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Research Article

Elevated Consumer Exposure to Volatile Organic Compounds During Do-It-Yourself Painting Oil-Based Wood Stain Evidenced by Passive Air Sampling and Urinary Metabolites

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Consumer products are significant contributors to indoor volatile organic compound (VOC) emissions, with oil-based wood stains, commonly used in do-it-yourself (DIY) projects, being particularly notable sources. This study was aimed at evaluating personal exposure to VOCs during DIY application of oil-based wood stains by integrating passive sampling, dermal exposure assessment, and urinary biomonitoring. Twenty-two volunteers wore a validated expanded polytetrafluoroethylene passive sampler (ePTFE PS) during indoor painting activities in naturally ventilated residential settings. Despite open-window ventilation, benzene concentrations increased from 4.5 to 5100 $\mu g/m^3$—a 1100-fold rise. Toluene, ethylbenzene, xylenes, and styrene showed similar increases ranging from 160 to 710 times. Limonene and α-pinene concentrations rose by 440% and 600%, respectively. A statistically significant correlation was observed between inhalation exposure to m-xylene and its urinary metabolites (p- and o-methylhippuric acids), with metabolite concentrations reaching up to 57.2 $\mu g/mg$ creatinine. Inhalation exposure was calculated to be 630–1100 times higher than dermal exposure. These findings highlight the dominance of the inhalation route and demonstrate that passive sampling is an effective and practical approach for assessing VOC exposure from consumer products in real-world environments.

Keywords: exposure; metabolite; painting; personal passive sampler; residential apartment; VOCs

1. Introduction

Volatile organic compounds (VOCs) are among the most widespread outdoor and indoor contaminants, posing significant risks to human health, including carcinogenic effects [1–3]. In residential settings, commonly used consumer products such as scented candles, air fresheners, and essential oil diffusers are substantial sources of indoor VOC emissions [4–7]. Other significant sources include building materials, paints, printers, and furnishings, which continuously release VOCs into the indoor environment [8–10]. Oil-based wood stains, widely used for preserving and enhancing wood surfaces, are particularly notable VOC emitters [11, 12]. Gennaro et al. [11] reported that total VOC emissions from oil-based wood stains averaged 0.190 $\pm$ 0.002 $mg\,m^{-2}\,min^{-1}$ over a 10-min period, with key compounds including benzene, toluene, ethylbenzene, xylenes, styrene, α-pinene, and limonene. Similarly, Park et al. [12] found emission rates ranging from 5987 to 26,165 $\mu g\,m^{-2}\,h^{-1}$ for total VOCs. With the growing trend of do-it-yourself (DIY) projects and the increased production of consumer products like oil-based wood stains for

DIY use, accurately assessing personal human exposure to VOCs is critical. Effective and reliable methods for evaluating such exposure are essential to better understand and mitigate the potential health risks associated with these widely used products [13–16].

To evaluate human exposure to VOCs, researchers employ both environmental and biomonitoring approaches. Biomarkers of exposure, typically quantified in biological specimens such as urine, serum, and hair, reflect internal exposure by measuring parent compounds or their metabolites. However, these biomarkers are subject to various sources, both between and within individuals. For instance, urinary metabolites often provide only a snapshot of recent exposure, rather than long-term exposure patterns [17]. In environmental monitoring, matrices like air and dust are analyzed to estimate external exposure through inhalation, inadvertent ingestion of dust, or hand-to-mouth contact. Active sampling, which uses pumps to collect air samples, is commonly employed for its high precision and accuracy in short-term monitoring [18–21]. However, active sampling is limited by its inability to capture long-term, fluctuating concentrations and its operational challenges, including bulky equipment and lack of practicality for extended use [22–26]. In contrast, passive sampling offers several advantages, such as simplicity, low cost, and ease of deployment [21]. While active sampling is more efficient for short-term monitoring, passive samplers are particularly effective for determining time-weighted average concentrations over extended periods, allowing for the capture of episodic contaminant fluctuations [27–30]. Given these strengths, passive sampling is widely used to assess human exposure to VOCs in various settings [31–34].

