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Occupational exposure and health risks of volatile organic compounds of hotel housekeepers: Field measurements of exposure and health risks

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Abstract

Hotel housekeepers represent a large, low-income, predominantly minority, and high-risk workforce. Little is known about their exposure to chemicals, including volatile organic compounds (VOCs). This study evaluates VOC exposures of housekeepers, sources and factors affecting VOC levels, and provides preliminary estimates of VOC-related health risks. We utilized indoor and personal sampling at two hotels, assessed ventilation, and characterized the VOC composition of cleaning agents. Personal sampling of hotel staff showed a total target VOC concentration of 57 ± 36 $\mu g/m^3$ (mean ± SD), about twice that of indoor samples. VOCs of greatest health significance included chloroform and formaldehyde. Several workers had exposure to alkanes that could cause non-cancer effects. VOC levels were negatively correlated with estimated air change rates. The composition and concentrations of the tested products and air samples helped identify possible emission sources, which included building sources (for formaldehyde), disinfection by-products in the laundry room, and cleaning products. VOC levels and the derived health risks in this study were at the lower range found in the US buildings. The excess lifetime cancer risk (average of 4.1×10^{-5}) still indicates a need to lower exposure by reducing or removing toxic constituents, especially formaldehyde, or by increasing ventilation rates.

KEYWORDS

exposure, formaldehyde, health risk, hotel housekeeper, personal samples, volatile organic compounds

1 | INTRODUCTION

Hotel housekeepers are the largest workforce in the hospitality industry, which is the third largest industry in the United States with 1.8 million workers.[1] Hotel housekeepers represent a low-income, minority, and high-risk group that has garnered little attention. Hotel housekeeping is a low-wage occupation, with a mean hourly wage of \$12.30.[1] Most hotel housekeepers are immigrant women, people of color, and contingent workers.[2,3] Hotel housekeepers have been identified as a high priority at-risk group in the US National Institute for Occupational Safety and Health (NIOSH) Total Worker Health initiative.[4] Improving these workers' exposure, safety and health aligns with priorities of the NIOSH and of the US Department of Health and Human Services.[5,6] The nature of the hotel housekeepers' job tasks, workload, and work intensity increase exposure to physical (back injuries and sprains), chemical (concentrated cleaning products and fragranced products), biological (blood, body fluids, and microbe), and psychosocial (low respect and discrimination) hazards.[7,8] Relatively little has been reported regarding exposures of these workers, particularly to volatile organic compounds (VOCs), the focus of the present work.

Cleaning and fragrance products contain many VOCs, such as benzene, chlorobenzene, chloroform, 1,4-dioxane, ethylbenzene, 1,1-dichloroethane, 1,2-dichloropropane, carbon tetrachloride, trichloroethene, bromodichloromethane, 1,2-dichlorobenzene, and 1,3-dichlorobenzene.[9,10] In a preliminary study, we found that cleaning products used in local hotels contained these and other VOCs, for example, toluene, ethylbenzene, xylene, styrene, α-pinene, n-decane, p-isopropyl toluene, limonene, nonanal, and n-dodecane. Several of these compounds have known or suspected adverse health effects, for example, irritation to eyes, skin, and the respiratory system; damage to the liver and kidney; reproductive effects; and carcinogenicity.[11,12] Unsaturated VOCs (eg, terpenes) can react with ozone in air to generate secondary pollutants, such as formaldehyde and acetaldehyde, free radicals, and ultrafine particles[13] that also pose health risks.[14] Epidemiological studies suggest that exposure to cleaning products can be associated with the development and/or exacerbation of respiratory symptoms and asthma.[15-18] We also note that the full chemical composition of cleaning products generally is not listed on product labels. Chemical disclosure is not required for the fragrances used in many products, which may be composed of mixtures of dozens to hundreds of chemicals.[19-21]

Volatile organic compound levels in hotels have been reported in a few studies,[22-24] but information regarding inhalation exposure of hotel workers is missing. This omission is important since personal measurements typically exceed levels measured using indoor or area sampling; in hotels, this may result due to housekeepers' close and direct contact with cleaning agents.[25] Thus, personal measurement data are needed to evaluate exposures and health risks of this vulnerable workgroup. The objectives of this study are to determine VOC exposure during hotel housekeepers' daily work, to assess VOC sources and factors governing exposure, and to provide a preliminary estimate of non-cancer and cancer risks (CRs) for this population.

Practical Implications

- Volatile organic compound (VOC) levels using personal measurements were nearly twice that of the indoor measurements, showing the need to utilize personal sampling when assessing occupational exposure.
- Hotel housekeepers in the two studied hotels were exposed to low levels of VOCs during work, which also derived low health risks. VOC exposure may not be a priority issue for hotel workers in this study.
- The estimated excess lifetime cancer risk of hotel workers was mainly from formaldehyde. Measures to decrease and potentially eliminate exposures would reduce this risk.
- Volatile organic compounds compositions of the tested products and indoor air suggested contributions from several indoor emission sources, for example, cleaning agents were a potential source of benzene, toluene, ethylbenzene, and xylene, although at low concentrations, and bleach products were a source of chloroform. Reducing or removing the toxic constituents in these products will help protect housekeepers' health.
- The negative correlation between VOC levels and air change rates suggests the significance of indoor sources, but the low VOC levels demonstrate that adequate ventilation can keep concentrations low.

2 | METHODS

2.1 | Sampling sites and population recruitment

We recruited workers in hotels located in Michigan, USA, that were previously studied by one of the authors (Rosemberg).[26,27] We first asked hotel managers about their interest in participating in this study. For the two hotels that responded positively, we conducted field sampling during which we recruited on-duty housekeepers who met the following inclusion criteria: (a) employed as a hotel housekeeper; (b) performed housekeeping or other work including contact with cleaning products; (c) aged at least 18 years; and (d) able to provide verbal and written consent in English or Spanish. A Spanish-English translator was hired to assist when Spanish-speaking hotel workers were recruited. We also recruited hotel office workers to provide a comparison with hotel housekeepers. As an incentive, $25 was paid to each participant per sampling day. Written informed consent in Spanish or English was obtained from all participants, and study protocols, consent forms, and other study aspects were approved by the University of Michigan IRB office.

Walkthrough inspections of the hotels were completed in which we measured room volumes and noted building, room, and mechanical system features. Both hotels were designated “smoke-free” hotels, but several guest rooms smelled of tobacco after occupancy, and several workers smoked outdoors during their break. Additional characteristics of the studied hotels are described in Section 3.1.

