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# Ventilation and posture effects on inhalation exposures to volatile cleaning ingredients in a simulated domestic worker cleaning environment

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## Abstract

Associations between cleaning chemical exposures and asthma have previously been identified in professional cleaners and healthcare workers. Domestic workers, including housecleaners and caregivers, may receive similar exposures but in residential environments with lower ventilation rates. Study objectives were to compare exposures to occupational exposure limits (OELs), to determine relative contributions from individual cleaning tasks to overall exposure, and to evaluate the effects of ventilation and posture on exposure. Airborne chemical concentrations of sprayed cleaning chemicals (acetic acid or ammonia) were measured during typical cleaning tasks in a simulated residential work environment. Whole-house cleaning exposures (18 cleaning tasks) were measured using integrated personal sampling methods. Individual task exposures were measured with a sampling line attached to subjects' breathing zones, with readings recorded by a ppbRAE monitor, equipped with a photoionization detector calibrated for ammonia and acetic acid measurements. Integrated sampling results indicated no exposures above OELs occurred, but 95th percentile air concentrations would require risk management decisions. Exposure reductions were observed with increased source distance, with lower exposures from mopping floors compared to kneeling. Exposure reductions were also observed for most but not all tasks when ventilation was used, with implications that alternative exposure reduction methods may be needed.

KEYWORDS

acetic acid, ammonia, exposure assessment, personal sampling, residential workplace, respiratory irritants

## 1 | INTRODUCTION

Despite reported associations between asthma and use of professional cleaning/disinfecting products,[1-10] exposure data for workers in cleaning professions such as domestic workers are sparse.[11] A causative link may be complicated by the complex nature of their work, involving multiple products containing complex chemical mixtures as well as other non-chemical factors. Domestic workers (DWs) are a generalized workforce that often perform residential cleaning tasks as part of their responsibilities and include nannies, housecleaners, and caregivers.[12] Multiple factors complicate the study of this unseen workgroup, including overlap of work classifications; for example, a caregiver and a home health aide may perform the same tasks in caring for a client, with one classified as a domestic worker and the other as a home care worker.[13] While cleaning chemical exposures may be expected for housecleaners and other domestic workers, recent surveys of home health aides (HHAs) indicate that they also have exposures to cleaning or disinfecting chemicals with multiple home visits (mean = 9.6 visits/week, SD = 9.7) during a typical workweek (mean = 25.5 hours/week, SD = 15.3).[12,14,15] However, occupational cleaning chemical exposures were not quantified in these studies.

Past exposure assessment studies have investigated common cleaning and disinfecting chemicals such as ammonia,[16] bleach or chlorine,[17] 2-butoxyethanol,[18,19] volatile organic compounds (VOCs),[20-23] and others.[24-26] However, exposures to other chemicals used in cleaning need to be characterized. For example, vinegar is often considered an environmentally friendly ingredient, with recipes for use available on the Internet.[27,28] Vinegar is often perceived as "safer" than traditional cleaning chemicals and is sometimes misrepresented as a "chemical-free" cleaner since it can be ingested.[29] The acetic acid in vinegar can evaporate, be inhaled, and act as an irritant,[30,31] as shown in a past study of a food processing facility using 4% acetic acid, where exposed workers demonstrated reduced spirometric performances.[32] Consumer-grade vinegar typically ranges in concentration from 4% to 8%, but published studies characterizing cleaning activities and associated exposures of domestic workers were not found in the literature.

Studies of cleaning chemical exposures have mostly focused on exposures occurring in hospital facilities or commercial buildings.[17-26] To date, relatively few studies have assessed exposures associated with cleaning chemical use in residential work environments.[1,16] One study reported exposures to chlorine (bleach) and ammonia in a group of ten professional house cleaners, with median exposures for both chemicals (0-0.4 ppm chlorine and 0.6-6.4 ppm ammonia) below 15-min short-term exposure limits (STELs), and peak concentrations (1.3 ppm chlorine, 50 ppm ammonia) often rising above the STEL concentrations.[1] While these occupational exposure data are useful, quantification of environmental factors producing those exposures would provide additional insights. Ammonia concentrations generated from simulated cleaning tasks were reported for three concentrations of ammonia, with the conclusion that typical use of ammonia cleaning products would not present significant risk to consumers unless unusual conditions such as spills arise.[16] This study suggests that a range of air concentrations are possible depending on concentration and use. For example, using NIOSH integrated methods, personal sampling results of 0.65 ppm for window cleaning and 10 ppm for bathroom cleaning and area sampling results of 9.1-13 ppm for bathroom cleaning when using 0.1% ammonia were reported.[16] However, exposure determinants potentially impacting these exposures were also not reported in this study.

Environmental conditions in the workplace play an important role in determining exposures. Hospital and commercial facilities often have ventilation systems that are continuously running to meet standards for indoor air quality. While the exposure data collected in those environments may be useful when comparing similar settings, the relevance to exposures in residences with different environmental conditions may be limited. Exposures in residential workplaces may be different from institutional buildings due to lower ventilation rates. The DW work environment is unique in that it has the potential to change with every home visited, and oversight and control of exposures may be less rigorous than with institutional settings. In addition to factors related to the built environment, since DWs are more likely to have many duties,[14,15] a specific focus on chemical safety training relevant to cleaning chemicals may be less structured than for full-time professional cleaning workers.

**Practical Implications**

This research provides exposure data for two cleaning chemicals in a residential work environment. While measured exposures were not above OELs for acetic acid or ammonia, they were in a range that may require risk management decisions. It was observed that use of ventilation reduced exposures for most but not all tasks, meaning that alternative control measures may need consideration in these environments. Posture differences (mopping vs kneeling to clean floors) also reduced exposures, possibly due to increased distance between subjects and the cleaned surfaces.

The overall goal of the current study was to measure the resultant exposures during simulated cleaning tasks in a home while accounting for underlying variables thought to influence breathing zone concentrations. The objectives were to (a) measure whole-house cleaning exposures for acetic acid and ammonia under real-world scenarios for comparison to occupational exposure limits (OELs), (b) evaluate individual cleaning tasks to determine their relative contributions to overall exposure, and (c) assess the influence of general ventilation and posture on breathing zone air concentrations.

## 2 | MATERIALS AND METHODS

Prior to the start of the project, a study protocol and consent form (Study ID 2017-0304) were prepared and reviewed by the University of Cincinnati (UC) Institutional Review Board (IRB) to ensure protection of human subjects performing cleaning tasks using chemicals with potential irritant health effects. Eight student subjects were recruited to complete cleaning tasks from late April-early June 2018 using solutions containing acetic acid (3%) or ammonia (0.1%). Preliminary screening excluded anyone with existing respiratory problems such as asthma. The study was designed to measure residential cleaning chemical exposures inside a two-bedroom residential space at Maple Knoll Village Innovation Collaboratory Smart House in Cincinnati, OH.