Although passive sampling is widely used for exposure assessment, a comprehensive evaluation of its utility compared to other established exposure assessment methods is essential. Such methods include biomarkers of exposure measured in biological matrices (e.g., urine) and direct dermal exposure assessments [34]. Due to their lipophilic nature, VOCs can permeate the skin barrier, leading to systemic distribution and potential health effects. This dermal absorption may occur independently of inhalation exposure, highlighting the need for standardized methodologies and tools to evaluate dermal exposure to airborne VOCs effectively. Studies examining correlations between passive sampling tools and biomarkers have provided valuable insights. For example, Dixon et al. [35] reported significant correlations between concentrations of polycyclic aromatic hydrocarbons (PAHs) detected on wristbands and levels of 6-hydroxy-PAHs among 11 urinary hydroxy-PAHs (Spearman's rank-order correlations, $r_s = 0.44$ to 0.76 and $p = 0.04$ to < 0.0001). Similarly, Levasseur et al. [36] demonstrated significant correlations between ethyl, methyl, and propylparaben levels measured on wristbands, hand wipes, and house dust and their respective urinary biomarkers. Wristband-measured chemicals generally showed stronger correlations with urinary biomarkers than those found in hand wipes or dust, underscoring the potential of passive sampling for external exposure assessment. While studies have predominantly focused on the use of passive sampling for semivolatile organic compounds (SVOCs) such as PAHs, including the use of silicone wristbands [37], similar evaluations for VOCs remain limited. To fully understand the efficacy of passive sampling for VOC exposure assessment, detailed comparisons with alternative methods—such as active sampling, urinary biomarkers, and dermal exposure assessments—are necessary for SVOC exposure assessment. Furthermore, kinetic evaluations of passive sampling methodologies in relation to these alternative tools remain underexplored, requiring future research to establish their reliability and validity comprehensively.

In a previous study, a passive sampler known as the expanded polytetrafluoroethylene passive sampler (ePTFE PS) was developed specifically to detect indoor VOCs [38]. This sampler demonstrated high accuracy and was minimally affected by air turbulence, making it a robust tool for VOC measurement. To further improve its utility, the ePTFE PS was modified to enhance its sampling rates and adapted into a wearable device for personal exposure monitoring [31]. It has been successfully employed to monitor VOCs in various living environments, including indoor spaces where essential oil diffusers, burning incense, and scented candles are used [32, 33]. In this study, the ePTFE PS was utilized to assess personal VOC exposure during the application of oil-based wood stains indoors. A total of 22 volunteers participated, with their inhalation exposure levels measured using the wearable ePTFE PS during DIY painting activities conducted inside residential apartments. To explore the relationship between personal exposure measured by passive sampling and internal human exposure, dermal exposure levels were simultaneously assessed alongside inhalation measurements. Internal VOC exposures were evaluated by measuring toluene and *m*-xylene metabolites in urine samples from volunteers in this study. Therefore, the main objective of this study was to assess personal exposure to VOCs during the DIY application of oil-based wood stains by comparing passive sampling results with dermal exposure measurements and urinary biomarkers in order to evaluate the effectiveness of passive samplers for comprehensive exposure assessment. This study hypothesized that (1) inhalation would be the dominant exposure pathway compared to dermal contact and (2) passive sampling could provide reliable and practical exposure estimates that correlate with internal biomarkers. By validating a wearable ePTFE PS in a real-world setting, this study seeks to fill a critical gap in the field of consumer product exposure assessment and offer a practical approach for identifying exposure risks associated with everyday indoor activities. Unlike prior studies that typically rely on either biomonitoring or ambient measurements alone, this study uniquely integrates all three assessment methods in a real-world residential setting using a wearable ePTFE PS. This comprehensive approach provides new insight into the relative contributions of different exposure routes and validates the utility of passive samplers for personal exposure assessment under practical conditions.

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2. Materials and Methods

2.1. Chemicals and Instruments. The standard target VOCs analyzed in this study included benzene, toluene, ethylbenzene, *m,p*-xylenes, *o*-xylene, styrene, limonene, and α-pinene, all of which were purchased from Sigma-Aldrich (Milwaukee, WI, United States), along with internal standards (ISs) toluene-d_8 and chlorobenzene-d_5. A solvent extraction method using dichloromethane (DCM) (Sigma-Aldrich) spiked with ISs was employed to extract VOCs from the adsorbent material. Gas chromatography–mass spectrometry (GC-MS) analysis was performed using an Agilent 6890A gas chromatograph coupled with an Agilent 5973N mass selective detector and equipped with an Agilent DB-5 column (30 m × 0.25 mm × 0.25 μm). The injection volume was 2 μL with a split ratio of 5:1, and helium served as the carrier gas at a constant flow rate of 1.0 mL min^{-1}. The oven temperature program began at 40°C (held for 2 min), followed by a ramp of 10°C min^{-1} to 100°C, and continued at the same rate until reaching a final temperature of 270°C. This protocol enabled efficient separation and quantification of the target VOCs.