We conducted sampling in three seasons (winter, spring, and summer). At each visit, a brief survey was administered to each housekeeper. Survey responses were used to place individuals into one of four groups: room cleaners, laundry workers, maintenance, and office workers.

2.2 | Personal, indoor, outdoor, and product sampling

Personal, indoor, and outdoor samples were used to monitor air quality and assess inhalation exposure. Personal samples (near or in the breathing zone) were collected for all participants while performing normal daily work using passive samplers, which consisted of 10-cm-long stainless tubes packed with 60/80 mesh Tenax GR (Scientific Instrument Services, Inc.) with a 0.5 cm diffusion gap. Tubes were pinned to shirts or blouse collars (see Figure S1). Indoor samples (Figure S1) were collected in the hotel lobbies, break rooms, laundry rooms, and guest rooms. These samplers were mounted on stands at breathing zone height (~1.5 m) and also used passive sampling. The selected guest rooms had been occupied the previous night, but were empty and scheduled to be cleaned on the sampling day. Outdoor samples were also collected during the study period.

Outdoor, indoor, and personal sampling was conducted simultaneously at each hotel while staff performed routine work. As examples, housekeepers cleaned rooms using detergents, cleaning products, and bleaches; laundry workers collected unwashed items throughout the hotel and used cleaning agents and bleaches in the laundry to wash and dry towels, sheets, etc.; maintenance workers checked, cleaned, and performed maintenance on various items throughout the hotel using lubricants, polishes, and other materials; and office staff mainly stayed in the lobby, office, and break room, but left occasionally to supervise room cleaning, fold clean towels, or perform light maintenance.

The duration of sampling events ranged from 6 to 9 hours; actual times were recorded. We collected a total of 23 personal samples (Hotel 1: three office workers, two laundry workers, 13 room cleaners, one maintenance worker; Hotel 2: one office worker, three room cleaners), 12 indoor samples (three lobby samples, three break room samples, three guest room samples, and three laundry room samples), and two outdoor samples. Due to a sampling error, an indoor sample (lobby) and a personal sample (office worker) were excluded.

Formaldehyde was monitored every 30 minutes using a colorimetric/photoelectric sensor (FM-801; GrayWolf Sensing Solutions). This instrument has a limit of detection (LOD) of 6 $\mu g/m^3$. Undetectable values were set to one-half of the LOD. Formaldehyde was monitored in the break and laundry rooms.

Temperature, relative humidity (RH), and carbon dioxide (CO_2) were monitored outdoors and in the break rooms, guest rooms, and laundry rooms using integrated loggers (HOBO MX CO_2 Data Logger; Onset Computer Corporation). These loggers were placed near the VOC stands and away from direct sunlight and obtained continuous 1-minute measurements simultaneously with the VOC samples. Temperature and RH are important comfort variables; temperature is also used to adjust the calculated sampler uptake rate; and CO_2 is an indicator of air change (see below). The loggers were equilibrated to ambient air in a traffic-free area, and CO_2 levels were manually set to 400 ppm prior to sampling.

Samples of all cleaning products used at Hotel 1 (except bleach) were collected for VOC analyses. This included three laundry products (detergent, booster, and fabric softener), a floor cleaner, a dust cleaner, a glass cleaner, and a smoke remover. At Hotel 1, laundry products were stored in the laundry room; other cleaning products were stored in a cabinet in the break room. These products were sampled using purge and trap methods as follows. A 100 μL aliquot of each product was transferred to a 40-mL glass vial, which was immediately sealed using a Teflon septum and a screw-on cap. After heating to 60°C for 10 minutes, pure nitrogen gas was purged into the liquid via a needle inserted through the septum for 30 minutes at 33 mL/min. Flow exiting the vial passed through a 10-cm–long stainless-steel adsorbent sampling tube, which was equipped with a needle inlet that also pierced the septum. The vial was maintained at 60°C throughout sampling. Tubes were packed with 150 mg anhydrous sodium sulfate (Fisher Scientific) to trap water vapor, followed by 160 mg of Tenax GR (Scientific Instrument Services, Inc.) to collect target chemicals. After sampling, the sodium sulfate was removed from the adsorbent tube, which was then capped until analysis. The purge duration and other method parameters were optimized to collect at least 90% of VOCs present in the samples, as determined in repeated (back-to-back) tests of the same sample.

2.3 | VOCs analysis, calibration, and quality control

After sampling at the hotels, VOC tubes were returned to the laboratory, refrigerated, and analyzed within 1 week. For analysis, tubes were injected with internal standards (fluorobenzene, *p*-bromofluorobenzene, and 1,2-dichlorobenzene-d_4) and then loaded into a short-path automated thermal desorption system (Scientific Instrument Services, Inc.). The system was coupled to a (GC-MS, Model 6890/5973; Agilent Technologies) equipped with a cryotrap/focuser (−140°C to focus, 250°C to inject).[28] Chromatographic separation was achieved using a capillary column (DB-VRX, 60 m × 0.25 mm, 1.4 μm film thickness; Agilent Technologies). The GC temperature program was as follows: 45°C and hold for 10 minutes, ramp at 8°C/min to 140°C and hold for 10 minutes, and ramp at 30°C/min to 225°C and hold for 13 minutes. The MS detector, transfer line, ion source, and quadrupole temperatures were 250, 300, 230, and 150°C, respectively. The MS was operated in scan mode from 27 to 270 atomic mass unit. Peak areas were extracted by a ChemStation macro program (G1701BA version B.01.00; Agilent Technologies), adjusted for internal standards, and transferred to a spreadsheet. Analyte masses (ng) were converted to concentrations ($\mu g/m^3$) by dividing by the calculated sampling volume (m^3, determined as the diffusion coefficient of the chemical × porosity of diffusion medium × tortuosity of diffusion medium × diffusion area × sampling time/diffusion distance).[29-31] Sampling protocols, including tube preparation, transport, storage, and analysis, are detailed elsewhere.[29,32,33]

Samples were analyzed for 98 target VOCs. All standards were purchased from MilliporeSigma as mixtures (four mixture standards for 60 target VOCs and one mixture for three internal standards) or as neat compounds (28 target VOCs). Stock solutions (2000 μg/mL and 200 μg/mL) were prepared in methanol; standard solutions for calibrations (0.5, 1.5, 5, 15, 50 μg/mL) were prepared in pentane, except for the four ketones in methanol. Multipoint calibrations (1, 3, 10, 30, and 100 ng) were performed. Recovery rates for most compounds ranged between 80% and 120%. Method detection limits (MDLs), determined as the standard deviation of seven replicate low concentration injections multiplied by 3.707,[34] ranged from 0.02 to 2.5 μg/m^3. Table S1 lists the target VOCs, MDLs, internal standards, and detection frequencies. Results below MDL were set to 0 and shown as "<MDL." The total target VOC (TTVOC) concentration was determined as the sum of target VOC concentrations excluding formaldehyde.

