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Increase of the indoor concentration of volatile organic compounds after the use of incense and scented candle in studio apartments determined using passive sampling

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HIGHLIGHTS

- Personal exposure to VOCs by using incense and scented candles was assessed.
- Burning incense significantly increased average levels of benzene by a factor of 73.
- Emission of VOCs was significantly influenced by personal habitual use patterns.
- The presence of a wood core in an incense is related with elevated benzene emission.
- This study can assist in reducing personal exposure to VOCs by using incense and scented candles.

GRAPHICAL ABSTRACT



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ABSTRACT

Burning incenses and scented candles may provide harmful chemicals. Although many studies have evaluated volatile organic chemicals emitted by their use and related health risks, extension of our understanding for guiding appropriate use under various use conditions is necessary. In this study, emission characteristics of commercial incenses and scented candles were evaluated in a laboratory chamber using real-time measurement and the time-weighted average exposure concentrations of monoaromatic compounds and monoterpenes were assessed using passive samplers while volunteers living in a studio apartment use them. After burning incense, the average levels of benzene increased from 1.4 to 100 μg m^{-3}. The presence of a wood core in commercial incense products was the main cause of high benzene emission by burning them although the increase in benzene

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was also influenced by factors such as the brand of the products, the number of incense sticks burned, the duration of each burning session, and ventilation period. Electrical warming of scented candles increased the levels of monoterpenes by factors of 16–30 on average. Considering the emission characteristics found in this study, exposure to benzene and monoterpenes could be mitigated by cautious use of those products in residential areas.

1. Introduction

Consumer products such as essential oil diffusers, air fresheners, and laundry detergents are ubiquitous sources of indoor volatile organic compounds (VOCs) (Nematollahi et al., 2019; Steinemann, 2015, 2019a, 2019b). Among these products, incense and scented candles are widely used for religious ritual and air fragrance, emitting VOCs such as benzene and limonene (Salthammer et al., 2021; Thuy et al., 2022; Wong et al., 2020).

Earlier studies revealed that using incense and scented candles could increase indoor VOCs. For example, Lee and Wang showed that the benzene concentrations of 10 tested incenses in a 18.26 m^3 test chamber ranged 20.2–117 μg m^{-3}, significantly higher than the recommended indoor air quality objectives for office buildings and public places in Hong Kong (16.1 μg m^{-3}) (Lee and Wang, 2004). In temples, the emission of benzene from burning incense resulted substantially higher indoor concentration (98.82 μg m^{-3}) than those in regular workplaces (22.61 μg m^{-3}) ($p < 0.01$) (Navasumrit et al., 2008). During peak ritual periods in two temples, benzene concentrations were measured at 146 ± 14 μg m^{-3} and 84 ± 7.4 μg m^{-3} (Wang et al., 2007). The carcinogenic potency of benzene is already well acknowledged based on epidemiological studies that benzene causes acute myeloid leukemia (Gong et al., 2017; Wickliffe et al., 2020). International Agency for Research on Cancer also adds that multiple myeloma, non-Hodgkin lymphoma, acute lymphocytic leukemia, and chronic lymphocytic leukemia have all been associated with benzene exposure (American Cancer Society, 2016). Given the frequent burning incense for air freshening in homes nowadays, it is necessary to investigate the impact of burning incense on indoor benzene levels in residences since previous investigations have been limited to environmental chambers, offices, and temples. Safety guidance for commercial product use is required to reduce personal exposure to benzene in residential environments. Therefore, it is necessary to investigate exposure parameters that influence the time-weighted average exposure concentration of benzene. Additionally, it is necessary to investigate how the characteristics of commercial products are related with the emission of benzene.

Scented candle can increase indoor terpenes like limonene. The emission rates of limonene from burning scented candles ranged from 4 to 1184 ng h^{-1} (Salthammer et al., 2021). Emitted terpenes are potential allergens, resulting in skin irritation, asthma, and chest tightness (Su et al., 2007; Wolkoff and Nielsen, 2017). Research has indicated that a 100% increase in indoor limonene levels correlates with a proportional increase of 17–18% in both wheezing and asthma, along with a 1.55% elevation in exhaled nitric oxide (Dales and Cakmak, 2019). These effects were notably more pronounced in children, where the increase in adverse effects was approximately twofold. Considering these health implications, according to the hazardous chemical information system of Australia, limonene has been categorized as having the potential to cause hazardous health problems, category 1 for both skin sensitization and aspiration hazard, and category 2 for skin irritation (Australia Safe Work, 2020). Furthermore, terpenes react with oxidants like ozone and hydroxyl radicals producing secondary products that can be harmful (Carslaw, 2013; Huang et al., 2012; Nørgaard et al., 2014).