Building infiltration rates were reported as air changes per hour (ACH) from tracer gas experiments measuring the exponential concentration decay of $CO_2$[33,34] using a Q-Trak Indoor Air Quality Monitor 7575 (TSI Incorporated). Eight ACH measurements per room, four without ($ACH_0$) and four with mechanical ventilation ($ACH_1$), were performed over the 6 weeks of experiments during unoccupied times. Non-ventilated conditions were defined as mechanical ventilation off and windows closed. Mechanical ventilation use was defined as the forced air system fan on for the kitchen and bedroom and bathroom fans on for each bathroom, with exterior windows closed. More detailed descriptions of the Maple Knoll facility, rooms, tasks, and ACHs are provided in Tables S1-S2 and Figures S1A,B.

Ammonia and acetic acid were chosen as cleaning chemicals in this study because they both generate air concentrations from evaporation (not from chemical reactions like bleach), they have OELs for comparison with integrated sampling results, and they can be measured using photoionization (PID) monitors. The acetic acid cleaning solution was prepared by diluting cleaning vinegar (6% acidity) with tap water (50% vinegar: 50% water) according to an online homemade recipe.[27] This was also in the range of concentrations recommended on the label (1:32 dilution up to full strength). The ammonia solution was prepared by diluting a concentrated commercial cleaning solution with tap water (10% ammonia: 90% water), which was within the range of dilution directions provided on the label (1/32 dilution up to 1/8 dilution). To determine ammonia solution concentration, a sample was sent for analysis (ALS). Analysis using Method SM4500 produced results of 11 000 mg $NH_3$-N/L. Converting 11 000 mg to grams (11 g N as ammonia) and 1 L water to grams (1000 g water) yields a concentration of 1.1% ammonia (11/1000 or 0.011), corresponding to 1.1%. The final solution concentrations were calculated to be 3% acetic acid and 0.11% ammonia, which were applied to surfaces using a plastic spray bottle with an adjustable nozzle (Sprayco) placed on a coarse spray setting (between fine mist and stream).

## 2.1 | Whole-house cleaning

Two whole-house cleanings (one for acetic acid and one for ammonia) consisting of 18 tasks were completed with mechanical ventilation off and windows closed. Exposures were measured using integrated sampling methods, NIOSH 1603 for Acetic Acid[35] and NIOSH 6015 for Ammonia.[36] These compound-specific analytical methods are considered the gold standard for exposure assessment. A personal sampling pump (AirChek TOUCH, SKC Inc Eighty Four, PA) was used to collect acetic acid air samples in the breathing zone on tubes containing charcoal (SKC 226-01) with a flow rate of 1.0 L/min. Ammonia samples were collected using sorbent tubes containing sulfuric acid-treated silica (SKC 226-10-06) with a flow rate of 0.2 L/min. Acetic acid samples were analyzed using gas chromatography (ALS) and included field blanks, a laboratory control sample, and a laboratory control sample duplicate. Ammonia samples were analyzed using visible absorption spectroscopy (ALS) and included field blanks, a method blank, a laboratory control sample, and a laboratory control sample duplicate. The order for cleaning rooms from first to last was bedroom, bathroom 1, kitchen, and bathroom 2, with subjects choosing the order of cleaning tasks within each room. A kneeling posture was used to clean the floors, and windows were cleaned facing them from the front. The time and mass of cleaning solution were also recorded between non-floor and floor surfaces in each room. Each whole-house cleaning without ventilation use lasted 20-30 minutes, with eight subjects using acetic acid once and ammonia once (16 trials total).

## 2.2 | Individual cleaning tasks

Individual cleaning task analysis was performed independently of the whole-house cleaning trials analysis. Using NIOSH integrated methods to assess individual short-term cleaning tasks exposures (<2 minutes) would likely produce results below the limit of detection (LOD) for each task, so a direct reading ppbRAE 3000 photoionization detector (PID) with 10.6 eV lamp (RAE Systems-Honeywell) was used to measure second-by-second exposures (range: 1-10 000 ppb) during individual tasks. Daily calibrations of the PID were performed in accordance with manufacturer instructions, after an initial warm-up period (>15 minutes) and consisted of a zero calibration and a span calibration using 10 ppm isobutylene gas standard.

PIDs are not specific to individual chemicals, so conversion factors (CFs) are used to calculate individual chemical concentrations. Even though RAE's published CFs for ammonia and acetic acid are 10.9 and 22, respectively,[37] an instrument-specific conversion factor was determined with a validation experiment using side-by-side sampling with NIOSH methods previously described.[35,36] Those validation experiments (Figures S2A-C) yielded CFs of 15 and 28 for ammonia and acetic acid, respectively. These instrument-specific CFs were used for final calculations.

Exposures were measured during individual cleaning tasks by attaching one end of tubing to the subject's lapel in the breathing zone, with the other end attached to the ppbRAE. In addition to completing the original 18 cleaning tasks for whole-house cleaning individually, four of the tasks were repeated with a different posture for a total of 22 individual cleaning tasks. For example, each floor was cleaned using a kneeling posture as well as with a mop (standing), while the bedroom window was cleaned from the front and from the left side. A trial was deemed complete when one subject performed 22 cleaning tasks using one chemical under one ventilation condition. Eight subjects completed trials for each of the two chemicals under the two ventilation conditions for a total of 32 trials. Information about the rooms and tasks is shown in Table 1, with more detailed descriptions provided in Table S1. A summary of the whole-house and individual task exposure scenarios is shown in Table 2. Each individual task was started at $t_o$ and continued until

**TABLE 1** List of cleaning tasks

| Room | Volume ($m^3$) | Air changes per Hour ($h^{-1}$) | Task # | Cleaning Task | Surface Area ($m^2$) |
|---|---|---|---|---|---|
| Kitchen | 12.4 | $ACH_0 = 0.11$ $ACH_1 = 0.22$ | 1 | Microwave | 0.9 |
| | | | 2 | Sink | 0.9 |
| | | | 3 | Refrigerator | 1.1 |
| | | | 4 | Left Counter | 0.6 |
| | | | 5 | Middle Counter | 0.6 |
| | | | 6 | Right Counter | 1.2 |
| | | | 7 | Floor- Mop | 3.9 |
| | | | 8 | Floor- Kneel | 3.9 |
| Bathroom 1 | 8.1 | $ACH_0 = 0.08$ $ACH_1 = 0.40$ | 9 | Mirror | 0.3 |
| | | | 10 | Sink | 0.3 |
| | | | 11 | Toilet | 1.0 |
| | | | 12 | Shower | 4.8 |
| | | | 13 | Floor- Mop | 1.8 |
| | | | 14 | Floor- Kneel | 1.8 |
| Bathroom 2 | 8.0 | $ACH_0 = 0.10$ $ACH_1 = 0.29$ | 15 | Mirror | 0.3 |
| | | | 16 | Sink | 0.3 |
| | | | 17 | Toilet | 1.0 |
| | | | 18 | Shower/Tub | 7.5 |
| | | | 19 | Floor- Mop | 1.8 |
| | | | 20 | Floor- Kneel | 1.8 |
| Bedroom | 49.5 | $ACH_0 = 0.10$ $ACH_1 = 0.25$ | 21 | Window- Front | 1.5 |
| | | | 22 | Window- Side | 1.5 |