Field blanks and duplicates, representing about 10% of samples, were utilized during each field sampling day. Laboratory blanks and duplicates (43% of samples) were also obtained when testing the cleaning products. The coefficient of variation (COV) of true duplicates averaged 39% across all analytes detected, and the COV was 22% for analytes detected at concentrations above 5 μg/m^3. Duplicates were averaged. A freshly loaded adsorbent tube injected with 10 ng of standards was analyzed daily, and differences between the daily checks and calibration results were within 30%. Trace level contamination (<8 ng) was detected in blanks for 10 compounds (methylene chloride, hexane, benzene, toluene, hexanal, ethylbenzene, *p*-, *m*-xylene, styrene, nonanal, and naphthalene); blank-corrected results were used for these compounds.

2.4 | Exposure and health risk

A preliminary or screening level evaluation of health risks from VOC exposure was conducted. Assuming a 40-hour work week, the noncancer hazard ratio (HR) and CR estimates during working years were calculated as:

$$\text{Hazard ratio} = C_i \times \frac{40\,\text{h/wk}/168\,\text{h/wk}}{\text{RfC}}, \tag{1}$$

$$\text{Cancer risk} = C_i \times \frac{40\,\text{h/wk}}{168\,\text{h/wk}} \times \text{UR}, \tag{2}$$

where C_i is the concentration (μg/m^3) of individual VOC; RfC is the reference concentration (μg/m^3) of individual VOCs; and UR is the unit risk (m^3/μg) of individual VOCs. Parameters including the RfC and UR values (Table S2) were obtained from the US Environmental Protection Agency (EPA)[35] and the Michigan Department of Environment, Great Lakes and Energy.[36] Concentrations monitored in personal samples were used for C_i; for formaldehyde, concentrations in laundry and break rooms were used to represent personal measurements of laundry workers and other workers, respectively.

2.5 | Data analysis

Air change rates (ACRs) were estimated for the break, guest, and laundry rooms using CO_2 as a "natural" tracer gas and the decay method.[37,38] The CO_2 concentration of replacement air was set to the measured outdoor level (399-404 ppm). Multiple decay curves of CO_2 levels were available for each space. We used as many decay curves as possible (at least two curves) for each space, selecting curves that had at least a 100 ppm change and that followed (at least roughly) the expected declining exponential trend. ACR estimates were estimated by minimizing residuals (using a nonlinear least-squares estimator) and then averaging among the estimates for each space.

Descriptive statistics (eg, means, standard deviations) were calculated for each data type. Differences were evaluated using the Mann-Whitney *U* for two samples and the Kruskal-Wallis *H* for multiple comparisons, both with two-sided statistical tests and a significance level of .05. Associations between ACRs, temperatures, and indoor TTVOC concentrations were quantified using Spearman's correlation coefficients. A principal component analysis (PCA) was performed to identify potential VOC sources using data from Hotel 1. Data were analyzed using SPSS (SPSS, Inc.) and R version 3.5.2 (R Core Team, 2019).[39]

3 | RESULTS

3.1 | Hotel and population characteristic

Hotel 1 was studied in January, April, and June of 2019. This one-floor motel has 107 rooms and is in a suburban location, about 200 m from a busy road and 500 m from a highway. It was built in 1993, and a renovation was completed in 2012. All spaces, including lobby, office, break, laundry, and guest rooms, were mechanically ventilated and used separate and independent unit ventilators that provided heating, cooling, and exchange with outdoor air. The break room for workers was connected to the lobby and office. Laundry room and guest rooms were all independent and separate from the lobby building. Only a few windows were openable, and these were rarely opened (none were observed open during the study). In the laundry room, dryers were operating only in the winter sampling. Hotel occupancy can vary widely, and staffing is adjusted to meet demand. Typically, staff include one to two office workers and five to seven hotel housekeepers (including one supervisor and one laundry worker). Housekeepers work for 3-8 h/d, depending on the workload, and each cleans an average of 14 ± 6 guest rooms daily. Cleaning time requires 20-30 minutes per room. The housekeepers at this hotel were 43% female, 57% individuals of color, and 14% immigrants. At this hotel, office workers sometimes assist with housekeeping, for example, folding clean towels, supervising room cleaning, and performing light maintenance. We obtained outdoor, indoor, and personal VOC samples, monitored temperature, RH, CO_2, formaldehyde, and collected samples of seven cleaning products for VOC compositional analysis.

Hotel 2 was studied in June 2019. This two-story building has 125 rooms and is located on a busy road (about 5 m distant) in a suburban area. It uses a central mechanical system for temperature control and ventilation. Housekeepers have relatively flexible working hours (to try to accommodate their personal schedules) and typically work 6-9 hours daily. Cleaning time is approximately 30 minutes per room. The four study participants at this hotel were 100% female, 75% persons of color, and 50% immigrants.

3.2 | VOC levels in outdoor, indoor, and personal samples

Total target VOC levels provide a summary indicator of VOC concentrations, although they give little indication of potential health impacts given that toxicities of individual compounds vary considerably. Table 1 summarizes TTVOC levels in outdoor, indoor (in rooms), and personal (worker) samples. For the indoor samples, TTVOC levels averaged 28 ± 15 μg/m^3 and varied seasonally (P = .06) from 19 ± 2 μg/m^3 in spring to 43 ± 24 μg/m^3 in summer. TTVOC levels did not vary significantly across rooms (P = .8), and outdoor levels were low, frequently below MDLs. For the personal samples, TTVOC levels averaged 57 ± 36 μg/m^3, nearly twice the indoor measurements (P = .008). TTVOC levels did not vary by worker group (P = .8), season (P = .4), or hotel (P = .2).

We detected 35 of the 98 target VOCs in the hotels, including aromatics, halohydrocarbons, esters, ketones, aldehydes, alkanes, and terpenes (Table S1). Mean concentrations of individual VOCs are summarized in Table S3, and Figure 1 depicts VOC levels in outdoor, indoor, and personal samples by compound class. (Since formaldehyde was not measured at all sites and seasons, it is not included in Table S3 and Figure 1.) Selected VOCs are discussed below.

