Passive diffusive badges with solid sorbents such as charcoal have similar ease of use as the Bottle-Vacs, but the former requires chemical desorption and is mostly useful at higher (parts-per-billion [ppb] level) analyte concentrations. The stability of the analyte on the solid sorbent as well as the adsorption and desorption efficiency may vary widely from compound to compound, restricting passive badges to the collection of a limited number of VOCs.[15] Stock et al.[16] showed that passive badges could be used for long-term sampling of ambient air when VOC concentrations are expected to be low. Like evacuated canisters, Bottle-Vacs allow for sample collection to passively flow from the external environment into the container via a pressure differential established in the laboratory before sampling. One factor that must be considered with this Bottle-Vac method is interaction and transformation effects in the container. Bottle-Vacs are treated with a proprietary deactivation process that has been shown by Entech to be inert for most VOCs. A significant advantage of Bottle-Vacs is the ability to collect a sample without a pump. The maintenance and effective performance of sampling pumps can add significantly to sample collection error and cost.

Use of sorbent tubes followed by chemical desorption is another alternative, but like thermal desorption of sorbent tubes this method is limited to sorbent specificity to chemical contaminants, interferences, artifacts, and breakthrough volumes.[17] Sorbent tube samples have commonly been analyzed using thermal desorption onto a gas chromatograph.[2,18–21] Thermal desorption without sorbent material has also been used for characterization of chemical composition of time-weighted average (TWA) filter samples.[22] Bottle-Vac whole-air samples are concentrated in the laboratory before analysis.

The specific aim of this paper is to evaluate the ability of an evacuated glass bottle, an Entech Bottle-Vac, to collect representative field samples in the low ppb range in indoor environments. Laboratory data were generated to evaluate the precision and accuracy of the Bottle-Vacs. The laboratory values were used to assess sampling bias associated with field sampling.

EXPERIMENTAL METHODS

Several guidelines for air sampling and analytical method development and evaluation were used as a reference for the required number of samples and determination of method precision from field measurements in an effort to validate the use of Bottle-Vacs for field sampling.[23,24] Accuracy has been documented in a laboratory setting for varying holding times and relative humidity (RH) conditions at 10 ppb. The detection limits were established for compounds listed in EPA Method TO-15 and for a select group of MVOCs. Laboratory reproducibility studies were performed by placing known concentrations of TO-15 VOCs in Bottle-Vacs to examine recovery rates and compound stability under varying analyte concentrations and storage conditions. These laboratory tests (performed at Entech Instruments) established precision and accuracy for the bottle sampling system in controlled environments. A field sampling campaign was initiated to examine the performance of the technique under actual field conditions for multiple tests. Temperature and RH were recorded at the sampling sites.

Table 1. RRFs and IDLs (ppb) for selected MVOCs.

Compound	IDL	Average RRF	SD	% RSD
2-Butanone	0.019	2.81	0.39	13.83
2-Methyl furan	0.011	6.54	0.92	14.11
Bromochloromethane (internal standard 1)	0.000	1.00	0.00	0.00
3-Methyl furan	0.013	0.87	0.07	8.27
2-Methyl-1-propanol	0.018	0.42	0.03	8.08
1,4-Difluorobenzene (internal standard 2)	0.000	1.00	0.00	0.00
3-Methyl-2-butanol	0.019	1.82	0.10	5.49
2-Pentanol	0.027	2.07	0.17	8.33
1,4-Dioxane	0.044	0.04	0.00	8.59
3-Methyl-1-butanol	0.022	0.49	0.06	11.86
2-Methyl-1-butanol	0.043	0.73	0.08	10.68
1-Pentanol	0.020	0.78	0.06	7.73
2-Hexanone	0.016	1.85	0.21	11.64
Chlorobenzene-d5 (internal standard 3)	0.000	1.00	0.00	0.00
2-Heptanone	0.017	2.56	0.22	8.66
Bromofluorobenzene (surrogate)	0.000	0.32	0.00	1.21
1-Octen-3-ol	0.023	2.23	0.38	16.98
3-Octanone	0.018	1.70	0.13	7.55
2-Pentyl furan	0.013	4.24	0.39	9.22
3-Octanol	0.029	1.13	0.15	13.10
2-Ethyl-1-hexanol	0.048	3.47	0.68	19.48
1-Octanol	0.018	0.83	0.17	20.30
Methoxypyrazine	0.030	1.57	0.08	4.84
2-Methylisoborneol	0.054	1.11	0.11	9.65
Geosmin	0.088	0.96	0.09	8.89

Laboratory Data

Instrument detection limits (IDLs) and relative response factors (RRFs) were calculated from a five-point calibration ranging from 0.4 to 10 ppb for MVOC compounds. Two week and 30-day holding studies were conducted on EPA Method TO-15 compounds at 10 ppb with three replicates per run. RH effects on MVOC compound recoveries were tested at 10, 50, and 100% RH with three replicates per humidity level.