**TABLE 2** Summary of exposure scenarios and sampling

| Chemical | Ventilation | Subjects | Integrated Samples | PID Trials/ Samples |
|---|---|---|---|---|
| Acetic Acid | Off | 8 | 8 × 1 trial (18 tasks)=8 | 8 × 22 tasks = 176 |
| | On | 8 | 0 | 8 × 22 tasks = 176 |
| Ammonia | Off | 8 | 8 × 1 trial (18 tasks)=8 | 8 × 22 tasks = 176 |
| | On | 8 | 0 | 8 × 22 tasks = 176 |

the subject was satisfied with the cleaning outcome ($t_x$). Briefly, to perform an individual non-floor task, the subject sprayed the cleaning solution on the surface, wiped it with a paper towel until clean, and then verbally told the study team that the task was finished ($t_x$). The paper towel used for cleaning was weighed before and after use and sealed in a plastic bag. Non-floor tasks were randomized with rotation between rooms to allow for dissipation of chemical air concentrations between tasks in the same room. Floor tasks were completed at the end of the experiment by alternating rooms to similarly allow dissipation of chemical air concentrations before returning to the same room. The masses of the bottle with cleaning solution were recorded before and after each task using a digital scale (0-1000 ± 0.1 g, Centech), with the difference defined as the mass applied. The ppbRAE monitor was used to record start and end times with the difference defined as the task duration and was used to cross-reference hand-written data. Data from each task recorded included airborne concentrations, pre- and post-task spray bottle mass, pre- and post-paper towel/bag mass, start ($t_o$) and end ($t_x$) time from the ppbRAE, surface temperature, air temperature, relative humidity, and distance (minimum, maximum, and mode) from breathing zone to the closest edge of the cleaned surface.

Data from the ppbRAE instrument were downloaded and converted to Excel files, where start and end times for each task were matched from the hand-written data sheets. The task time frame was delayed four seconds for acetic acid and ten seconds for ammonia due to the different lengths of tubing (two feet vs five feet) used for each experiment. The background reading was identified as the lowest instrument reading during the task or ten seconds prior to task start, which was subtracted from each reading within the determined task time frame. The background-corrected reading was then multiplied by the instrument-specific conversion factor (CF) for each chemical. While the majority of the background readings (71%) were within ten seconds of task start, several background readings occurred later in the task, often when ventilation was being used. While the large air flow fluctuations in a small space with an exhaust fan running overhead is not ideal, it is part of the challenge of collecting subject data in real-world environments.

For individual task outcomes, peak values were defined as the maximum reading during the task time frame. Area under curve (AUC) values were calculated from the summation of readings over the task duration divided by 60 seconds to convert the final units to ppm × min. Peak values indicate threshold values reached during the task, while AUC values are a cumulative measure incorporating both intensity and duration that condense the air concentrations experienced during the exposure window into a unit (ppm × min) for comparison. Examples of exposure windows and AUC calculations for tasks can be found in Figures S3A-G and Table S3.

### 2.3 | Data analysis

The 95th percentile for log-transformed data collected using integrated sampling was calculated using IHSTAT, an excel-based spreadsheet available from the American Industrial Hygiene Association.[38] Statistical analysis of individual task results (peak and AUC values) was performed using R software.[39] Data were prepared by segregating tasks by rooms, since there were multiple tasks in each room and no tasks were common to all rooms. Mean and standard deviations for peak and AUC exposures for both chemicals were calculated using the "dplyr" package.[40] Repeated measures analysis was performed to evaluate subject effects, but the intraclass correlation coefficient (ICC) for each room was less than 0.35. Since ICCs were not substantial, we took the liberty of performing traditional ANOVA analysis, which allowed us additional insight into the data. Two-way ANOVA was carried out, with factor 1 being "task" and factor 2 being "ventilation status" for each of the responses "Peak" and "AUC." ANOVA (*aov* in "stats" package)[39] was used to calculate ventilation and task effects, as well as potential interactions for each chemical, as shown in Table S4ai. In order to check normality assumptions, the Shapiro test (*shapiro.test* in "stats" package)[39] was performed on each ANOVA analysis, followed by the Kruskal-Wallis test (*kruskal.test* in "stats" package)[39] when normality assumptions were not endorsed. Table S4aii provides a comparison of ANOVA results, with ANOVA on the mixed-effects model (subject as random effect) and two-way ANOVA.

The percent change in exposure values by using mechanical ventilation was calculated as the difference between exposures divided by the exposure without ventilation, and exposures for each task (with and without mechanical ventilation) were compared using a two-sided t test and the Wilcoxon test (*t.test* and *wilcox.test* in "stats" package),[39] with results shown in Tables S4B-E and Figure S4. The same method was used to compare exposures from tasks using two different postures (Tables S5A-D and Figure S5). Boxplots of exposures were created (*boxplot* in "graphics" package)[39] for tasks in each room (Figures S6A-L) in order to show exposure distributions by task.

Acetic acid data (with ventilation) were not recorded by the ppbRAE monitor during one subject's tasks, while another subject's ammonia data (without ventilation) were removed from calculations due to suspected systematic instrument error (zeroes reported for 16 of 22 tasks). This did not seem likely with ventilation off and was more than all other "zeroes" for both chemicals combined (11/660 = 1.7%). The latter 11 zeroes across other subjects/tasks were more random and were always for tasks with ventilation use (where ventilation may provide exposure reduction) and only with acetic acid. Zero values were also observed for short tasks (less than 60 seconds), such as mirrors, windows, refrigerator, and kitchen counters (8 of the 11) or when mopping floors (3 of the 11), which typically had the lowest exposures of all tasks. Therefore, without additional information to prove otherwise, zero values for these short-duration tasks did not have sufficient evidence to be excluded.