As general people spend approximately 90% and 50% of their lives in indoors and home, respectively (Klepeis et al., 2001; Kornartit et al., 2010; Robinson and Nelson, 1995), a competent method detecting indoor VOCs for evaluating time-weighted average exposure is needed after the combustion of incense and scented candle in living environment (Guo et al., 2004; McAlary et al., 2015; Mølhave, 1991; Weisel et al., 2008; Zhou et al., 2011). Active sampling is commonly used to monitor short-term exposure to VOCs because it is a straightforward method (Amaral et al., 2010; Gallego et al., 2017; Horii et al., 2017). However, it may not be suitable for long-term monitoring or for places where the use of an air pump is limited (Li et al., 2020; Seethapathy et al., 2008; Vallecillos et al., 2019, 2020, 2021). Alternatively, passive sampling is convenient, simple, and an inexpensive substitute to circumvent troubles of active sampling (Bohlin et al., 2007). A passive sampler was previously developed for detecting VOCs in indoor air using an expanded polytetrafluoroethylene (ePTFE) membrane with an adsorbent (Kim et al., 2021). After comparing with real-time monitoring using a proton-transfer-reaction mass spectrometer, the developed sampler has high accuracy and is rarely affected by air turbulence. The developed sampler was improved to increase its sampling rates and made wearable for measuring personal exposure (Kim et al., 2023). The improved sampler, called ePTFE PS, demonstrated high accuracy and was successfully utilized to monitor terpenes in living environments. Additionally, the tubes and adsorbents used in the ePTFE PS were relatively cheap, making it a cost-effective option.

This study determined the levels of volatile aromatic hydrocarbons and monoterpenes under the normal use conditions of incenses and scented candles as a significant source of indoor VOCs, using the ePTFE PS. Emission characteristics of commercial products were observed in a 125 L acrylic test chamber by real-time measurement. To assess personal exposure to VOCs by using those consumer products in a limited space, 50 volunteers who lived in studio apartments were recruited, and their exposure to benzene and monoterpenes was quantified. To closely simulate real-life conditions, volunteers used consumer products as usual, and their use patterns were recorded. Based on the volunteer survey and chemical analyses of products, exposure parameters affecting the time-weighted average exposure concentrations of benzene were identified for guiding appropriate use.

2. Materials and methods

2.1. Chemicals and instruments

The target VOCs, benzene, toluene, ethylbenzene, *m*, *p*-xylenes, styrene, limonene, α- and β-pinenes, γ-terpinene, and internal standards (toluene-d_8, chlorobenzene-d_5) were purchased from Sigma-Aldrich (Milwaukee, WI, USA). A solvent extraction method using dichloromethane (DCM) (Sigma-Aldrich) spiked with internal standards was employed to extract VOCs from the adsorbent. Gas chromatography-mass spectrometry (GC-MS) analysis was performed using an Agilent 6890A gas chromatograph (Santa Clara, CA, USA) and an Agilent 5973 N mass selective detector equipped with an Agilent 7683 auto-injector and an Agilent DB-5 column (30 m × 0.25 mm × 0.25 μm). During the analysis, the injection volume was 2 μL and the split ratio was 5:1. Helium served as the carrier gas, maintained at a constant flow rate of 1.0 mL min^{-1} The oven temperature followed a specific protocol: it was initially set to 40 °C for 2 min, then increased at a rate of 10 °C min^{-1} until reaching 100 °C, and finally further increased at the same rate to reach 270 °C.