2.2. ePTFE PS. The passive sampler utilized in this study comprised 500-mm ePTFE tubes (ID 2 mm; OD 4 mm) sourced from Huizhou Besteflon Industries Co. Ltd. (Guangdong, Sijiaolou Industrial Zone) and 0.9 g of Optipore-L493 (Sigma-Aldrich), an adsorbent known for its high VOC sorption capacity [39]. Before use, the ePTFE tubes were cleaned via Soxhlet extraction for 12 h using a 1:1 mixture of 50 mL *n*-hexane and 50 mL acetone to remove potential contaminants [38]. The ePTFE PS was designed to be worn as a wristband (Figure S1). Following the exposure period, the samplers were immersed in 40-mL vials containing 10 mL of DCM and left for 1 day to extract the adsorbed VOCs. The VOC concentrations in the DCM extracts were analyzed using GC-MS. Previous research demonstrated that the ePTFE PS achieves high accuracy compared to real-time analysis and active sampling techniques [39, 31]. Sampling rates and method detection limits (MDLs) established in a prior study were used [32]. Additionally, background VOC levels were assessed using 20 blank ePTFE PS samples. Calibration of extracted samples was performed using the ISs toluene-d_8 and chlorobenzene-d_5 to ensure reliable quantification.

2.3. Dermal Exposure. Dermal exposure to toluene and *m*-xylene was assessed following the painting activity. The exposed skin area (30 × 30 mm^2) was washed four times using an alcohol swab to collect surface residues. The skin samples were collected from the area below the elbow, near the forearm muscles, and the same site was sampled for all participants. Each swab was soaked in 5 mL of methanol for extraction, referred to as the skin wash (SW) sample. To evaluate VOC penetration into the skin, the stratum corneum (SC) was sampled using a tape-stripping method. A single Scotch tape (30 × 30 mm^2, 3M, Maplewood, MN, United States) was applied and removed 10 times from the same area. This process was repeated in triplicate. The collected tape strips were soaked in 5 mL of methanol to extract the VOCs, forming the SC sample. Both the SW and SC extracts were centrifuged at 3000 rpm for 5 min, and the supernatants were filtered using a 0.22-μm filter. The resulting extracts were analyzed by GC-MS to quantify the levels of toluene and *m*-xylene. This methodology enabled the differentiation between surface-level and dermally absorbed VOCs.

2.4. Metabolites. Urine samples were collected over a 4-day period, starting 1 day prior to the painting activity. These samples were analyzed for the concentrations of toluene metabolite (hippuric acid) and *m*-xylene metabolites (*p*- and *o*-methylhippuric acids), providing biomarker-based insights into internal VOC exposure. To quantify hippuric acid in urine, an aliquot of 10 μL of IS solution (100 μg mL^{-1} creatinine-d_3) was added to 1 mL of human urine in a 10 mL tube. A secondary sample was prepared by adding 10 μL of IS to 0.1 mL of human urine, followed by the addition of 900 μL of deionized water. The resulting mixture was vortexed for 20 s and subsequently mixed with 2 mL of acetonitrile. The volume was then adjusted to 10 mL using distilled water. Following a 1-min agitation, the sample was centrifuged at 2100 × g for 3 min at 15°C. The supernatant (100 μL) was diluted with 900 μL of deionized water to prepare the urinary extract. This extract was filtered using a 0.22 μm nylon filter before 5 μL of the filtrate was injected into the liquid chromatography–tandem mass spectrometry (LC-MS/MS) system. The LC system consisted of a UPLC system equipped with a Phenomenex Luna Omega C18 column (100 × 2.1 mm; 1.6 μm) and a Phenomenex Security Guard Ultra holder. The column temperature was maintained at 35°C, and a sample injection volume was 5 μL. The mobile phases were prepared as follows: Mobile Phase A consisted of 0.025% formic acid and 0.05% acetic acid in an aqueous solution, while Mobile Phase B contained 0.025% formic acid and 0.1% acetic acid in methanol. The flow rate was set at 0.25 mL min^{-1}, and the total run time was 7 min. A linear gradient elution program was employed as follows: for the first 4 min, 25% of Mobile Phase B was maintained; between 4 and 5 min, the proportion of B was increased to 90%; between 5 and 5.3 min, the proportion was further increased to 99%; and finally, between 5.6 and 5.8 min, the proportion of B was decreased back to 25%. The mass spectrometer operated in negative polarity, with electrospray ionization (ESI) as the ion source. The ion spray voltage was set to −1500 V, the desolvation gas flow was 400 L h^{-1}, and the desolvation temperature was maintained at 200°C.