## 3 | RESULTS AND DISCUSSION

This study was conducted to characterize the magnitude and variability of exposures during cleaning activities in a residential work environment. Ammonia is considered a traditional cleaning chemical,[41] while acetic acid has been labeled a safer cleaning chemical as a window/glass cleaner as well as a general purpose cleaner.[42] Kitchens and bathrooms are cleaned by 80% of home health aides (one class of domestic workers),[14] so a subset of cleaning tasks were chosen for those rooms in this study. Kneeling to clean was reported by 46% of domestic workers,[12] so two postures to clean floors (mopping and kneeling) were also incorporated into the study. Spraying cleaning chemicals to clean floors was consistent with how other tasks were performed to allow for comparisons.

### 3.1 | Whole-house cleaning

Whole-house cleaning exposures (ie, exposure while completing all 18 tasks) are shown in Table 3. Acetic acid exposures averaged 3.9 ppm, with most exposures at 10%-50% of the STEL and one exposure at 50%-100% of the STEL. Ammonia exposures averaged 3.4 ppm, with half at 10%-50% of the STEL and half below 10% of the STEL. While whole-house cleaning trials were completed in ~26-27 minutes, a 15-minute STEL is most appropriate for comparison.[43,44] According to ACGIH, the STEL is a "15-minute exposure that should not be exceeded at any time during a workday."[45] While it is theoretically possible that one 15-minute exposure could exceed the STEL, the remaining portion of the time would need to be almost zero in order for the average to "hide" such an overexposure.

**TABLE 3** Whole-house cleaning exposure summary (18 tasks, without ventilation)

| | 3% Acetic Acid (NIOSH 1603)[35] | 0.1% Ammonia (NIOSH 6015)[36] |
|---|---|---|
| N | 8[a] | 8 |
| 15-min STEL | 15 ppm[74] | 35 ppm[75] |
| Mean (SD) | 3.9 ppm (2.3)[a] | 3.4 ppm (1.6) |
| <10% of STEL | 1 (12.5%)[a] | 4 (50%) |
| 10%-50% of STEL | 6 (75%) | 4 (50%) |
| 50%-100% of STEL | 1 (12.5%) | |
| Geometric Mean (GSD)[38] | 2.6 ppm (3.9)[a] | 3.1 ppm (1.7) |
| 95th-percentile[38] | 7.6 ppm[a] | 6.0 ppm |
| Mass applied (g), SD | 219.3 (64.9) | 199.7 (38.1) |
| Time (min), SD | 26.1 (2.4) | 27.0 (3.2) |

*Note:* Instead of 0 ppm, LOD/√2 was used.[76] Without this sample, the acetic acid mean (SD)= 4.4 ppm (1.8), geometric mean (GSD)= 4.1 ppm (1.5), 95th-percentile = 7.4 ppm.

[a]One exposure was below LOD (0.14 ppm).

Simultaneous sampling performed on one subject for ammonia indicated a fairly even distribution between the three rooms, making such "hidden" overexposures unlikely.

Ammonia is a common cleaning chemical, found in many glass cleaners as well as in concentrated products.[41] Using 0.11% ammonia for this study's whole-house cleaning scenario produced a mean task time-weighted average (TWA) ammonia air concentration of 3.4 ppm. This is lower than a 10-ppm exposure previously observed from cleaning three residential bathrooms with 0.1% ammonia,[16] but both mean TWAs are well below the published STEL for ammonia (35 ppm). One possible reason for air concentration differences between the two studies is that with the earlier study, floors were the first cleaning task in each bathroom, whereas floors were the last task in each room in this study. Cleaning a large surface first would be more likely to promote cumulative buildup of air concentrations as other tasks are performed in the room. Other differences between current and previous studies can be postulated, but several factors affecting exposure in the earlier study were not reported so direct quantitative comparisons cannot be done.

A second chemical, acetic acid, was also used to perform whole-house cleaning in this study, with mean air concentrations of 3.9 ppm. The only study that has measured acetic acid air concentrations during cleaning only evaluated floor mopping,[46] making it difficult to compare to the whole-house cleaning results reported here. Vinegar (4%-8% acetic acid) is commonly considered an alternative to more traditional cleaning chemicals, but as it has been noted, if substitute chemicals are chosen for cleaning, their exposure potential still needs consideration, with possible risk reduction measures necessary.[47] One study investigating health effects of acetic acid vapors observed mild nasal irritation at 10 ppm but no pulmonary effects at 5 or 10 ppm,[48] while another study observed an increase in nasal airway resistance at 15 ppm in subjects with seasonal allergic rhinitis.[49] Workplace exposure limits are based on exposures to healthy workers and may not account for hypersensitive individuals, so air concentrations below exposure limits may still cause health effects.[16] While the task-based exposures reported in our study are below those reported with clear adverse health effects, additional safety factors applied to OELs for irritant chemicals have been suggested to ensure protection of individuals who respond to low irritant concentrations.[50]

The whole-house cleaning exposures for both chemicals did not produce any exposures over current published STELs, and only one of the whole-house exposures was above the 50% of STEL cutoff for each chemical. However, current industrial hygiene practice goes beyond simply verifying that air concentrations do not exceed OELs to ensuring worker protection. AIHA has provided guidance regarding exposures based on the fraction of the OEL, with exposures above 10% of the STEL justifying chemical-specific risk management/control measures.[51] The 95th percentile values from exposure distributions represent upper tails that should be used for decision-making. Thus, the 95th percentile values, 7.6 ppm for acetic acid and 6.0 ppm for ammonia, indicate that it is unlikely that an exposure over the STEL would occur under the conditions present. However, these values are noteworthy, representing 51% and 17% of STELs for acetic acid and ammonia, respectively. Based on AIHA guidance, additional risk management actions such as hazard communication and exposure monitoring would be recommended.[51] Additionally, adjusting work practices such as avoiding the use of sprays and decreasing cleaning solution concentrations would be expected to reduce workplace exposures. As an alternative to acetic acid, citric acid is a similar antimicrobial cleaning ingredient but is non-volatile, with reduced ability to be inhaled.[31,52-54]

## 3.2 | Individual cleaning tasks

Individual cleaning task analysis was conducted for each of the same 18 tasks with four of the tasks repeated using different postures (mopping floors instead of kneeling and standing to the side of window instead of in front) for a total of 22 tasks (Table 1). Task-based exposure outcomes were reported as peak or AUC (cumulative) values. While there is a relationship between peak and AUC exposures, other factors also play a role. Peak values are often higher than AUC for many shorter tasks, while AUC values may be higher for longer tasks with sustained air concentrations, since longer durations also increase AUC values. Both metrics were reported for the information they provide; peak values describe the maximum concentration (not captured by integrated sampling), and AUC values represent a cumulative metric that accounts for both exposure intensity and duration.