Field Sample Campaign Locations

A total of 10 locations in northern New York were sampled during 18 different sampling periods from July 2006 to August 2007 with most samples collected in the summer. Locations were selected based on three levels of mold contamination: (1) no visible mold growth, (2) a medium amount of mold growth (<10 ft^2), and (3) a high level of mold growth (>10 ft^2). Mold growth area discrimination criteria were based on New York City Department of Health mold remediation guidelines.[25] At least one pair of Bottle-Vacs was sampled per location, but generally two or more pairs were used.

Sample Collection and Analysis

Environmental conditions such as temperature and RH were recorded during each sampling period. MVOC samples were collected in Bottle-Vacs (Entech, Simi Valley, CA) with one of two techniques recommended by the manufacturer: around the valve (ATV) or through the valve (TTV). ATV sampling involved removing the top off of the evacuated glass bottle. TTV sampling required actuating the Micro-QT valve at the top of the bottle. Before sampling, a subset of bottles was checked with an analog pressure gauge to ensure proper vacuum was maintained. Samplers were shipped to Entech for analysis. A chain-of-custody form accompanied all samplers to ensure proper sample handling. Samples were analyzed on a 7500 Autosampler attached to a 7100A Extended Cold Trap Dehydration Preconcentrator (Entech Instruments Inc.) coupled with an Agilent 6890/5973N gas chromatography (GC)/mass spectrometer (MS) (Agilent Technologies, Santa Clara, CA). The GC column was a DB-1 60-m by 0.32-mm inner diameter with a film thickness of 1 μm. Gas calibration standards were internal and external standards. Internal standards consisted of bromochloromethane, 1,4-difluorobenzene, and chlorobenzene-d5. A gas surrogate, bromofluorobenzene, was also included. RRFs were calculated for MVOCs of interest. Most samples were analyzed within 1 month of sampling: only two samples were analyzed 31 and 32 days after sampling. Twenty-two chemicals were tracked as representative MVOCs from a range of chemicals known to be emitted by mold during metabolic activity. All concentrations were blank-corrected.

Statistical Analysis

The goal of statistical analysis was to assess reproducibility. Below-detection-limit values were replaced with the specific chemical method detection limit divided by the square root of 2 under the assumption that the distribution of below-detection-limit values are better approximated with a triangle than a rectangle.[26] This value was chosen so that the comparative analysis between paired samples could be performed without eliminating data and so that the natural log-transformed data ($\ln(x)$) could be obtained.

Linear regression was performed in Origin 7 (OriginLab Corporation, Northampton, MA) to assess the relationship between paired samples. Origin 7 was also used for some statistical analyses. Paired *t* tests were performed using Systat 10 (Systat Software, Inc., San Jose, CA). All statistical analyses were performed at $\alpha = 0.05$.

RESULTS

Laboratory Recoveries (Method Accuracy)

IDLs and RRFs for MVOCs, displayed in Table 1, were calculated from a five-point calibration. Relative standard deviations (RSDs) ranged from 1.2 to 20.3% with a median of 8.8% for 21 compounds. All chemicals were within the EPA Method TO-15 technical acceptance criterion that the percent RSD of the RRF for each compound is below 30%.[14] Thirteen of 22 chemicals had RSDs below 10%.

A 2-wk holding study for EPA Method TO-15 compounds was conducted to assess the losses associated with sample storage. The results are displayed in Table 2. RSDs ranged from 0.9 to 11.9% with a median of 4.4%. Fractional recoveries, not shown, ranged from 0.82 to 1.01 with a median of 0.96.

Two-week and 30-day holding study percent recoveries are displayed in Table 3 for EPA Method TO-15 compounds at 10 ppb. Two-week percent recoveries ranged from 82 to 112% with a median of 97%. One-month percent recoveries ranged from 75 to 128% with a median of 95%.