Among the target VOCs, alkanes often had the highest concentrations. In the break room, alkane levels were slightly higher than levels elsewhere (22 ± 17 μg/m^3 vs 6.2 ± 6.0 μg/m^3, P = .09), largely due to *n*-tetradecane (11 μg/m^3 vs 0.8 μg/m^3, P < .05). Office workers, who frequented the break room, also had higher personal measurements of n-tetradecane than the housekeepers (7.2 ± 4.1 μg/m^3 vs 2.0 ± 3.8 μg/m^3, P = .01). Maintenance workers had higher personal concentrations of *n*-nonane (24 μg/m^3) and *n*-undecane (8.3 μg/m^3) than other workers (0.5 and 0.1 μg/m^3, respectively, P = 0.09), possibly reflecting use of lubricants.

Aromatic VOCs had lower levels in the lobby than other indoor sites (0.9 ± 0.3 μg/m^3 vs 3.9 ± 3.2 μg/m^3, P = .07), and laundry workers had the highest personal measurements among hotel workers (8.6 ± 0.8 μg/m^3 vs 3.7 ± 2.3 μg/m^3, P = .02). Levels of the BTEX compounds (benzene, toluene, ethylbenzene, xylene) varied seasonally in indoor samples (P = .09) and were higher in summer (6.0 ± 3.9 μg/m^3) than in other seasons (1.9 ± 1.6 μg/m^3, P < .05). BTEX levels were higher in guest and laundry rooms (4.4 ± 3.3 μg/m^3) and lower in the lobby (0.7 ± 0.05 μg/m^3). Laundry workers also had personal measurements of BTEX compounds (8.2 ± 1.4 μg/m^3) that exceeded those of other workers (3.4 ± 2.1 μg/m^3; P = .02). Toluene was the dominant BTEX component (6.6 ± 3.7 μg/m^3 for laundry workers), and this compound was found in most indoor and personal samples (both 73%); a laundry worker had the highest personal measurement (9.2 μg/m^3). Benzene was found in most indoor and personal samples (91% and 82%), and a room cleaner had the highest personal measurement (3.0 μg/m^3).

Halohydrocarbons were found in most of the personal samples (except the maintenance workers). Methylene chloride was found in all personal and lobby samples in winter (average of 7.5 ± 2.5 μg/m^3 among housekeepers), and office workers had the highest personal concentrations, 22 μg/m^3, just similar to the lobby level (28 μg/m^3). Carbon tetrachloride was found only in one room cleaner sample, 2.0 μg/m^3 (the global background level is 0.6 μg/m^3, below the MDL

TABLE 1 Means and standard deviations of TTVOCs (μg/m^3, formaldehyde excluded) of outdoor, indoor, and personal samples in three seasons

	Winter		Spring		Summer		Total	
Site or population	**N**	**TTVOCs**	**N**	**TTVOCs**	**N**	**TTVOCs**	**N**	**TTVOCs**
Outdoor	0	—	1	2.4	1	<MDL	2	1.2
Indoor								
Lobby	1	29.4	1	19.4	0	—	2	24.4
Break room	1	31.0	1	16.8	1	70.4	3	39.4
Laundry room	1	17.7	1	20.6	1	25.2	3	21.2
Guest room	1	23.3	1	18.8	1	33.0	3	25.0
All indoor areas	4	25.3 ± 6.1	4	18.9 ± 1.6	3	42.9 ± 24.2	11	27.8 ± 15.2
Personal								
Office worker	1	117.8	1	56.6	1	43.3	3	72.6
Room cleaner	5	62.1 ± 39.5	5	55.5 ± 50.5	6	53.8 ± 38.4	16	56.9 ± 36.8
Laundry worker	1	71.0	0	—	1	12.3	2	41.6
Maintenance worker	0	—	0	—	1	43.6	1	43.6
All workers	7	71.3 ± 32.8	6	55.7 ± 45.1	9	46.9 ± 30.7	22	57.1 ± 35.5

Abbreviation: TTVOC, total target volatile organic compound.

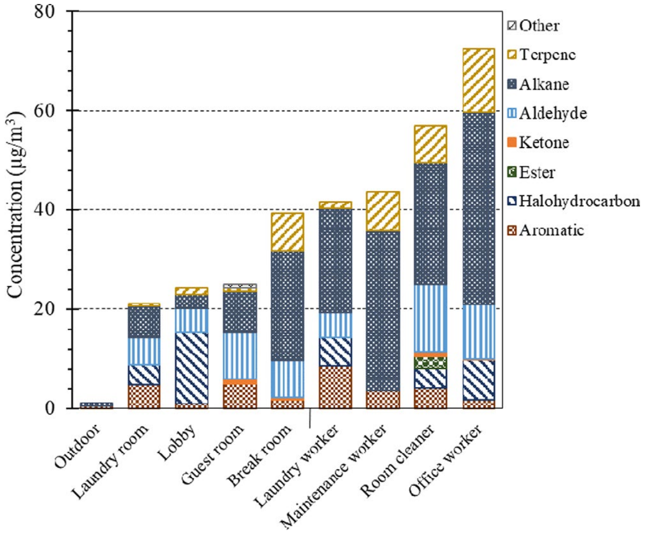

FIGURE 1 Volatile organic compound compositions of outdoor samples, indoor samples at different sites, and personal samples among different hotel workers in the study. All seasons are combined. Sample sizes: two outdoor samples, three laundry room samples, two lobby samples, three guest room samples, and three break room samples; two laundry worker samples, one maintenance worker sample, 16 room cleaner samples, and three office worker samples.

of 1.0 μg/m^3 in present study). 1,4-dichlorobenzene was found only in personal samples of room cleaners (average of 0.3 μg/m^3). Chloroform averaged 4.0 μg/m^3 in the laundry room, significantly higher than at other locations (average of 0.04 μg/m^3, $P = .02$), and personal measurements averaged 3.3 μg/m^3 among the laundry workers, although this was not significantly higher than other workers.

Formaldehyde, a toxic aldehyde, averaged 10 ± 6 and 14 ± 6 μg/m^3 in the break and laundry rooms, respectively. Several other aldehydes were found at higher concentrations, and several were found only among the room cleaners and guest rooms (Table S3). Hexanal was found in nine room cleaner samples and one laundry worker sample, mostly during winter sampling. Also in winter, hexanal concentrations of the laundry worker were lower than room cleaners (1.7 μg/m^3 vs 2.7 ± 0.9 μg/m^3). Among personal samples, heptanal and octanal were detected in only room cleaners, averaging 0.8 and 1.5 μg/m^3, respectively. Pentanal was found in all guest rooms, averaging 4.4 ± 2.7 μg/m^3, significantly higher than other indoor sites (1.0 μg/m^3, $P < .05$). Hexanal was found in two guest room samples and two laundry room samples; the level in the guest rooms was higher than in the laundry rooms.