2.2. ePTFE PS

The passive sampler consisted of 500 mm ePTFE tubes (ID 2 mm; OD

4 mm, Huizhou Besteflon Industries Co. Ltd., Guangdong, Sijiaolou Industrial Zone) and 0.9 g of Optipore-L493 (Sigma Aldrich) adsorbent with a high sorption capacity for VOCs (Bonifacio et al., 2017). The tubes were washed with a mixture of 50 mL *n*-hexane and 50 mL acetone using Soxhlet extraction for 12 h. The ePTFE PS was designed to be wearable as a wristband (Fig. S1, Supplementary Material). After the exposure period, the ePTFE PS was immersed in a 40-mL vial containing 10 mL of DCM and left for 1 d to extract VOCs. The concentration of VOCs in DCM was determined using GC-MS.

2.3. Evaluation of performance characteristics of ePTFE PS for detecting volatile aromatic hydrocarbons

Predetermined volumes, 0.5, 1, and 1.5 μL, of benzene, toluene, ethylbenzene, *m,p*-xylenes, and styrene were injected into the closed 125 L acrylic chamber maintained at 23 ± 1 °C and the aliquot was allowed to evaporate completely. Three ePTFE PS were placed for 5, 10, and 15 min in the chamber containing desired concentration of VOCs and were extracted for determining the sampling rates. The mass accumulation rates [μg h^{-1}] were determined by applying linear regression between the extracted mass of target VOCs and the sampling time. Then, the sampling rate [L h^{-1}] was calculated by dividing the mass accumulation rate by the concentration of VOCs in the chamber [μg L^{-1}]. In our previous studies, ePTFE PS showed high accuracy compared with real-time analysis and active sampling technique (Kim et al., 2021, 2023). Additionally, ePTFE PS was validated for assessing the time-weighted exposure concentration of VOCs under real exposure conditions (Kim et al., 2023). For terpenes, the sampling rate measured from a previous study were used (Kim et al., 2023). To determine the concentration of indoor VOCs [μg m^{-3}], extracted mass [μg] of VOCs from sampler was divided by sampling volume [m^3], which was calculated by multiplying the sampling rate of VOCs with sampling time, 3 h. The linear mass accumulation of ePTFE PS for all target VOCs was monitored over a period of 3 h in the preliminary experiments.

2.4. Commercial products

Emission characteristics of commercial products were tested in the closed 125 L acrylic chamber maintained at 23 ± 1 °C and 70 ± 10% (relative humidity) by real-time measurement using a proton transfer reaction time-of-flight mass spectrometer (PTR-TOF-MS) (IONICON, Innsbruck, Austria) in which H_3O^+ as the selective reagent ion. The gas flow rate, inlet temperature, E/N ratio, and the pressure of the drift tube were set as 2.00 cm^3 min^{-1}, 80.0 °C, 140 Td, and 2.3 mbar, respectively. The *m/z* values of 79.0542 ($(C_6H_6)H^+$) and 137.1325 ($(C_{10}H_{16})H^+$) were used to analyze benzene and monoterpenes, respectively (Yuan et al., 2017). Scented candles used in an electrical warmer were chosen considering the market share of major brands. For incense, the same products used by volunteers were evaluated without changing their habitual use patterns. They reported eleven different brands of incense products, among which products C (4 volunteers) and D (7 volunteers) were most frequently used, as shown in Table S1. Product I, which did not seem to emit benzene, was selected for control. Product C, D, and I burned out for 42, 59, and 27 min, respectively, in the 125 L acrylic chamber.

For the calibration of PTR-TOF-MS for benzene, aliquots of 5% (v/v) benzene solution in ethanol was dropped on the bottom of the closed chamber and allowed to volatilize. After complete volatilization in 10 min, more aliquots of the solution were added to increase benzene concentration. The PTR-TOF-MS signal for benzene was monitored by incremental addition to nominal concentrations of 0.15–22 μg L^{-1}. Signals in arbitrary units measured by PTR-TOF-MS and spiked concentration of benzene in chamber showed high linearity, with R^2 of 0.99 as shown in Fig. S2. After sufficient ventilation (>1 d), model scented candle in an electrical warmer was deployed in the chamber for 2.3 h, and benzene and monoterpenes were analyzed simultaneously.

To compare the contribution of commercial incense characteristics to benzene emissions, commercial product C, D, and I were selected. They burned for 48, 60, and 30 min, respectively, and then turned off by themselves in the 125 L acrylic chamber. The elevation of CO and CO_2 in each chamber after combustion was monitored with a Combo Air Quality Meter (DAIHAN®, Gangwon-do, Republic of Korea).