To quantify *p*- and *o*-methylhippuric acids in urine, 25 μL of an IS solution (1 μg mL^{-1}) was added to a 0.5 mL urine sample, followed by the addition of 0.5 mL of a 1% formic acid solution. The sample was vortexed for thorough mixing and then subjected to centrifugation at 17,136 relative centrifugal force for 5 min (Labnet, Edison, NJ, United States). After centrifugation, the sample was transferred into an autosampler vial for further analysis. The analysis was performed using high-performance liquid chromatography (HPLC) coupled with mass spectrometry (MS) on a

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Phenomenex Luna Omega C18 column (100 × 2.1 mm; 1.6 μm). The column temperature was maintained at 40°C, and 5 μL of the sample was injected into the system. The mobile phases used were a 0.1% formic acid solution (Mobile Phase A) and methanol (Mobile Phase B). The flow rate was set at 0.4 mL min^{-1}, and the total run time was 7 min. The following linear gradient was applied: for the first 4 min, Mobile Phase B was maintained at 25%; between 4 and 5 min, the proportion of B increased to 90%; between 5 and 5.3 min, B was further increased to 99%; and finally, between 5.6 and 5.8 min, the proportion of B was decreased back to 25%. The mass spectrometer operated in negative polarity with ESI as the ion source. The ion spray voltage was set to 4500 V, with a curtain gas flow of 40 psi and medium collision gas. These parameters allowed for the effective quantification of *p*- and *o*-methylhippuric acids in urine. A brief summary table listing all analytical instruments, sample types, and the corresponding analytes measured is shown as Table 1.

2.5. Panel Study. A total of 22 volunteers, residing in residential apartments, were recruited for the study. These participants were instructed to wear an ePTFE PS, as shown in Figure S1, for a period of 1 h prior to the commencement of painting and throughout the 30-min process of applying oil-based wood stain (Mycolor, Chungnam, Republic of Korea) to plywood. The DIY painting was conducted on a balcony, with all windows fully open. The volume of the balcony and the mass of the oil-based wood stain utilized are delineated in Table S1. Following the painting process, dermal exposure to toluene and *m*-xylene was measured. This procedure was repeated twice, with a 1-h interval between the two applications to allow for drying of the first coat. The second application was made on the previously painted plywood. During the painting procedure, the volunteers were instructed to remain away from the VOC source, except for the duration of the application. The indoor temperature of the residential apartment was assumed to remain stable at 23°C, which was consistent with the temperature used to calibrate the sampling rates of the ePTFE PS in laboratory conditions. Previous research indicated that temperature variations within 10°C had a negligible effect on passive sampling results [32]. Urine samples were collected over a 4-day period, starting 1 day prior to the painting session. The detailed schedule of the panel study is shown in Table 2. The study received approval from the Institutional Review Board (IRB) of Korea University (Approval Number: KUIRB-2023-0122) and was conducted in October 2023.