Among the terpenoid VOCs, limonene and α-pinene were found in most samples, and personal levels were considerably higher than the indoor samples. Terpenes averaged 7.5 ± 6.7 μg/m^3 in the break room, slightly higher than at other indoor sites (0.9 ± 1.0 μg/m^3, $P = .09$). Office workers, who spent time mainly in the lobby, office, and break rooms, had slightly higher personal concentrations of limonene than housekeepers (12 ± 9 μg/m^3 vs 5.7 ± 8.4 μg/m^3, $P = .07$); this may reflect the storage of cleaning products and folding of laundry in the break room. The maintenance workers had higher personal concentrations of α-pinene than other workers (7.8 μg/m^3 vs 0.9 μg/m^3, $P = .09$).

Principal component analysis results obtained using guest room and room cleaner VOC levels in Hotel 1 (Table S4) yielded nine factors and many overlapping VOC groups, reflecting the multiple emission sources in hotels. Factor 1 had high loadings of heptanal, octanal, nonanal (aldehydes), limonene (terpene), and *n*-tetradecane and *n*-pentadecane (alkanes). Based on the composition and concentrations of cleaning products, this factor likely reflected emission from the multiple cleaning products used. Factor 2 had high loadings of chloroform and carbon tetrachloride, reflecting contributions from bleach. Most of the other factors had a single dominant VOC. The PCA results are also limited by the sample size.

Overall, VOC levels in personal samples exceeded levels in the indoor samples. The similarity of VOC compositions in the break room to personal samples suggests that most workers spent at least some time in the break room (Figure 1).

3.3 | CO_2 and ACRs

Indoor CO_2 concentrations in Hotel 1 averaged 604 ± 196 ppm (Table 2) and levels depended on the number of occupants, ventilation conditions, and other factors. The break room, which usually had the most occupants, had the highest average CO_2 level (716 ± 239 ppm) compared to the laundry (550 ± 125 ppm) and guest rooms (491 ± 46 ppm). Outdoor CO_2 levels averaged 414 ± 27 ppm. Based on the decay models, ACRs in guest rooms averaged 1.5 h^{-1} and did not vary by season. The ACR in the break room was higher, 2.8 h^{-1}, and the most variable (COV = 57% in summer). The ACR in the laundry room was similar, 2.6 h^{-1}, and changed seasonally (lower in summer compared to winter or spring, $P = .04$). The ACRs are approximate for several reasons, for example, measurements can be affected by changes in occupancy, heating, ventilation, and air conditionning (HVAC) system operation, opening or closing of doors, and the weather during the measurement period. To our knowledge, HVAC systems in the rooms were continuously operating during the measurements. In addition, ACRs derived using CO_2 may incompletely account for interzonal flows (from other interior spaces); this is unlikely to affect estimates for the guest and laundry rooms; however, since the break room door was usually opened to the lobby, break room ACR estimates may be affected. ACRs were negatively associated with TTVOC levels (Figure 2; $P = .01$; this excludes one summer observation in the break room that appears to be an outlier). This association confirms the presence of indoor VOC sources (outdoor sources would not display this relationship), and it suggests the importance of appropriate ventilation rates.

3.4 | VOCs in products

We detected 38 VOCs in the three laundry products tested. TTVOC concentrations in detergent, booster, and fabric softener were 96,

TABLE 2 Size, temperature (mean and range of 1-min measurement), relative humidity, and CO_2 (mean and range) in different locations of Hotel 1 in three seasons

Location	Size (m^3)	Temperature (°C)			Relative humidity (%)			CO_2 (ppm)		
		Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer
Outdoor	—	−1[a]	16 (12-19)	33 (27-36)	—	25 (19-32)	53 (43-75)	—	428 (377-474)	399 (329-465)
Lobby	—	25 (25-25)	22 (21-23)	24 (23-25)	15 (15-15)	24 (22-26)	54 (50-57)	—	—	—
Break Room	35	23 (22-23)	20 (18-23)	22 (21-25)	23 (19-26)	27 (24-29)	64 (52-70)	1038 (651-1584)	569 (448-1064)	638 (513-1030)
Laundry Room	95	19 (16-21)	18 (13-25)	27 (24-30)	24 (22-32)	24 (17-31)	59 (45-77)	689 (510-1304)	454 (372-632)	552 (394-660)
Guest Room	55	20 (16-21)	19 (19-19)	27 (25-28)	19 (18-23)	45 (36-47)	68 (63-71)	525 (486-588)	—	463 (405-582)

[a] From meteorological record.

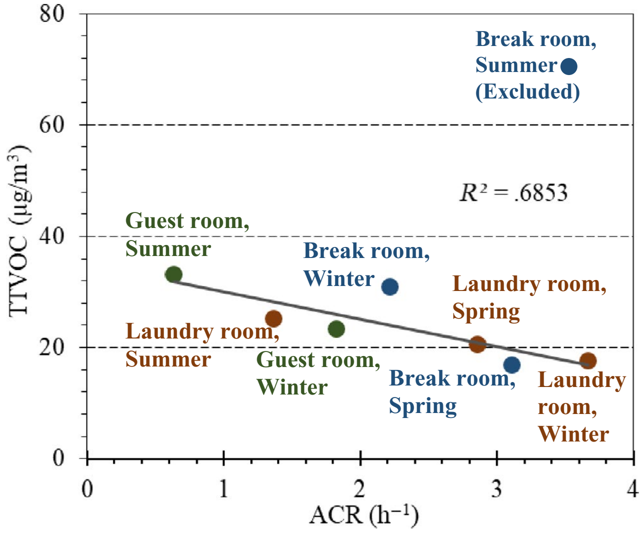

FIGURE 2 Association between air change rates (ACRs) and concentrations of total target volatile organic compound (TTVOCs) in Hotel 1.