2.5. Panel study

A consumer panel of 25 volunteers (mostly university students) living in studio apartments, who had experience using scented candles, was recruited for the study. The volunteers were instructed to wear an ePTFE PS or hung it up near their activity area while using the model scented candle with an electrical warmer for 3 h.

The impacts on indoor VOCs levels by burning incense was assessed with another group of 25 volunteers who regularly used incense. The group was asked to wear an ePTFE PS or hung it up near their activity area for 3 h after starting to use incense as they usually would.

For the sampling process, each of 50 volunteers was provided with two ePTFE PS and two 40-mL vials containing 10 mL of DCM. After sampling, the ePTFE PS was submerged in the vials for extraction.

The indoor temperature of the studio apartment was assumed to be remained relatively stable at 23 °C at which the sampling rates of the ePTFE PS for VOCs were calibrated in the laboratory experiment. As temperature changes, the diffusion coefficients of VOCs in ePTFE PS can be altered, although not to a significant extent. According to the user manual of a commercial Radiello™ passive sampler, which has a similar composition to ePTFE PS, the estimated diffusion coefficients of benzene, ethylbenzene, and *m,p*-xylenes in air at 23 °C are 1.1 times greater than the corresponding values at 10 °C (Król et al., 2012). In a previous study, the effect of temperature on the 3M 3520 passive sampler was observed (Chung et al., 1999). The sampling rates of benzene, toluene, and styrene at 25 °C increased by factors of 1.15, 1.16, and 1.04, respectively, compared to the corresponding values at 10 °C. Therefore, it was hypothesized that the effect of temperature on passive sampling is not significant within the temperature variation of 10 °C. The study was approved by the Institutional Review Board (IRB) of Korea University (approval number: KUIRB-2022-0264). The panel study was conducted during April and May 2023.

2.6. Quality assurance and quality control

To establish the method detection limits (MDLs) of ePTFE PS, seven ePTFE PS were spiked for 1 h with benzene, toluene, ethylbenzene, *m,p*-xylenes, and styrene at concentrations of 0.48, 2.9, 1.8, 2.0, and 1.9 μg m^{-3}, respectively. The MDLs of the ePTFE PS for the 5 VOCs were calculated by multiplying the standard deviations of the spiked VOCs with 3.14 (Glaser et al., 1981). The determined MDL values of the ePTFE PS for benzene, toluene, ethylbenzene, *m,p*-xylenes, and styrene were 0.23, 1.4, 0.90, 0.66, and 0.56 μg m^{-3}, respectively, when the sampling time was set to 3 h. For terpenes, the MDL measured from a previous study were used (Kim et al., 2023). When calculating the time-weighted average concentrations of VOCs, the mass of VOCs in the 20 blank ePTFE PS samples was considered. The extracted samples were calibrated using the internal standards toluene-d_8 and chlorobenzene-d_5.

3. Results and discussion

3.1. Evaluation of ePFTE PS for detecting volatile aromatic hydrocarbons

The mass accumulation rates of ePTFE PS for target VOCs are shown in Fig. S3. The slopes in Fig. S3 were used as the mass accumulation rates [μg h^{-1}], and the mass accumulation of VOCs increased linearly over time. The mass accumulation rate of the ePTFE PS showed a linear increase in relation to the concentration in the air, with R^2 exceeding 0.99, as shown in Fig. 1. The slopes in Fig. 1 are showing the sampling rates (L