The results of RH effects on recoveries for MVOCs at 2 ppb are displayed in Table 4. At 10% RH, percent recoveries ranged from 41.3 to 149.7% with a median of 107.2%. Percent recoveries ranged from 74.6 to 253.9% with a median of 121.1% at a more realistic field setting value of 50% RH. At 100% RH, percent recoveries ranged from 117.3 to 811.8% with a median of 130.7%. Although it was beyond the scope of this research to investigate the artifacts from the chemical interactions within the Bottle-Vacs, clearly the methylfurans and some alcohols had characteristically high recoveries presumably because of interferences or chemical reactions in the sampling vessel at elevated RH.

Field Precision (Method Precision)

Outside temperature ranged from 16.3 to 18.7 °C and inside temperature ranged from 16 to 17.8 °C between July and August. Outside temperature ranged from −3.9 to 13.2 °C and inside temperature ranged from 15.2 to 19.3 °C between October and December. RH ranged from 50.2 to 81.4% with insignificant seasonal or outside-inside location influence.

A total of 31 ATV pairs and 26 TTV pairs were collected and analyzed. Linear regressions of log-transformed ATV and TTV paired samples are displayed in Figures 2 and 3, respectively. A good correlation exists between paired samples. ATV paired regression indicates a slope of 0.976 and an intercept of −0.047 with an R^2 of 0.98 (n = 704). TTV paired regression indicates a slope of 0.943 and an intercept of −0.146 with an R^2 of 0.91 (n = 601).

Linear regressions of individual chemicals (not log-transformed) from the paired sampling that were consistently above the method detection limit are displayed in

Table 2. Two-week holding study of EPA Method TO-15 compounds at 10 ppb in Bottle-Vacs.

Compound	Average	SD	% RSD
Propene	9.57	0.21	2.14
Dichlorodifluoroethane	9.76	0.64	6.56
Chloromethane	9.78	0.59	6.07
Dichlorotetrafluoorethane	9.88	0.64	6.51
Vinyl chloride	9.91	0.64	6.46
1,3-Butadiene	10.00	0.69	6.92
Bromomethane	9.91	0.64	6.48
Chloroethane	9.53	0.55	5.8
Bromoethene	10.00	0.58	5.83
Trichlorofluoromethane	9.88	0.50	5.07
Acetone	9.01	0.61	6.72
Isopropyl alcohol	9.21	0.64	6.97
1,1-Dichloroethene	9.57	0.40	4.15
Trichlorotrifluoroethane	9.43	0.41	4.32
Allyl chloride	9.47	0.34	3.55
Methylene chloride	9.57	0.38	3.93
Carbon disulfide	9.51	0.43	4.48
trans-1,2-dichloroethene	9.37	0.44	4.69
Methyl tertiary butyl ether	8.77	0.49	5.62
Vinyl acetate	8.79	0.30	3.41
1,1-Dichloroethane	9.40	0.38	4.01
2-Butanone	8.69	0.46	5.32
Hexane	9.30	0.37	3.98
cis-1,2-Dichloroethene	9.42	0.40	4.3
Ethyl acetate	9.02	0.40	4.47
Chloroform	9.37	0.42	4.53
Tetrahydrofuran	8.50	0.48	5.59
1,1,1-Trichloroethane	9.39	0.40	4.28
1,2-Dichloroethane	9.38	0.36	3.87
Benzene	9.38	0.44	4.68
Carbon tetrachloride	9.35	0.44	4.73
Cyclohexane	9.28	0.45	4.86
2,2,4-Trimethylpentane	9.90	0.51	5.17
Heptane	9.74	0.47	4.86
Trichloroethene	9.90	0.43	4.38
1,2-Dichloropropane	9.85	0.55	5.61
1,4-Dioxane	9.19	0.67	7.30
Bromodichloromethane	9.87	0.48	4.82
cis-1,3-Dichloropropene	9.74	0.40	4.12
4-Methyl-2-pentanone	9.34	0.64	6.85
trans-1,3-Dichloropropene	9.64	0.34	3.50
Toluene	9.75	0.43	4.40
1,1,2-Trichloroethane	9.80	0.39	4.01
2-Hexanone	8.87	0.65	7.34
Dibromochloromethane	9.82	0.47	4.84
Tetrachloroethene	9.91	0.38	3.85
1,2-Dibromoethane	9.78	0.32	3.25
Chlorobenzene	9.89	0.16	1.61
Ethyl benzene	9.67	0.17	1.74
m-Xylene	9.79	0.29	2.94
p-Xylene	9.79	0.29	2.94
Styrene	9.82	0.13	1.37
o-Xylene	9.91	0.24	2.39
Bromoform	9.65	0.38	3.88
1,1,2,2-Tetrachloroethane	10.14	0.17	1.71
4-Ethyl toluene	9.23	0.32	3.46
1,3,5-Trimethylbenzene	9.45	0.14	1.50
1,2,4-Trimethylbenzene	9.39	0.09	0.91
1,3-Dichlorobenzene	9.86	0.15	1.55
Benzyl chloride	9.18	0.39	4.21
1,4-Dichlorobenzene	9.77	0.18	1.88
1,2-Dichlorobenzene	9.76	0.17	1.69
1,2,4-Trichlorobenzene	8.22	0.59	7.15
Hexachlorobutadiene	8.58	1.03	11.99