0.1, and 35 μg/mL, respectively. The dominant VOCs in these products were alkanes (detergent), terpenes (fabric softener), and aldehydes (booster; Table S5 and Figure S2). The most prevalent VOCs in detergent were alkanes (87 μg/mL, primarily *n*-tetradecane), which is consistent with the composition of personal samples of laundry workers (Figure 1). Several halohydrocarbons were detected in the fabric softener and booster (0.09 and 0.01 μg/mL), but not in the detergent. Chloroform was not detected in the laundry products; however, this is a common by-product of bleach, which is used liberally in hotels[10,40]; chloroform is also a water disinfection by-product that is volatilized from tap water, particularly from showers and dishwashers.[41,42]

A total of 31 VOCs was detected in the four cleaning products, and TTVOC levels were 0.3, 1.0, 0.2, and 69 μg/mL in the dust, floor, glass, and smoke cleaners, respectively. Terpenes (mainly limonene) were the dominant VOC in dust cleaners (0.1 μg/mL), floor cleaners (0.7 μg/mL), and smoke remover (64 μg/mL). Alkanes were the dominant (79%) VOC in the glass cleaner (mainly *n*-hexadecane; Figure S2 and Table S5).

3.5 | Comfort

In Hotel 1, temperatures mostly remained within the comfort range (20-27°C).[43] Temperatures in the connected lobby and break rooms were similar and did not vary seasonally; temperatures in the laundry and guest rooms, which are separate and independent spaces, were correlated with outdoor temperatures (Table 2). In contrast, the RH was not consistently maintained in the comfort range (30%-60%),[43] peaking to 63 ± 7% in summer, and falling to 21 ± 3% in the winter heating season. Indoor temperatures and TTVOC concentrations were positively correlated (Figure S3, $P = .02$).

3.6 | Health risks

The estimated excess CR due to VOC exposure averaged 4.1×10^{-5} among the workers; laundry workers had the highest CR ($6.4 \pm 2.8 \times 10^{-5}$, $P = .05$). Most (>68%) of the CR is due to formaldehyde, followed by chloroform and benzene (Table 3).

Hazard ratios, which reflect the possibility of non-cancer health effects due to VOC exposure, averaged 0.3 ± 0.06 among workers in the study; laundry and maintenance workers had slightly higher HRs (0.4 and 0.5, respectively; Table 3). For maintenance workers, formaldehyde (46%) and *n*-nonane (54%) were the largest contributors to the HR. For other hotel workers, most (>84%) of the non-CR was from formaldehyde. The relatively high HR and low CR for the maintenance worker resulted from *n*-nonane (24 μg/m^3), which is associated with eye, skin, and respiratory tract irritation and central nervous system effects, but not cancer.[44]

4 | DISCUSSION

4.1 | VOC levels in the literature

While VOC levels have been characterized in many buildings, levels in hotels and exposures among hotel housekeepers have received little attention. Available hotel studies are summarized in Table S6. Given the differences among studies, including the nature of sampling (eg, indoor vs personal samples), testing methods, and the target VOCs measured,[45] semi-quantitative comparisons are most informative. Several studies conducted in industrial areas in China have reported high indoor BTEX and TTVOC levels (even though relatively few target VOCs were included) as well as high outdoor levels (averaging 420 μg/m^3).[22-24] In hostels in New Delhi, India, TTVOC levels (11 target compounds) averaged 120 μg/m^3.[46] In the United States, the only hotel study identified sampled exhaust air in a large atrium hotel and reported TTVOC levels of 1125 μg/m^3 (27 compounds, aldehydes excluded) and toluene levels of 6.2 μg/m^3.[47] However, the exhaust air included bathroom exhaust, which may be atypical of indoor levels.

Study results may be compared to indoor measurements in other types of spaces, such as residences and office.[48] For example, in 126 homes in Detroit, Michigan, USA, TTVOC concentrations averaged 150 μg/m^3 (range: 14-2274 μg/m^3).[31] In offices in California, levels of individual VOCs ranged from non-detect to over 1000 μg/m^3.[49,50] Formaldehyde has been measured in many buildings with typical (eg, mean) levels of ~20 μg/m^3 in US stores, restaurants, and residences, and higher levels, ~60 μg/m^3, in mobile homes.[51] These measurements frequently exceed the US EPA reference value of 9.8 μg/m^3 (non-cancer RfC for chronic inhalation exposure).[35] Much higher formaldehyde levels have been reported in Chinese hotel rooms, for example, 60-290 μg/m^3,[52] 114 μg/m^3 in new hotels,[22] 140 μg/m^3 in newly furnished rooms, and 10 μg/m^3 in older rooms.[53] In the US hotel (exhaust air sample), formaldehyde averaged 28 μg/m^3.[47] In the present study, formaldehyde levels in the break and laundry rooms averaged 12 μg/m^3, at the lower range found in the US buildings.

Personal measurements in similar service industries (eg, retail stores, restaurants) are rare; thus, we compare indoor concentrations in these settings to our measurements. Measurements in 14 US retail stores[54] showed slightly higher levels of formaldehyde (averaging 18 ppb = 22 μg/m^3) and BTEX (9.5 ppb) than the present study (personal measurements of 12 and 4.0 μg/m^3, respectively); similar results were found in stores, restaurants, and transportation in Boston, USA, in 2006.[55] Restaurants had higher levels of BTEX and sometimes chloroform, especially near cooking stoves in dining areas, for example, at Korean barbeque restaurants.[55,56] Samples collected at 10 retail shops in a large shopping center from 2002 to 2004 had high levels of toluene and xylene (144 and 3.5 μg/m^3, respectively), but slightly lower levels of chloroform, methylene chloride, heptane, and hexane (0.5, 0.8, 1.8 and 3.2 μg/m^3) than the present study.[57] Personal samples of housekeepers at hospitals showed relatively low VOC concentrations (geometric mean of 16 ppb for 11 target VOCs).[58]

Overall, we found low VOC levels in the two hotels, for example, indoor and personal samples averaged 28 and 57 μg/m^3 for TTVOC, respectively; BTEX averaged 3.0 and 3.8 μg/m^3; and toluene averaged 1.7 and 2.3 μg/m^3. Formaldehyde concentrations were also relatively low, although they exceeded the US EPA reference value. Many of the target VOCs were undetected, either due to a lack of sources or due to somewhat high MDLs, largely caused by the relatively short sampling periods (6-9 hours) needed to match the housekeepers' schedules. In comparison with studies in US offices, we found similar levels of BTEX, styrene, and terpenes, somewhat lower formaldehyde levels, and higher chloroform levels, especially in laundry rooms. In comparison with retail and restaurant industries, hotel housekeepers had lower levels of formaldehyde and BTEX. The VOC measurements reflect both low outdoor concentrations, particularly in comparison with the hotel studies in China that were conducted in polluted industrial areas, as well as few strong indoor sources. VOC levels in the studied hotels reflect the buildings' age (26 years old), the lack of new furnishings and recent or ongoing renovation activities (last renovation was in 2012), and ACRs sufficient to dilute indoor emissions. VOC levels can increase considerably with new construction, certain building products and renovations.[53]

4.2 | VOC sources

Although VOC levels were not high, indoor levels exceeded outdoor levels and the negative association with ACRs indicates that VOCs primarily arose from indoor sources. Here, we discuss potential VOC sources in hotels.