3. Results and Discussion

3.1. Time-Weighted Average Concentration Measured by Passive Sampling. Table S2 presents the concentrations of target VOCs in residential apartments before and during the painting activity. Applying oil-based wood stains significantly increased VOC concentrations in the apartments of all 22 volunteers. The primary compounds detected included benzene, toluene, ethylbenzene, xylenes, styrene, α-pinene, and limonene, which were consistent with those monitored by Gennaro et al. [11]. Concentrations of all target VOCs significantly increased during both the first and second painting sessions, with *p* values of paired *t*-test consistently below 0.05 at the 95% confidence level. The concentrations of the target VOCs measured during the first and second painting sessions were found to differ by a factor of 1.0–1.4, indicating that the two sessions produced nearly identical increases in indoor VOC levels. As shown in Figure 1, the concentration of benzene increased from an average of 4.5–5100 μg m^{-3} and 4800 μg m^{-3} after the first and second painting sessions, respectively. Despite the ventilation provided by the balcony, the benzene concentration increased by a factor of approximately 1100, compared to prepainting levels. Benzene is a well-documented human carcinogen [40, 41], with epidemiological studies linking its exposure to acute myeloid leukemia. Furthermore, the International Agency for Research on Cancer (IARC) has established a connection between benzene exposure and the development of multiple myeloma, non-Hodgkin's lymphoma, acute lymphocytic leukemia, and chronic lymphocytic leukemia [42]. Styrene, classified as a Group 2A carcinogen by the IARC [43, 44], exhibited an increase in concentration from 2.1 to 150 μg m^{-3} and 170 μg m^{-3} after the first and second painting sessions, respectively. Other target VOCs, such as toluene, xylenes, and ethylbenzene, demonstrated substantial increases, ranging from 160 to 710 times the baseline levels after the painting activities. These VOCs, while not classified as carcinogenic, are associated with significant noncarcinogenic risks [45].

The application of paint led to a significant increase in the average concentrations of limonene and α-pinene, with values that were four to six times higher than prepainting levels in the residential apartments of the 22 volunteers, as shown in Figure 1g,h. Terpenes such as limonene and α-pinene are widely used in the global fragrance industry due to their relatively low toxicity and risk [5, 6]. However, these compounds have been identified as potential allergens, capable of causing skin irritation, asthma, and chest tightness [46–48]. For example, a 100% increase in the indoor concentration of limonene has been associated with a 17%–18% increase in wheezing and asthma symptoms, along with a 1.55% rise in exhaled nitric oxide [49]. These adverse effects were found to be significantly more pronounced in children, with an approximate two-fold increase in respiratory symptoms. Consequently, limonene has been classified as a potentially hazardous chemical by the Australian Hazardous Chemical Information System [50]. The findings of this study revealed an average increase of 440% in limonene levels following painting, suggesting a potential risk for the onset of wheezing and asthma symptoms. Furthermore, secondary pollutants are generated when terpenes react with atmospheric oxidants such as ozone and hydroxyl radicals [46, 51, 52]. These byproducts have been shown to have adverse health effects.

3.2. Correlation Between Internal and External Exposure. Table S3 displays the concentrations (μg mg^{-1} creatinine) of hippuric acid, *p*-methylhippuric acid, and *o*-

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TABLE 1: List of all analytical instruments, sample types, and the corresponding analytes measured.

Instruments	Sample types	Analytes
Gas chromatography–mass spectrometry	Adsorbent	Benzene, toluene, ethylbenzene, *m,p*-xylenes, *o*-xylene, styrene, limonene, and α-pinene
Gas chromatography–mass spectrometry	Skin wash and stratum corneum	Toluene and *m*-xylene
Liquid chromatography–tandem mass spectrometry and high-performance liquid chromatography coupled with mass spectrometry	Urine	Toluene metabolite (hippuric acid) and *m*-xylene metabolites (*p*- and *o*-methylhippuric acids)

TABLE 2: Time table of panel study.

	First day	Second day	Third day	Fourth day
Painting	×	○	×	×
Passive sampling	×	○	×	×
Dermal exposure measurement	×	○	×	×
Collecting urine	○	○	○	○