Figure 1A,B show mass and duration of applied cleaning solution. The mass and durations associated with individual tasks appear to be similar, regardless of whether acetic acid or ammonia was used. However, there was considerable variability in mass applied and duration among different tasks. The tasks with the highest mass applied were the shower/tub in bathroom 2 (Task 18) and the kitchen floor (Tasks 7 and 8), with each having an average of 30 g of solution applied. The shower in bathroom 1 (Task 12) and the bathroom floors (Tasks 13, 14, 19, and 20) were next highest with about 20 g

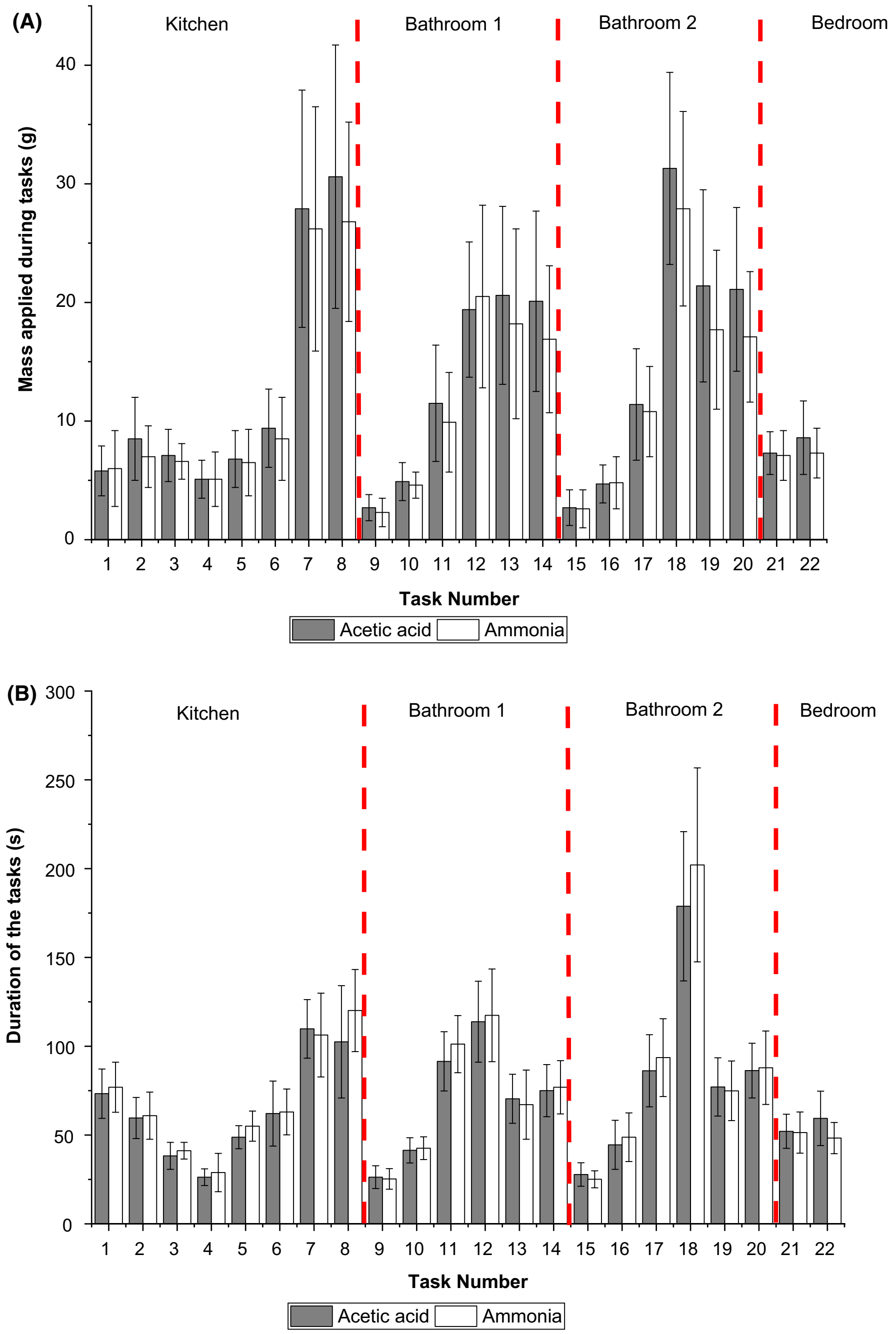


**FIGURE 1** A, Mass applied during cleaning tasks using acetic acid or ammonia. The bar height shows the arithmetic mean with the standard deviation represented as brackets. B, Duration of 22 cleaning tasks, using acetic acid or ammonia. The bar height shows the arithmetic mean with the standard deviation represented as brackets

applied. Most other tasks had about 5-10 g applied, except for the bathroom mirrors (Tasks 9 and 15), which were lowest with about 2.5 g applied. The shower/tub in bathroom 2 (Task 18) required the most cleaning time with about 3 minutes, followed by the bathroom 1 shower (Task 12), the kitchen floor (Tasks 7 and 8), and the toilets (Tasks 11 and 17) which each required about 2 minutes. Most other tasks took less than a minute, with mirrors (Tasks 9 and 15) and the left counter (Task 4) requiring the least time at less than 30 seconds.

Figure 2A,B show peak and AUC exposures, respectively, for acetic acid (with exposure distributions shown in Figures S6A-F). In experiments with acetic acid, the showers (Tasks 12 and 18) produced the highest peak exposures, with an average of about 3 ppm. Most of the other tasks had peaks at 30%-70% of the showers, except for mopping floors (Tasks 7, 13, and 19), with the lowest peaks (0.6-0.7 ppm). AUC task differences were greater, with the showers having the highest AUCs (4.6 and 2.7 ppm × min), followed by toilets (~1.3 ppm × min). All other tasks were at or below 1 ppm × min.