Table 3. Two-week and 30-day percent recoveries for EPA Method TO-15 compounds at 10 ppb in Bottle-Vacs.

Compound	2-wk	30-day
Propene	100	91
Dichlorodifluoromethane	102	95
Chloromethane	95	85
Dichlorotetrafluoromethane	95	96
Acetaldehyde	96	104
Vinyl chloride	96	95
1,3-Butadiene	95	100
Bromomethane	97	101
Chloroethane	96	93
Bromoethene	97	93
Trichlorofluoromethane	97	94
Acetone	103	102
Propanal	100	87
Isopropyl alcohol	99	116
1,1-Dichloroethene	95	98
1,1,2-Trichloro-1,2,2-trifluoroethane	98	98
Methylene chloride	99	99
Allyl chloride	98	92
Carbon disulfide	97	99
trans-1,2-Dichloroethene	96	97
Methyl tertiary butyl ether	93	92
1,1-Dichloroethane	95	96
Vinyl acetate	94	92
2-Butanone	109	104
Hexane	99	99
cis-1,2-Dichloroethene	97	89
Ethyl acetate	93	94
Chloroform	95	95
Tetrahydrofuran	94	128
1,1,1-Trichloroethane	94	94
1,2-Dichloroethane	96	94
Benzene	100	102
Carbon tetrachloride	95	93
Cyclohexane	97	98
2,2,4-Trimethylpentane	96	96
Heptane	97	96
1,2-Dichloropropane	98	94
Trichloroethene	97	94
Bromodichloromethane	95	96
1,4-Dioxane	97	94
cis-1,3-Dichloropropene	97	91
4-Methyl-2-pentanone	96	94
trans-1,3-Dichloropropane	97	97
Toluene	100	100
1,1,2-Trichloroethane	96	97
2-Hexanone	112	100
Dibromochloromethane	97	93
1,2-Dibromoethane	99	96
Tetrachloroethene	99	94
Chlorobenzene	102	95
Ethyl benzene	100	93
Bromoform	99	97
Styrene	100	99
o-Xylene	101	96
1,1,2,2-Tetrachloroethane	99	103
4-Ethyl toluene	102	92
1,3,5-Trimethylbenzene	106	98
1,2,4-Trimethylbenzene	99	95
1,3-Dichlorobenzene	97	93
Benzyl chloride	99	83
1,4-Dichlorobenzene	98	95
1,2-Dichlorobenzene	96	94
1,2,4-Trichlorobenzene	82	75
Hexachlorobutadiene	89	84

Table 4. Percent recoveries of MVOCs at 2 ppb and 10, 50, and 100% RH.

Compound	10% RH	50% RH	100% RH
2-Methylfuran	149.7	158.4	164.7
2-Butanone	107.2	117.5	121.0
3-Methylfuran	147.3	155.8	162.8
2-Methyl-1-propanol	88.2	112.0	159.8
2-Methyl-2-butanol	113.2	123.9	128.3
1-Butanol	104.3	253.9	811.8
3-Methyl-2-butanol	107.5	115.0	121.8
2-Pentanol	110.5	121.1	127.5
1,4-Dioxane	112.2	128.5	135.7
3-Methyl-1-butanol	106.2	119.1	127.0
2-Methyl-1-butanol	109.8	121.6	130.7
1-Pentanol	109.7	125.6	133.2
2-Hexanone	108.3	118.5	125.2
2-Heptanone	96.2	110.6	119.0
1-Octen-3-ol	98.2	128.5	142.5
3-Octanone	89.7	107.9	117.3
2-Pentylfuran	123.0	129.9	138.7
3-Octanol	89.3	115.5	128.8
2-Ethyl-1-hexanol	41.3	74.6	233.2
1-Octanol	90.5	134.5	161.2
2-Isopropyl-3-methoxypyrazine	96.0	114.0	118.2
2-Methylisoborneol	133.7	161.9	174.2
Geosmin	98.7	110.9	125.7