methylhippuric acid in urine samples. The relationship between hippuric acid levels and personal exposure to toluene, as measured by passive sampling, was found to be insignificant, likely due to the various routes through which toluene exposure can occur [53]. However, a significant correlation was observed between the concentrations of *p*-methylhippuric acid and *o*-methylhippuric acid and personal inhalation exposure to *m*-xylene, as quantified by passive sampling (Figure 2). Four response groups were identified based on their metabolite levels measured after the painting experiment. In Group 1, the concentrations of both *m*-xylene metabolites (*p*-methylhippuric acid and *o*-methylhippuric acid) were undetectable following product use. In Group 2, metabolite levels were below $10\,\mu g\,mg^{-1}$ creatinine. Group 3 exhibited metabolite concentrations ranging from 10 to $50\,\mu g\,mg^{-1}$ creatinine, while in Group 4, concentrations exceeded $50\,\mu g\,mg^{-1}$ creatinine. The time-weighted average concentrations of *m*-xylene in air correlated with the concentration of its metabolites (*p*-methylhippuric acid and *o*-methylhippuric acid), with the exception of data from Volunteer 8. Both *m*-xylene and *p*-xylene were detected in the oil-based wood stain, with *m*-xylene constituting 1.1% and *p*-xylene constituting 0.28% of the formulation. As a result, it was assumed that the sum of concentrations of *m*-, *p*-, and *m*-xylene are identical. For the 12 volunteers whose *p*- and *o*-methylhippuric acid concentrations were undetected in urine, the average concentrations of *m*-xylene were below $10{,}200\,\mu g\,m^{-3}$ following both the first and second painting sessions. In contrast, for four volunteers with urinary concentrations of *p*- and *o*-methylhippuric acids under $10\,\mu g\,mg^{-1}$ creatinine, the average concentrations of *m*-xylene were 14,000 and $13{,}000\,\mu g\,m^{-3}$ after the first and second sessions, respectively. In volunteers whose urinary metabolite concentrations ranged from 10 to $50\,\mu g\,mg^{-1}$ creatinine (four individuals), the average *m*-xylene concentrations were 21,000 and $20{,}000\,\mu g\,m^{-3}$ after the first and second painting sessions, respectively. For the remaining three volunteers, whose *p*- or *o*-methylhippuric acid concentrations were higher than $50\,\mu g\,mg^{-1}$ creatinine, the average *m*-xylene concentrations were 29,000 and $27{,}000\,\mu g\,m^{-3}$, respectively, following the two painting sessions. With the exception of Volunteer 8, the sum of *p*- and *o*-methylhippuric acid concentrations in urine following both the first and second painting sessions demonstrated statistically significant correlations with personal inhalation exposure to *m*-xylene. The ANOVA *p*-values for these correlations were 9.4×10^{-9} and 6.3×10^{-8}, respectively, indicating strong associations at the 95% confidence level.

The dermal exposure to toluene and *m*-xylene, as measured in the SC and SW before and during the painting process, is presented in Table S4. Prior to painting, dermal exposure to both toluene and *m*-xylene was undetected, except for Panels 2, 3, and 19, where the measurements were unsuccessful. The sum of SC and SW concentrations for *m*-xylene exhibited a statistically significant correlation with the inhalation exposure to *m*-xylene during both the first and second painting sessions. The ANOVA *p* values were 6.8×10^{-8} and 2.5×10^{-7}, respectively, at the 95% confidence level. However, it is noteworthy that, with the exception of Panels 2, 3, and 19, no statistically significant correlation was found between the sum of *p*- and *o*-methylhippuric acid concentrations in urine after the first and second painting sessions and the sum of SC and SW for *m*-xylene. In both cases, the ANOVA *p* values exceeded 0.05, indicating a lack of correlation at the 95% significance level. Similarly, the sum of SC and SW concentrations for toluene demonstrated a statistically significant correlation with inhalation exposure to toluene during both the first and second painting sessions. The ANOVA *p* values were 3.6×10^{-7} and 6.7×10^{-7}, respectively, at the 95% significance level. These findings are consistent with the study by Levasseur et al. [36], which observed a significant correlation between the levels of ethyl, methyl, and propylparabens in hand wipes and wristbands, and their associated urinary biomarkers. In general, the chemicals present in passive samplers