Figure 3A,B show peak and AUC exposures, respectively, for ammonia (with exposure distributions shown in Figures S6G-L). For ammonia experiments, the showers (Tasks 12 and 18) and the kitchen sink (Task 2) produced the highest peak exposures (2.7-2.8 ppm). Most of the remaining tasks produced peaks less than 50% of this value, with mopping floors (Tasks 7, 13, and 19) producing the lowest peak exposures (<0.5 ppm). The highest AUC exposures were observed with the two shower tasks (Tasks 12 and 18, at 2.4 and 3.6 ppm × min), followed by the kitchen sink

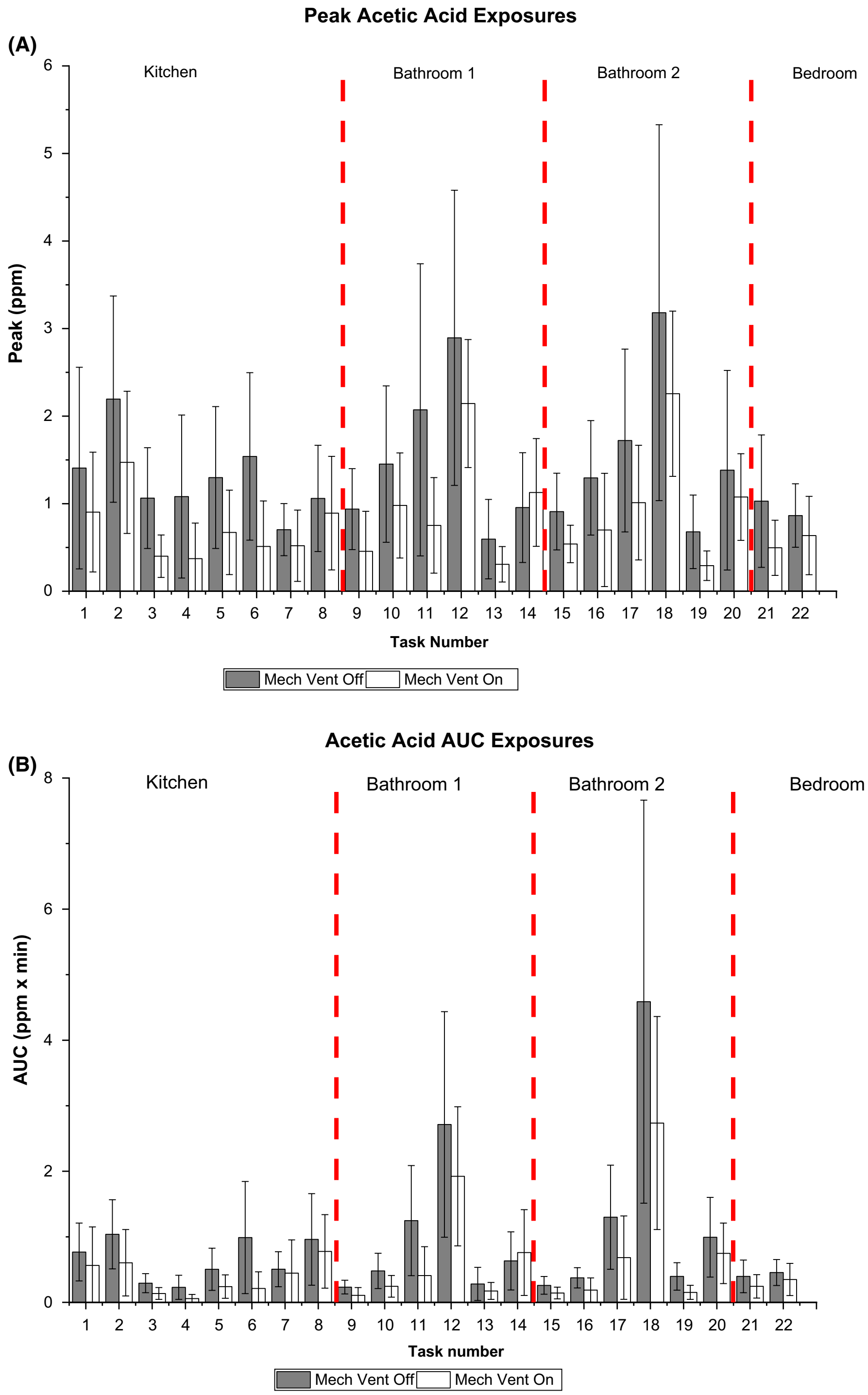


**FIGURE 2** A, Peak acetic acid exposures for 22 tasks under two ventilation conditions, with non-ventilated conditions in dark bars and ventilated conditions in light bars. The bar height shows the arithmetic mean with the standard deviation represented as brackets for each task. B, Acetic acid AUC exposures for 22 tasks under two ventilation conditions, with non-ventilated conditions in dark bars and ventilated conditions in light bars. The bar height shows the arithmetic mean with the standard deviation represented as brackets for each task

(Task 2) and kitchen floor-kneeling (Task 8) around 1.3 ppm × min. All other tasks were below 1 ppm × min. Data tables with numerical values supporting the figures are in Tables S4C-F.

Comparing the relative contributions of individual tasks to overall exposure indicate that the shower/tub and walk-in shower produced the highest peak and AUC exposures, with most other tasks considerably lower. Different investigators have emphasized underlying causative factors to varying degrees. For example, the maximum airborne mass concentration will be determined by the amount applied, the volatile ingredient concentration and vapor pressure, mode of application, room size, and ventilation rates.[55] In our study, the cleaning solution concentrations, application mode (spray), and vapor pressure were unchanged for each chemical. However, the mass applied varied considerably from task to task. The shower/tub task had the highest mass applied (~30 g), but kitchen floors had similar applied masses with much lower peak and AUC exposures. Similarly, the walk-in shower had applied masses comparable to the bathroom floors (~20 g), but the floors produced much lower peak and AUC exposures. Therefore, applied mass of cleaning solution is not the only factor affecting peak and AUC exposures in our study.