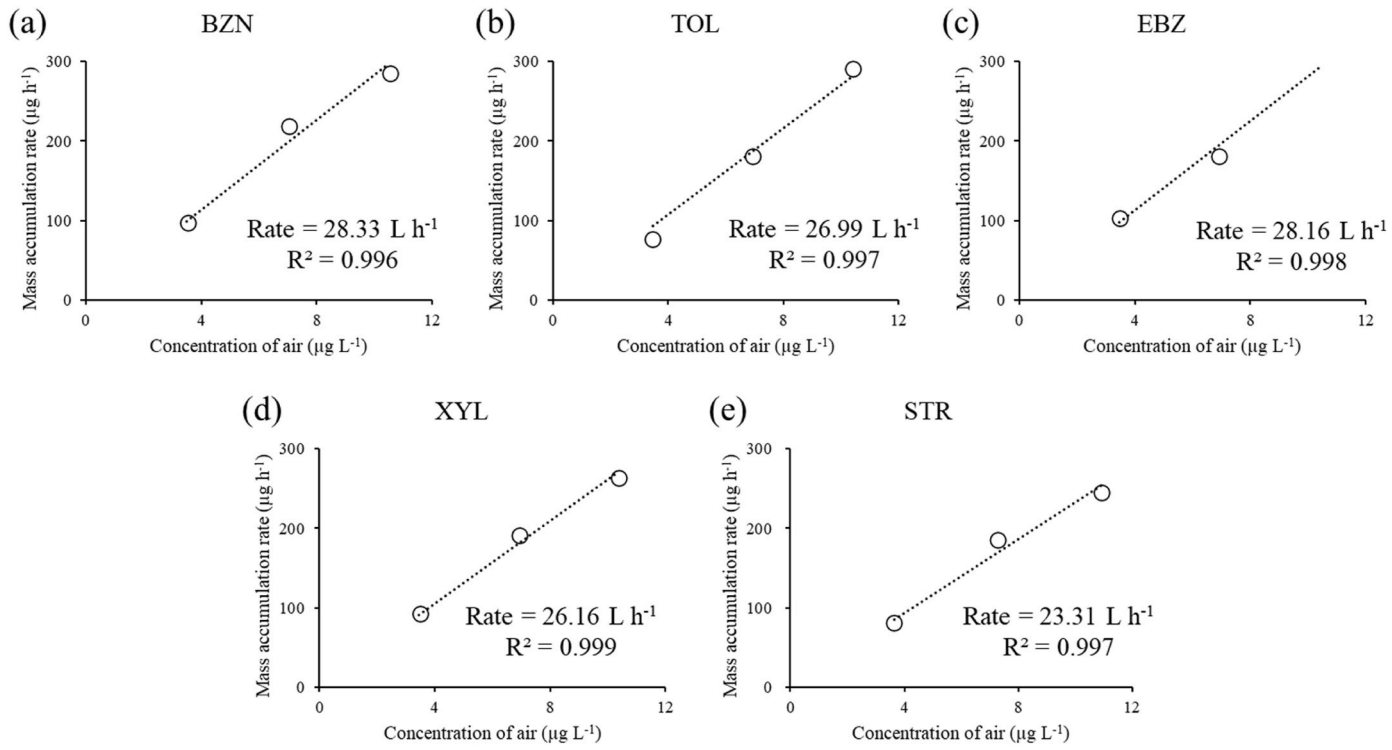


Fig. 1. Sampling rates (L h^{-1}) of (a) benzene, (b) toluene, (c) ethylbenzene, (d) *m, p*-xylenes and (e) styrene.

h^{-1}). Compared to the sampling rates of commercial passive samplers for VOCs, including the SKC Ultra passive sampler (SKC Ltd., Dorset, UK), the Radiello diffusive sampler (Fondazione Salvatore Maugeri, Padova, Italy), and a cylindrical sampler containing Tenax, which varied between 1 and 1.8 L h^{-1} (Coutant et al., 1986; Król et al., 2012; Lewis and Mulik, 1985; Lewis et al., 1985; McAlary et al., 2015; Pennequin-Cardinal et al., 2005), the ePTFE PS, which has a higher sampling rate, can be a cost-effective and efficient alternative to existing passive samplers for VOC monitoring.