As mentioned, alkanes were one of the dominant VOC groups in indoor and personal samples and a relatively large contributor (35%) in cleaning products. Most indoor and personal samples (91%-95%) contained alkanes, which averaged 33%-42% of TTVOC concentrations. All of the tested cleaning products contained alkanes with an

TABLE 3 Mean hazard ratios and cancer risks of exposure to individual VOCs among hotel workers.

	Hazard ratio				Cancer risk ($\times10^{-6}$)			
VOC	Office worker	Room cleaner	Laundry worker	Maintenance worker	Office worker	Room cleaner	Laundry worker	Maintenance worker
Aromatic								
Benzene	0.009	0.01	0.007		2.1	2.2	1.6	
Toluene	<0.0001	0.0001	0.0003	0.0002				
Ethylbenzene		<0.0001	0.0001			0.1	0.2	
p-, *m*-Xylene		0.0006	0.0006					
o-Xylene		0.0003	0.0004					
Styrene		<0.0001	0.0001			0.02	0.04	
p-Isopropyltoluene		0.006	0.004					
Halohydrocarbon								
Methylene chloride	0.003	0.001	0.0009		0.02	0.006	0.005	
Chloroform	0.001	0.003	0.008		2.9	6.4	18	
Carbon tetrachloride		0.0003				0.2		
1,4-Dichlorobenzene		0.0001				0.7		
Ester								
Ethyl acetate		0.007						
n-Butyl acetate		<0.0001						
Ketone								
2-Butanone	<0.0001	<0.0001						
Aldehyde								
Pentanal		0.0001	0.0003					
Formaldehyde	0.2	0.2	0.3	0.2	30	30	44	30
Alkane								
n-Hexane	0.007	0.005	0.007					
n-Heptane		0.003						
n-Nonane	0.004	0.007	0.003	0.28				
Terpene								
Limonene (R)-(+)	0.0004	0.0002	0.0001					
Total	0.3	0.3	0.4	0.5	35	40	64	30

Abbreviation: VOC, volatile organic compound.

average proportion of 35% (91% and 79% in the laundry detergent and glass cleaner, respectively). Break rooms and office workers had high levels of n-tetradecane, probably from the stacked clean towels and the laundry detergent. As shown in Table S5, the laundry detergent contained a high concentration of *n*-tetradecane. Alkanes are in numerous products used indoors, for example, paints, solvents, pesticides, oils, and lubricants; in addition, they are used in the production of detergents.[59-61]

Formaldehyde emissions from building materials and furnishings are well recognized.[62] Formaldehyde also is used in numerous products including paper, fabrics, and synthetic fibers.[63] In past decades, formaldehyde emissions have been reduced due to manufacturing changes and standards.[64,65] Still, the large amount of bedding and towels used in hotels that contain even low levels of formaldehyde will contribute to housekeeper exposures, although several washings are expected to substantially decrease emissions.[66] Formaldehyde is also a possible reaction product between terpenes in cleaning and laundry products and ozone[13]; however, airborne terpene levels were low in the study and no seasonal differences were observed (ozone increases in the summer). Additional studies are needed to verify formaldehyde sources in hotels.

Benzene, toluene, ethylbenzene, xylene compounds are often an indicator of combustion emissions and gasoline vapors, for example, traffic, gas stations, industry.[67,68] While the studied hotels were near busy roads and other VOC sources (eg, gas station ~200 m distant), outdoor VOC levels were low (eg, benzene levels did not exceed 0.8 $\mu g/m^3$), and no combustion sources in the studied hotels were observed. As noted, the hotels had "smoke-free" policies although room cleaners reported tobacco odors in some rooms, and some workers smoked outside during break time. We found no significant difference in BTEX concentrations among smoking and non-smoking workers, or between workers that reported exposure to passive smoke (cleaning rooms with tobacco odors) and others. The higher levels of BTEX compounds found in laundry and guest rooms, the higher personal concentrations of laundry workers, and the presence of BTEX compounds in cleaning products suggest that cleaning products are an important source of BTEX (especially toluene) in hotels.

Chloroform and carbon tetrachloride are the dominant halogenated VOCs formed by chlorine bleach.[10,69] A large amount of bleach was used for laundry and room cleaning, suggesting the importance of this source[10,69] and possibly tap water, which frequently contains chloroform as a disinfection by-product.[70] Chlorinated compounds include relatively non-polar solvents that are also found in cleansing agents,[71] as found in several cleaning products in this study (Table S5). While present in the laundry room at 4 μg/m^3, chloroform was not present in the laundry products, and chloroform levels in personal samples of the laundry workers were not significantly elevated, possibly because these workers did not remain in the laundry room as their work included collecting unwashed items in all rooms. Methylene chloride was not found in any cleaning products, but this compound was found in the lobby and in personal samples of office workers (often staying in the office and lobby). Methylene chloride sources include products such as paint stripper.[72]

Fragrances are widely used to mask unpleasant odors (including smoke) and to impart a “pleasing” aroma. Fragrances can contain hundreds of chemicals, some of which may induce adverse health effects, even those labeled as “organic,” “green,” or “all natural.”[73] Terpenes, for example, limonene and α-pinene, are abundant in laundry and cleaning products.[21,74-76] All cleaning products in this study contained terpenes, averaging 13 μg/mL (40% of TTVOCs); the smoke remover contained 64 μg/mL. Most (82%-86%) of the indoor and personal samples contained terpenes, with an average level of 2.7 and 7.7 μg/m^3, respectively. Terpenes were not detected in outdoor samples. Cleaning products were likely the major source of terpenes (Table S4).