Table 5. Indicators of a good comparison are a slope approaching 1 and Pearson's correlation coefficient approaching 1. Five chemicals sampled TTV appeared to be the most influential to the paired analysis by their correlation and slope values: 1-octen-3-ol, 2-butanone, 2-methyl-1-butanol, 2-methyl-1-propanol, and 3-octanone. These same five chemicals displayed an influence when sampling ATV; in addition, 2-pentylfuran, 2-hexanone, and 1-pentanol appeared to be influential in the ATV paired analysis. Some pairs were visually identified as outliers and removed from the statistical analysis, which is acceptable in a two-dimensional space.[27]

No statistical difference was observed for ATV paired samples (data not shown). Probabilities were greater than

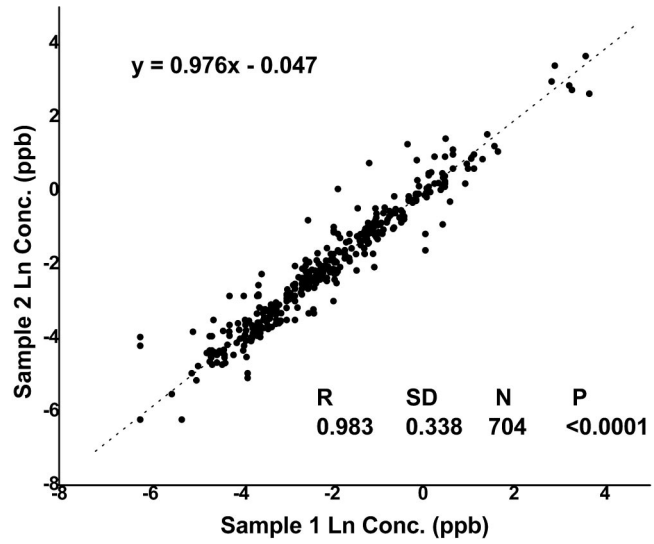

Figure 2. Linear regression of ATV Bottle-Vac paired samples (log-transformed).

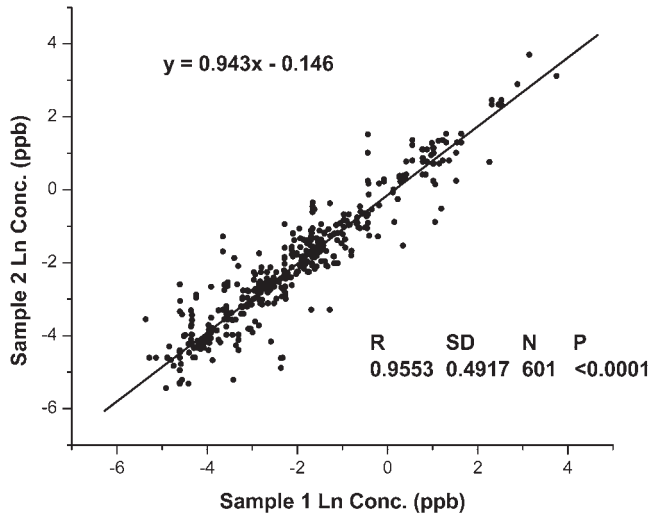

Figure 3. Linear regression of TTV Bottle-Vac paired samples (log-transformed).

0.05 but mostly greater than 0.3, indicating no difference between paired samples. TTV samples were statistically different in 6 of 26 paired comparisons (23.1% of the time).

DISCUSSION

Environmental conditions were reported but they will have a limited influence on the assessment of reproducibility of this technique because of collocated paired sampling.

Indoor air quality is a major concern for residential and commercial built environments. A fast, effective, and reliable grab sampling technique that can be used by the building occupant or indoor air quality practitioner and shipped to a laboratory for analysis would allow assessment of indoor air chemical constituents to be accessible to the populace. A significant benefit of Bottle-Vacs is that they are reusable. The cost of sampling is drastically reduced when compared with one-time-use samplers such as sorbents or passive badges. Given this advantage, the number of samples collected may be increased, which will increase the statistical power of the investigation and therefore strengthen the conclusions drawn from these results. Also, the lack of chemical desorption solvents makes this technique a low-waste-producing alternative to currently used sampling techniques. The field of indoor air sampling should consider not only the cost of sampling but also the environmental effects produced from analysis or production of sorbent-based sampling technologies.