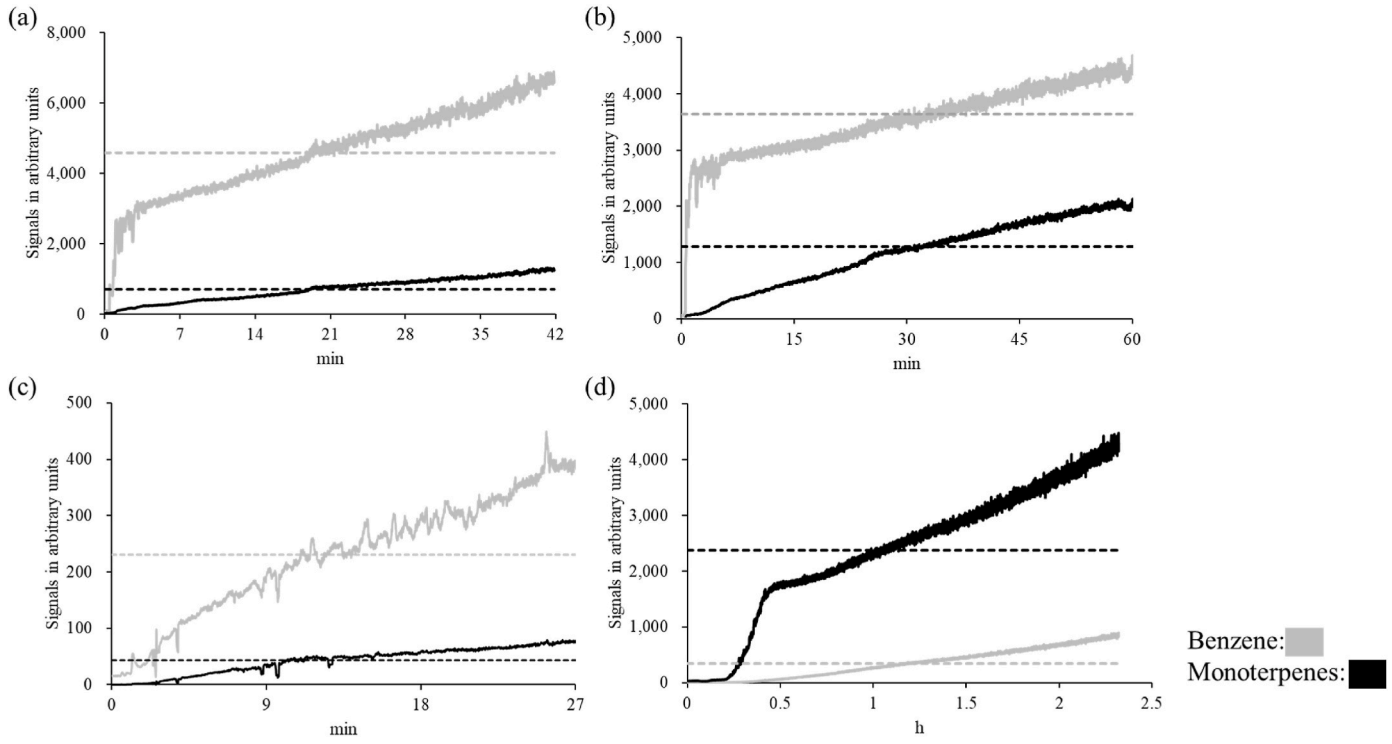


Fig. 2. Signals in arbitrary units of benzene and monoterpenes measured by PTR-TOF-MS while burning an incense stick, product C (a), D (b), and I (c) before turning off by themselves. Signals in arbitrary units of benzene and monoterpenes measured by PTR- TOF-MS while deploying a model scented candle for 2.3 h (d). Line means real-time analysis and dotted line means time weighted average concentrations.

3.2. Emission characteristics of commercial products

As shown in Fig. 2(a)-(c), the average signals in arbitrary units of benzene and monoterpenes were increased during the burning of an incense stick in a 125 L chamber. Since monoterpenes with the same molecular weight cannot be specified into isomers, limonene, α- and β-pinenes, and γ-terpinene, using the PTR-TOF-MS, individual calibration was not possible. Therefore, an arbitrary unit was employed for comparison. For products C, D, and I, the average signals in arbitrary units of benzene were higher than those of monoterpenes by factors of 6.5, 3.0 and 5.3, respectively. As shown in Fig. 2(d), the average signals in arbitrary units of benzene and monoterpenes were 350 and 2400, respectively. The signals in arbitrary units of monoterpenes were 6.9 times higher than those of benzene. The burning of incense and the use of scented candles emitted predominantly benzene and monoterpenes, respectively. After an incense stick was extinguished by itself, the signals in arbitrary units of benzene and monoterpenes reached a plateau, suggesting that chemicals are emitted only while an incense stick is burning. Therefore, the time spent burning incense per session and the number of incense sticks burned may affect the mass of chemicals emitted. As shown in Fig. S4, slope of Fig. S2 was used to quantify the concentration of benzene in the chamber. The mass of benzene emitted by burning an incense stick, which was calculated with the volume of chamber, 125 L, differed significantly between product manufacturers. The time-weighted average mass of benzene emitted by burning products C, D and I were estimated 220, 110 and 16 μg min^{-1}, respectively. The results suggest that the type of products can significantly affect the emission of benzene. In Fig. 2(a), (b), and (d), which show high emission of VOCs by using products, the initial emission increased drastically with sharp slope, while Fig. 2(c) shows linear emission with constant slope. Insufficient mixing in the chamber and direct injection of VOCs from the products into the PTR-TOF-MS could be a reason.