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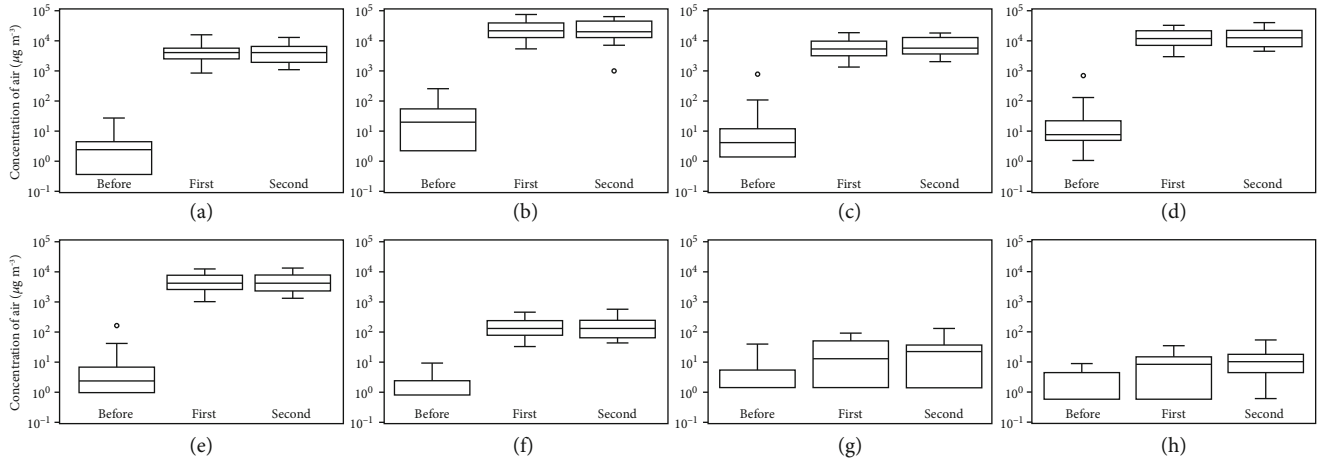

FIGURE 1: Box and whisker plot showing the log concentrations ($\mu g\,m^{-3}$) of (a) benzene, (b) toluene, (c) ethylbenzene, (d) *m,p*-xylenes, (e) *o*-xylene, (f) styrene, (g) limonene, and (h) α-pinene in apartments of 22 participants before, first, and second painting, respectively. The median is shown as the vertical line splitting the box into two means. The upper and lower boxes are the upper and lower quartiles. The whiskers are the two lines outside the box; the minimum value is at the start of the box, while the maximum value is at the end of the box. Points outside the box are potential outliers.

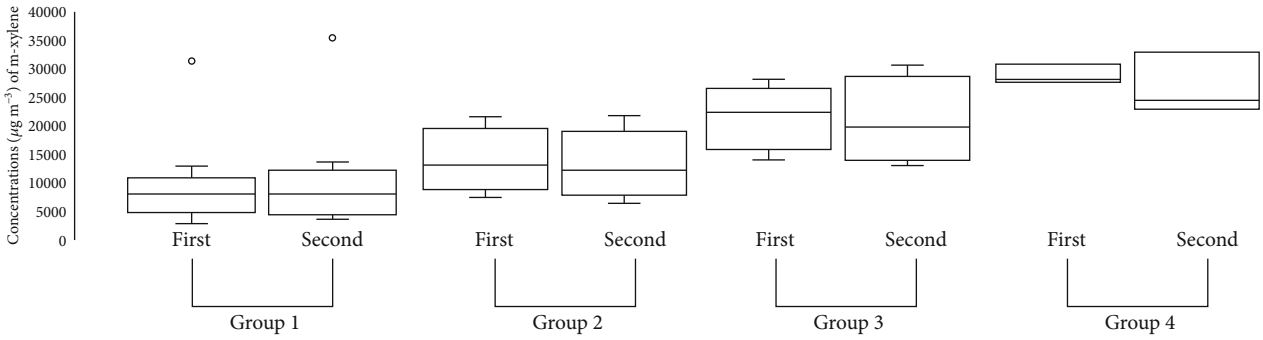

FIGURE 2: Box and whisker plots showing time-weighted mean concentrations ($\mu g\,m^{-3}$) of *m*-xylene in air as a function of *m*-xylene metabolite (*p*-methylhippuric acid and *o*-methylhippuric acid) concentration ($\mu g\,mg^{-1}$ creatinine) following exposure to oil-based wood stain paint during the first and second painting. Twelve panels in Group 1 had both metabolites undetectable after product use, four in Group 2 had either metabolite less than $10\,\mu g\,mg^{-1}$ creatinine, four in Group 3 had either metabolite between 10 and $50\,\mu g\,mg^{-1}$ creatinine, and three in Group 4 had either metabolite greater than $50\,\mu g\,mg^{-1}$ creatinine. The median is shown as the horizontal line splitting the box in two means. The upper and lower boxes are the upper and lower quartiles. The whiskers are the two lines outside the box; the minimum value is at the start of the box, while the maximum value is at the end of the box. Points outside the box are potential outliers.

exhibited a stronger correlation with urinary biomarkers than those found on hand wipes, which was similarly observed in the current study. The results suggest that inhalation exposure assessment using passive sampling provides a likely adequate understanding of human exposure to a wide range of VOCs emitted by consumer products.