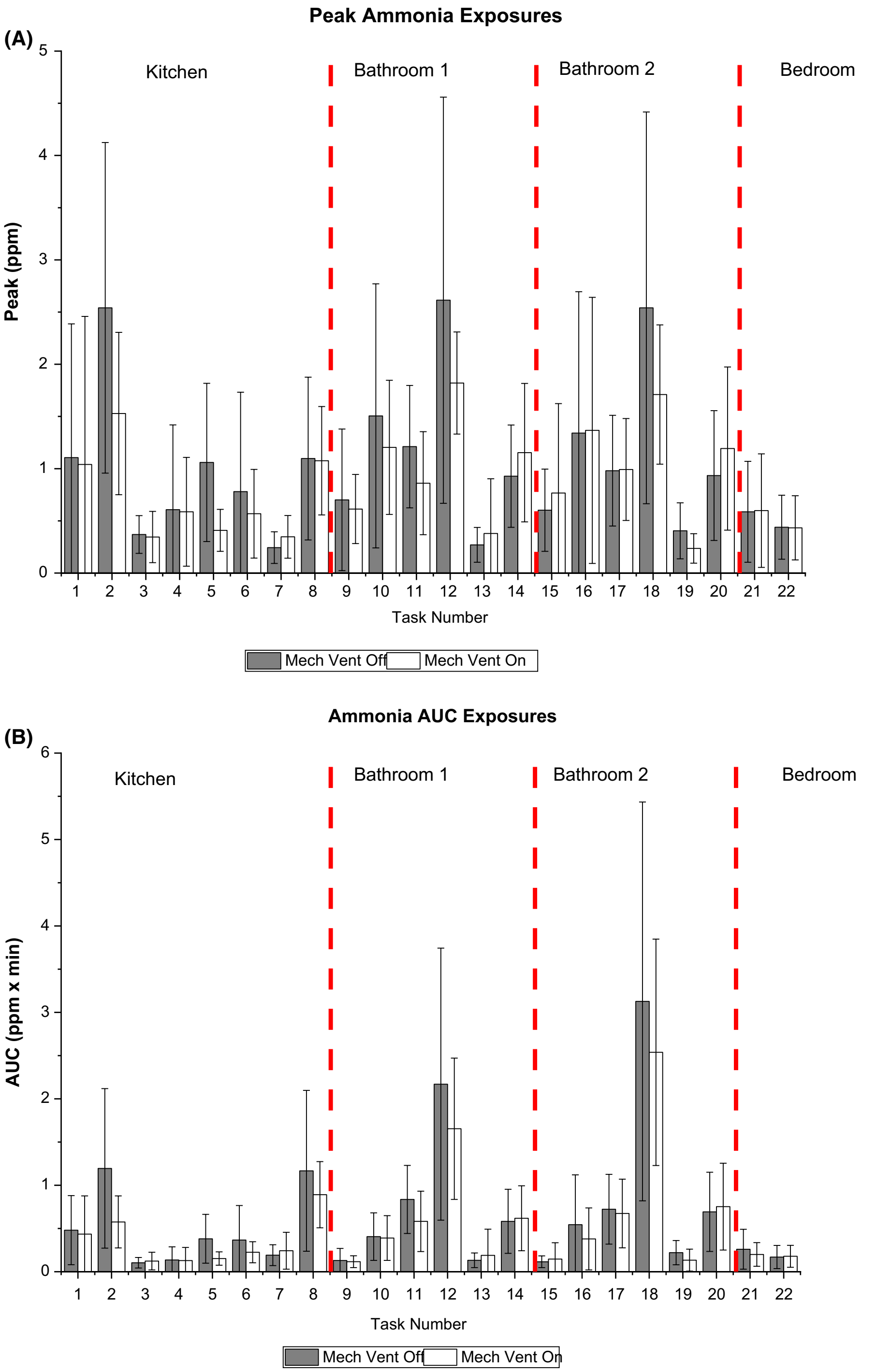


**FIGURE 3** A, Peak ammonia exposures for 22 tasks under two ventilation conditions, with non-ventilated conditions in dark bars and ventilated conditions in light bars. The bar height shows the arithmetic mean with the standard deviation represented as brackets for each task. B, Ammonia AUC Exposures for 22 tasks under two ventilation conditions, with non-ventilated conditions in dark bars and ventilated conditions in light bars. The bar height shows the arithmetic mean with the standard deviation represented as brackets for each task

The highest average peak ammonia concentrations were just below 5 ppm. This was consistent with another study (Fedoruk, et al 2005) reporting peak ammonia exposures of less than 5 ppm using a window cleaner (0.1% ammonia) in a residential environment.[16] It has been reported that use of 3% ammonia solutions can produce peak concentrations over 50 ppm during regular cleaning and spills.[1,16] Acetic acid concentrations followed a similar pattern, with showers producing the highest exposures and mopping floors producing the lowest peak exposures. The mopping exposures using ventilation were consistent with those reported in the sole previous acetic acid cleaning study (<0.5 ppm up to 2 minutes), despite higher weight percent solution concentrations and higher ventilation rates in that study.[46]

## 3.3 | Posture/distance effects on task exposures

Exposures often decrease with increasing distance from a source, making the distance between the breathing zone and the emission source a potential factor in determining exposure.[56] In order to investigate this further, different postures were used for cleaning the bedroom patio window (front vs side posture) and floors (kneeling vs mopping). There was no significant difference observed in chemical exposures using either of the two window cleaning postures, but postures affected exposures more during floor cleaning (Tables S5A-D, Figure S5). This is likely due to large distance differences between floor postures (extended arm length for kneeling vs standing breathing zone height for mopping) with smaller differences for window cleaning postures (similar arm lengths but at different angles). A reduction in all exposures (34%-83%) was observed by using a mopping posture instead of kneeling, with statistical significance shown about 75% of the time. This is consistent with previous studies that observed decreased concentrations with increased distance,[57-61] but the decreased concentrations with height may also be attributed to inhibited vertical mixing/stratification.[59,60] The only previous study noting distance effects specifically with cleaning activities observed lower air concentrations of ammonia with increased distance for spill scenarios but no difference between kneeling and mopping postures when cleaning floors, leading authors to conclude that factors other than distance may be responsible.[16] Other studies observed the effect of distance on air concentrations in unoccupied spaces, so empirical data in which human subjects influence local airflows during work tasks are still needed.

### 3.4 | Ventilation effects on task exposures

Ventilation is often used as an engineering control to reduce exposures in work environments.[62] To work effectively, ventilation rates must provide sufficient dilution to remove the contaminant, with fresh replacement air brought in. Healthcare facilities typically have high ventilation rates, with recommendations ranging from 6 ACH for patient rooms to 15 ACH for procedure rooms.[63,64] With dramatically higher ACHs to assist in diluting and removing contaminants, exposure studies performed in hospitals may not correlate with exposures experienced in residential environments. Therefore, residential work environments provide unique conditions in need of study.

Residential HVAC systems are designed to recirculate air with energy efficiency prioritized. In most systems, outdoor air is not introduced.[65] The relatively small increase in ACH in the kitchen and bedroom using the HVAC fan is likely due to this recirculation, while the slightly higher ACHs seen in the bathrooms were likely due to bathroom fans pulling air outside, with more replacement air pulled into the structure. Residential ACHs can vary somewhat depending on a variety of factors such as building location and age, but other studies would indicate that the Collaboratory House's ACHs during mechanical ventilation use would still be considered lower than the average house, while ACHs with mechanical ventilation off would represent a “tight” house and a close to worst-case ventilation environment.[65-67]

After performing each cleaning task without ventilation to determine its overall contribution to exposure, cleaning tasks were repeated with mechanical ventilation turned on. Reduction in exposures due to ventilation use was significant for the kitchen (120 observations) and both bathrooms (90 observations) using acetic acid, while only kitchen exposures were significantly reduced when ammonia was used (Tables S4A). However, individual task exposures varied tremendously when using ventilation, with differences from ventilation use often not reaching significance for individual tasks (Tables S4B-E, Figure S4). Most tasks showed reductions in both peak and AUC exposures, but many reductions were minor, and some tasks showed increases with ventilation use. Two factors could have affected these results: variability in chemical motion near the source and variability in chemical dispersion from subjects performing the cleaning. Previous studies have observed complex room air mixing patterns and much higher variability in air concentrations less than 2 m from a source, compared to more distant locations.[58-60] Additionally, variability between subjects can also occur with applied mass and task duration.[68-70] It is also possible that the small differences between $ACH_0$ and $ACH_1$ may be insufficient for detecting differences in impacts on exposure. This was seen in a study reporting formaldehyde (and other cleaning chemical) modeling results, with exposure models showing little difference in peak formaldehyde concentrations at 0.1 and 0.35 ACH.[67] The physicochemical properties of different chemicals used in each study make a direct comparison difficult, but the presence of similar effects in our study remains a possibility.