After burning products C, D, and I in the 125 L acrylic chamber, the levels of CO in each chamber were 820, 820, and 300 ppm, respectively. The corresponding levels of CO_2 were 5500, 4900, and 2400 ppm, respectively. Prior to burning the incense, the background concentrations of CO and CO_2 were below the detection limit (10 ppm) and 800 ppm, respectively. Products C and D emitted more CO and CO_2 than product I due to greater mass and longer burning time. The degree of incomplete combustion as appeared in the ratio of emitted CO to CO_2 for products C, D, and I were 0.17, 0.20, and 0.17, respectively, deducting the background concentration of CO_2. This indicates that incomplete combustion is not the cause of the significant difference in benzene emission. Commercial incense products can be classified into two types based on the presence or absence of a wood core. Products C and D, which include a wood core, emitted much higher levels of benzene than product I, which excludes a wood core. Therefore, the presence of a wood core in commercial incense products appears to be the main reason for high benzene emission.

3.3. Panel study

The concentrations of VOCs in the studio apartments before and after incense burning are shown in Table S2. Burning incense significantly increased benzene in the studio apartments of 22 volunteers, as shown in Fig. 3. On average, benzene concentrations increased from 1.4 to 100 μg m^{-3} after incense burning. Lee and Wang (2004) demonstrated a comparable range of benzene concentrations (20.2–117 μg m^{-3}) in an 18.26 m^3 test chamber after incense burning. The effect of burning incense was statistically significant only for benzene among the target VOCs, the *p*-value of the paired sample *t*-test was 0.034 at the 95% confidence level. Several factors such as product brand, amount of incense burned, duration of each burning session, ventilation, and volume of studio apartments were recorded as given in Table S1. Direct comparisons of the exposure to emitted mass (μg) of benzene among volunteers showing the effects of those exposure factors are summarized in Table 1. As this comparison was based on only one volunteer against another, with only a single test each, larger scale comparison is necessary. The amount of benzene emitted was calculated using the volume of each volunteer's studio apartment. The effect of the number of incense sticks burned can be observed by comparing the panel study results of volunteers 15 and 17, as shown in Table 1. Their exposure factors of using incense were the same except for the number of incense sticks burned. Volunteer 15 burned only one incense stick for 3 h, while volunteer 17 burned 3 incense sticks during the same period. The mass of benzene emitted by incense burning in the studio apartment of volunteer 17 was 3.4 times higher than that of volunteer 15. Similarly, the effect of the time spent burning incense per session can be seen by comparing the results of the panel study of volunteers 4 and 11. Volunteers 4 and 11 burned an incense stick for 11 and 50 min, respectively. The mass of benzene emitted by incense burning in the studio apartment of volunteer 11 was 3.3 times higher than that of volunteer 4. The effect of the duration of ventilation can be observed when comparing the results of the panel study of volunteers 7 and 13. While volunteer 7 closed the window and door during the panel study, volunteer 13 ventilated for 3 h. The mass of benzene emitted by incense burning in the studio apartment of volunteer 7 was 2 times higher than that of volunteer 13, relatively lower effects than other factors. The effect of product brand can be seen when comparing the results of the panel study of volunteers 1 and 2, using products A and B, respectively. The mass of benzene emitted by incense burning in the studio apartment of volunteer 2 was 2.5 times higher than that of volunteer 1, even though volunteer 1 burned 2 incense sticks. A wood core was absent in products A, E, F, H, I, J, and K, while products B, C, D, and G contain a wood core. Panel study strongly supports that incense