4.3 | Factors influencing VOC level

Our results suggest several factors influencing VOC levels. The significant association between room temperature and indoor TTVOC level suggested the importance of seasonal factors and temperature, likely due to increased volatility. The importance of ACR was demonstrated by the strong negative association between ACRs and TTVOC concentrations (Figure 2). We estimated an average ACR of 2.5 h^{-1} (range: 0.6-3.7 h^{-1}), similar to previous studies.[22,77-79] Lower ACRs in summer, as reported elsewhere,[79] can result from the use of air conditioning, reduced HVAC fan speeds, smaller indoor-outdoor temperature gradients, and lower wind velocities. In hotels and many other buildings, ACRs depend on the design and operation of the mechanical systems, infiltration rates (which depend on indoor-outdoor temperature differences and wind speed[80]), building design, and other factors. In the guest and break rooms, ACRs did not vary by season and were likely governed by the HVAC system. However, in laundries, cloth dryers exhaust humid air and draw make-up air from the room, which can increase ACRs when the laundry is operating. In Hotel 1, the dryers operated only in the winter sampling period, when we determined a relatively high ACR of 3.7 h^{-1} (compared to 2.9 and 1.4 h^{-1} in spring and summer, respectively). VOC levels in hotels may be highest in summer due to increased volatility and lower ACRs. Still, the low VOC (and CO_2) levels found in the study hotels demonstrate the effectiveness of appropriate ventilation rates in minimizing exposure.

Personal samples had almost twice the concentrations of VOCs than the indoor samples. Personal samples are generally considered to be more representative of occupational exposure than indoor samples.[25] For housekeepers, such samples reflect the potential of closer contact with VOCs in cleaning products and other products. VOC patterns observed among both indoor and personal samples are not unique or distinctive since work tasks and work sites are dynamic and overlap, for example, laundry workers also collect items throughout the hotel, and office workers may assist with housekeeping (folding clean towels), provide supervision throughout the building, and perform light maintenance.

4.4 | Health risks

We present preliminary or screening level estimates of health risks that are attributable to VOC inhalation based on short-term measurements of a small number of hotel workers. While not necessarily representative of long-term exposures or a broader population, our data suggest several findings. Non-cancer risks were driven by n-nonane and formaldehyde, which are irritants to the eyes, mucous membranes, and upper respiratory tract.[61,81,82] Calculated HRs fall below one (range: 0.3-0.5), which suggest a low likelihood of adverse effects, although a HR threshold of 0.1 is sometimes used to provide an extra margin of safety.[83]

Cancer risks were driven by chloroform and formaldehyde. At high exposures (not found in this study), chloroform can cause central nervous system effects, respiratory depression, delayed hepatotoxicity,[84] kidney and liver damage, and reproductive effects.[85,86] Chloroform is classified as a likely human carcinogen by the US EPA[87] and as possibly carcinogenic to humans by the International Agency for Research on Cancer (IARC)[88]; it is associated with kidney, liver, and bladder tumors.[88,89] Formaldehyde is classified as a probable human carcinogen by the US EPA[90] and as a human carcinogen by the IARC[91,92]; it is associated with nasopharynx, sinonasal, and leukemia cancers.[93] Estimated lifetime risks for these chemicals, in the range of 3-44 × 10^{-6}, indicate a need to reduce exposures. This particularly applies to formaldehyde, which is a widespread indoor air pollutant affecting homes, schools, and many other environments.[94-96]

Workers in the studied hotels were exposed to low levels of VOCs, which resulted in low health risks from VOC exposure. In our small sample of hotels, this suggests that VOC exposure is not a priority issue for hotel housekeepers. However, conditions in the study hotels cannot be assumed to apply more broadly, and studies at additional hotels are needed to characterize chemical exposure in the large population of hotel housekeepers. In addition, we did find that CR exceeded recommended guidelines (1×10^{-6} of excess lifetime CR), largely due to formaldehyde, and that personal measurements were considerably higher than indoor measurements. Thus, we recommend estimating health risks based on personal sampling and accounting for low concentration but high toxicity VOCs like formaldehyde.

4.5 | Study strengths and limitations

The present study has several strengths. To our knowledge, it is the first study to provide comprehensive measurements of VOCs levels in US hotels. We contrasted indoor and personal samples, the latter which helps address a gap in understanding occupational exposures of hotel housekeepers, a vulnerable population. We included a wide range of VOCs, assessed ventilation rates, and performed a screening level risk assessment. This information allows practical and constructive recommendations that can improve working conditions of hotel housekeepers. We also evaluated several factors and emission sources that provided supporting information.

We recognized limitations due to the study's small sample size, which incompletely accounts for temporal and geographical variability; analyses of specific work sites or work groups (eg, maintenance workers) may be particularly hindered by this issue. A smaller set of formaldehyde measurements was obtained, which limited our ability to estimate distributions and analyze personal exposures; also, formaldehyde measurements may be underestimated due to the relatively high LOD (6 $\mu g/m^3$). Due to constraints including the hotel manager's decisions, repeated and seasonal measurements were not obtained in one hotel. The ACR estimates derived from CO_2 measurements are approximate, although the decay method can provide robust results. We did not evaluate occupational risks and hazards other than from VOC exposures; ergonomic and other concerns are also important. Studies at other hotels, including both new and old buildings and a range of locations, would increase the representativeness of findings and improve the understanding of occupational VOC exposures and other stressors experienced by housekeepers.

5 | CONCLUSIONS

Hotel housekeepers are a potentially susceptible and vulnerable population. In this study, we obtained indoor and personal measurements of VOCs at two hotels and evaluated potential sources and factors affecting concentrations. Concentrations measured using personal sampling were about twice those of the indoor sampling. Formaldehyde, chloroform, and several alkanes were the most significant VOCs from a health risk perspective. While indoor sources were identified, appropriate ventilation helped keep VOC concentrations and derived health risks low, and thus, VOC exposure may not be a priority occupational risk for hotel housekeepers in this study. Inhalation exposures can be further reduced by reducing or removing toxic constituents in cleaning products and other materials, and by increasing ACRs. Cleaning products (especially laundry products) contained a number of aromatic compounds, and the use of bleach was an important chloroform source. Formaldehyde, contributing over half of the health risk in this study, is a particular target for mitigation to protect hotel housekeepers' health.

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CONFLICT OF INTEREST

The authors declare no competing financial interest.

AUTHOR CONTRIBUTION

Nan Lin: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing-original draft (equal); Writing-review & editing (equal). **Marie-Anne Rosemberg:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing-review & editing (equal). **Wei Li:** Investigation (equal); Project administration (equal); Resources (equal); Writing-review & editing (equal). **Emily Meza-Wilson:** Investigation (equal); Writing-original draft (equal); Writing-review & editing (equal). **Christopher Godwin:** Methodology (equal); Writing-review & editing (equal). **Stuart Batterman:** Conceptualization (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing-original draft (equal); Writing-review & editing (equal).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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