For the ventilation comparison, exposure reductions were not observed when mechanical ventilation was used for several tasks (often floor tasks). This is consistent with a previous hospital bathroom cleaning study, for which the overall trend showed higher exposures with ventilation off, but higher concentrations with mechanical ventilation use were also observed at times.[18] Additionally, a study measuring residential CO dispersal from a point source using natural ventilation observed that higher concentrations were produced in one home when higher ACHs occurred.[60] These findings are counterintuitive, but airflow rate, locations of supply/exhaust, thermal plumes, and occupant motion can produce non-uniform airflow around subjects, resulting in air dispersion patterns that can lead to higher personal exposures than ambient concentrations, even with ventilation use.[71-73] This could explain exposure increases for floor cleaning tasks, where ceiling exhaust vents may draw air currents upwards from the floor and through the breathing zone. Together these findings indicate that while ventilation can be an important engineering control, exposure reduction with its use is not guaranteed, and reliance only on this type of household ventilation for exposure control is not necessarily sufficient.

Therefore, if ventilation is used to control workplace exposures, verification of ventilation effectiveness is also needed. As a decentralized workforce, DWs may visit multiple homes per day, with each home providing a unique exposure environment with different ventilation conditions, making this verification difficult. Lowering ingredient concentrations, eliminating sprays, and other preventive methods may be more reliable ways of reducing cleaning chemical exposures in this workforce.

There are several limitations of our study that may impact the generalizability of the results. In this study, students performed cleaning tasks, and it is unknown whether actual domestic workers would clean in a similar way. Also, the environment at Maple Knoll Collaboratory House represents realistic but close to worst-case scenario conditions (low ACH, small rooms) in a residence representing some US homes in northern climates, where natural ventilation is often not used during winter or summer months. The current study results will not represent the range of residential environments that are present in homes using natural ventilation or that have mechanical ventilation with an outdoor air supply, nor the varied conditions domestic workers experience over a shift.

A second limitation is that the exposure periods recorded by the ppbRAE do not completely account for the entire exposure from individual tasks. Task start and end times defined exposure periods used for calculations, but exposures continue to occur until the individual leaves the room/house. Other studies have reported that air concentrations of a cleaning chemical can remain for considerable lengths of time before returning to background concentrations.[16,19] Therefore, the PID results in our study would likely underestimate the true total exposure from each task. Additional time (10-15 seconds) added to the end of each task window would represent the time needed to leave the area and would more accurately reflect the task exposure. Additionally, despite room rotation to allow for steady-state conditions, background concentrations may still be slowly decreasing during the task, which would produce measurements lower than what is actually present (due to background correction) and signifies a limitation of our attempt to isolate the contribution of individual tasks.

Another limitation is that the whole-house and task-specific measurements cannot be compared directly. First, the two sets of measurements were not done simultaneously, meaning that the variety of factors affecting exposures could be different. Second, background levels generated from previous tasks in the room were treated differently. In the whole-house cleaning, all the tasks in the room were captured as a cumulative concentration buildup, but with the task-specific measurements, background concentrations were minimized with room rotation and then subtracted from air concentrations measured during the task, meaning that only contributions from single tasks were measured, not cumulative concentrations. Lastly, during the whole-house measurements, 18 tasks were completed sequentially with exposures occurring between individual tasks captured as part of the measurement. During the real-time sampling, only the time for the task was accounted for, and additional time between tasks that still produce exposures (weighing bottles, handing off towels, etc) were not captured.

## 4 | CONCLUSION

This study provides valuable information about the home environments domestic workers encounter: cleaning chemical exposure data generated from a real-world residential environment, contributions of individual residential cleaning tasks to overall exposure, comparison of exposures from an environmentally friendly and a traditional chemical, comparison of exposures from two different postures, and comparison of exposures under two ventilation modes. Our integrated sampling results from an environment with limited airflow indicate that there is considerable variability among a group of subjects performing cleaning activities and that exposures will likely be below current published exposure limits but at levels that may still require risk management activities. Additionally, ventilation use had limited effectiveness for reducing exposures during several floor cleaning tasks but mopping instead of kneeling was effective at reducing floor cleaning exposures.

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### CONFLICTS OF INTEREST

One author (AM) who did not receive industry funding for this research, has conducted funded research on health hazards of cleaning product ingredients from industry organizations in the last 3 years. Another author (SA) conducted a simulated cleaning product exposure study that was partially supported by the American Cleaning Institute in 2016-17. The other authors do not have any conflicts of interest.

### AUTHOR CONTRIBUTION

**Michael Leo Benjamin:** Conceptualization (lead); Data curation (equal); Formal analysis (lead); Investigation (lead); Methodology (equal); Project administration (lead); Validation (equal); Writing-original draft (lead); Writing-review & editing (lead). **Susan Arnold:** Conceptualization (equal); Formal analysis (supporting); Methodology (equal); Supervision (supporting); Validation (equal); Writing-original draft (supporting); Writing-review & editing (supporting). **Marepalli Rao:** Conceptualization (supporting); Formal analysis (lead); Methodology (equal); Supervision (supporting); Writing-original draft (supporting); Writing-review & editing (supporting). **Kermit Davis:** Conceptualization (equal); Formal analysis (supporting); Investigation (supporting); Methodology (equal); Project administration (supporting); Supervision (supporting); Writing-original draft (supporting); Writing-review & editing (supporting). **Andrew Maier:** Conceptualization (equal); Formal analysis (supporting); Methodology (equal); Project administration (supporting); Supervision (supporting); Writing-original draft (supporting); Writing-review & editing (supporting). **Jurate Virkutyte:** Conceptualization (equal); Data curation (equal); Formal analysis (supporting); Investigation (supporting); Methodology (equal); Project administration (supporting); Supervision (lead); Writing-original draft (supporting); Writing-review & editing (supporting).

### PEER REVIEW

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## SUPPORTING INFORMATION

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

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