Inhalation exposure was calculated using the inhalation rate for adults, which is $0.833\,m^3\,h^{-1}$ [54]. The indoor concentrations of toluene and *m*- and *p*-xylenes, measured after the first and second painting sessions and adjusted for baseline values prior to painting, were multiplied by the inhalation rate and the sampling duration of 30 min. On average, indoor toluene levels were 12,000 and 11,000 μg during the first and second painting sessions, respectively, while the corresponding concentrations for *m*- and *p*-xylenes were 5900 and 6000 μg, respectively. For dermal exposure, the sum of the SC and SW concentrations was divided by $9\,cm^2$, the exposed skin area during the panel study, and then adjusted to reflect the body surface area of an average adult, excluding the head, which is approximately $15{,}670\,cm^2$ [55]. The estimated inhalation exposure exceeded dermal exposure by several orders of magnitude, supporting the hypothesis that airborne VOCs are primarily absorbed via the respiratory tract during short-term indoor painting activities. This dominance of inhalation is consistent with the physicochemical properties of VOCs, particularly their high volatility and low dermal permeability. Moreover, the limited skin surface area exposed during the task further constrained dermal uptake, reinforcing the need

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to prioritize respiratory protection in DIY indoor environments. The dominant contribution of inhalation exposure over dermal exposure is likely attributable to the high volatility of VOCs, which facilitates their dispersion in air, whereas the skin acts as a protective barrier that limits the extent of systemic absorption through dermal contact.

4. Conclusions

Inhalation exposure to VOCs during the application of oil-based wood stain was assessed using ePTFE PS. Given these findings, caution should be exercised when painting indoors, as maintaining indoor air quality is crucial for protecting human health [56]. A statistically significant correlation was found between the inhalation exposure to *m*-xylene and toluene and the corresponding dermal exposure measurements. Additionally, statistically significant associations were observed between the inhalation exposure to *m*-xylene and its metabolite, whereas no significant correlations were detected between dermal exposure measurements and these variables. The findings suggest that passive sampling could serve as a viable alternative method for assessing human exposure. Notably, the inhalation exposure levels were found to be 630–1100 times higher than the corresponding dermal exposure levels in this study. These findings underscore the dominant role of inhalation as the primary exposure pathway for VOCs during indoor DIY painting activities, highlighting the need for stricter ventilation guidelines and consumer safety information. Furthermore, the demonstrated effectiveness of the ePTFE PS suggests it can serve as a valuable tool in real-world exposure assessment and public health risk mitigation strategies for VOC-emitting consumer products.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Pil-Gon Kim: writing—original draft, supervision, project administration, methodology, investigation, formal analysis, data curation, and conceptualization. Arum Lee: investigation, formal analysis, data curation, project administration, and methodology. Jee-Hyun Hwang: investigation, formal analysis, and data curation. Jaeho Shin: investigation, formal analysis, and data curation. Stefana Sochichiu: investigation, formal analysis, and data curation. Eugene Song: investigation, funding acquisition, and formal analysis. Kyung-Min Lim: investigation and formal analysis. Jaeyun Choi: investigation and formal analysis. Jung-Hwan Kwon: writing—review and editing, supervision, funding acquisition, and conceptualization. Pil-Gon Kim and Arum Lee contributed equally to this work.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* Figure S1: A photo image of a wearable ePTFE PS. Table S1: Volume (m^{-3}) of the balcony of apartments and used mass (grams) of oil-based stain during the first and second painting. Table S2: Concentrations ($\mu g\,m^{-3}$) of VOCs in the balcony of apartments before and while painting. Table S3: Concentrations (micrograms per milligram creatinine) of metabolite in the urine of volunteers. ND means not detected. Table S4: Dermally exposed mass (nanograms) of toluene and *m*-xylene before and while painting.

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