In this assessment of the precision of replicate field measurements, Bottle-Vacs were found to be a simplistic yet powerful means of sampling residential environments. When the sample is concentrated before analysis, low-ppb VOC concentrations may be accurately determined in the laboratory. Rossner et al.[13] showed canister precision values within the range of this study, although they were looking at occupationally typical levels of Styrene ranging from approximately 5 to 50 parts per million (ppm). Batterman et al.[15] found coefficients of variation less than or equal to 20% when sampling VOCs found in printing facilities with thermal desorption tube sampling. Considering the study presented here looked at much lower concentration levels than either of these two studies, a comparable range of uncertainty is remarkable. Ribes et al.[28] looked at 45 VOCs sampled with Tenax tubes for the determination of nuisance odors and air-quality VOCs. They found similar precision values using a thermal desorption technique followed by a preconcentrator as was found in this study using Bottle-Vacs. One of the benefits of the Bottle-Vac system lies in the elimination of cumbersome sampling pumps that need to be routinely calibrated and maintained.

In addition, the day-to-day variability in chemical concentrations within microenvironments far outweighs the variability of the sampling technique.[29] Although the Bottle-Vacs displayed a good accuracy and precision in the study presented here, their greatest advantage is their ease of use, which will allow for a greater number of samples to be collected in any given sampling campaign. As the number of samples is increased, a more complete understanding of the profile of airborne contaminants is obtained.

Although the study presented here used grab sampling, TWA sampling could be accomplished by incorporation of an internal[13] or external[12] flow controller. Ochiai et al.[30] showed a good agreement between daily and weekly averaged VOC concentrations in SUMMA canisters using an external flow controller. Although TWA sampling with Bottle-Vacs would require further

Table 5. Linear regression of individual chemicals sampled TTV and ATV.

Chemical	Sampling	Slope	Intercept	R	*n*
1-Octanol	TTV	0.16	0.24	0.16	26
	ATV	0.80	0.09	0.54	26
1-Octen-3-ol	TTV	1.16	0.00	0.85	26
	ATV	0.96	0.00	0.94	25
1-Pentanol	TTV	0.50	0.15	0.59	26
	ATV	1.04	−0.01	0.99	30
2-Butanone	TTV	1.16	0.14	0.96	21
	ATV	0.85	0.11	0.91	29
2-Ethyl-1-hexanol	TTV	0.87	0.32	0.90	20
	ATV	0.57	0.66	0.66	30
2-Heptanone	TTV	0.52	0.07	0.68	25
	ATV	0.78	0.05	0.90	30
2-Hexanone	TTV	0.47	0.07	0.52	25
	ATV	1.00	0.01	0.85	30
2-Methyl-1-butanol	TTV	0.80	0.03	0.95	26
	ATV	0.96	0.00	0.91	22
2-Methyl-1-propanol	TTV	0.92	0.01	0.98	26
	ATV	0.92	0.05	0.92	25
2-Methyl-2-butanol	TTV[a]	0.30	0.01	0.29	25
	ATV	NA	NA	NA	NA
2-Methylfuran	TTV[a]	0.37	0.04	0.32	26
	ATV	0.70	0.03	0.71	30
2-Pentylfuran	TTV	0.38	0.04	0.45	26
	ATV	0.96	0.01	0.99	28
3-Methylfuran	TTV	0.47	0.04	0.41	26
	ATV	0.83	0.01	0.85	30
3-Octanone	TTV	0.84	0.00	0.73	24
	ATV	0.94	0.00	0.95	23

Notes: [a]Not statistically significant. NA = not applicable, R = Pearson correlation coefficient, and *n* = number of samples.

research, this technique may be useful for capturing VOC concentrations over a longer time period without significantly changing accuracy and precision.

CONCLUSIONS

The goal of the study was to assess the reproducibility of Bottle-Vac samplers by observing sample recoveries as well as effects of sample storage and varying RH. Percent RSDs ranged from 1.2 to 20.3% with a median of 8.8%. Linear regressions of ATV and TTV sample collection into Bottle-Vacs show that these two sampling techniques are reproducible. Paired *t* test results show that ATV sampling is somewhat more reproducible than TTV; ATV paired samples were statistically the same 100% of the time, whereas TTV paired samples were statistically the same 76.9% of the time. Bottle-Vacs are an easy-to-use field sampler for collection of whole-air grab samples that can be used by building occupants and air quality sampling professionals. The reusability of the device makes this an economical alternative to certain air sampling techniques such as badges or sorbent tube sampling. The ease of cleaning and preparing the bottles can increase the efficiency of any chemical air sampling campaign.

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