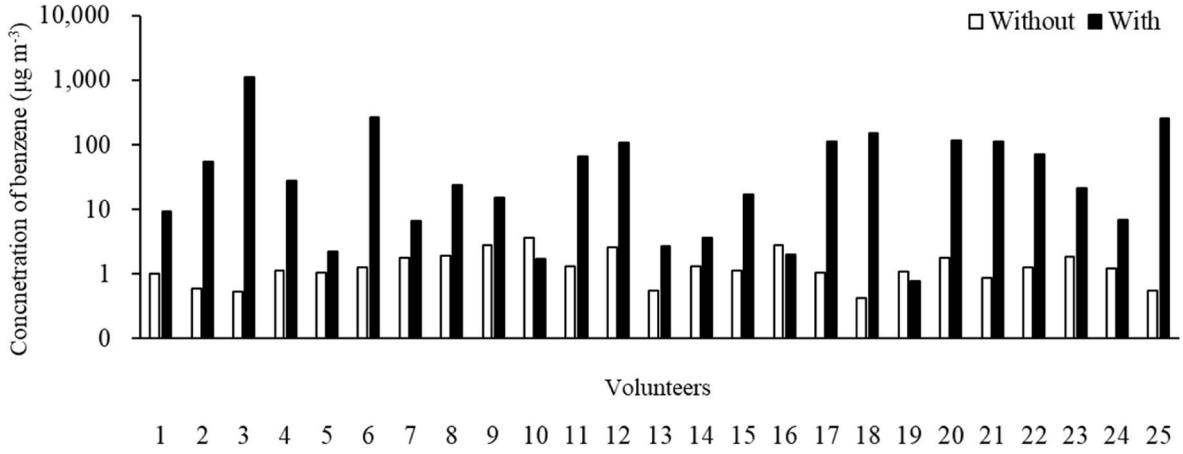


Fig. 3. Concentrations of benzene (μg m^{-3}) in studio apartments with and without burning incense.

Table 1
Effects of exposure factors on the mass of emitted benzene for selected volunteers showing contrasts in their normal use habits.

Exposure factors	Product brand	The time spent burning incense per session (min)	The number of incense sticks	The duration of ventilation (min)	The mass of emitted benzene (μg)
Product brand	A (volunteer 1)	60	2	180	540
	B (volunteer 2)	60	1	180	1300
The time spent burning incense per session	D (volunteer 4)	11	1	55	1000
	D (volunteer 11)	50	1	65	3300
The number of incense sticks	G (volunteer 15)	60	1	180	740
	G (volunteer 17)	60	3	180	2500
The duration of ventilation	F (volunteer 7)	30	1	0	180
	F (volunteer 13)	20	1	180	90

sticks with a wood core emits much more benzene than those without. After burning products without a wood core, the average increase of benzene in studio apartments was 4.4 ± 3.6 times higher than before, with a range of 0.47–12. When burning products with a wood core, the average increase of benzene in studio apartments was 120 ± 130 times higher, ranging from 3 to 460, except for panel 3 who burned 5 incense sticks for 3 h. Although there were uncertainties in ventilation rate, spatial uncertainties associated with the location of passive samplers from the source (Jung et al., 2021), this dramatic differences in the exposure concentration of benzene suggests that a wood core should be removed at the expense of brittleness of the product.

The indoor benzene concentration increased the most, by a factor of 2100, in the studio apartment of volunteer 3. This can be explained by the greatest use frequency, burning 5 sticks for 3 h. Product D was the most frequently used (n = 7), followed by product C (n = 4). Burning product C resulted in the highest average increase in benzene with a factor of 670. The average increase in benzene by burning product D was a factor of 130. On the other hand, products I and J were used by only one volunteer each and their effects on indoor benzene were considered insignificant. As products that are commonly used tend to emit higher levels of benzene, it is important to be cautious when selecting products. The products used by several volunteers increased benzene in all the studio apartments tested, except for product F. Burning product F increased benzene in the apartments of volunteers 7 and 10 by a factor of 4 and 5, respectively. Although volunteer 10 used 2 incense sticks of product F for 3 h, the benzene concentration decreased. As the time spent burning incense per session can affect the mass of chemicals emitted, the shorter duration of incense burning sessions, 10 min, could potentially explain this decrease.

The concentrations of VOCs in studio apartments before and after using a model scented candle are shown in Table S3. Using a scented candle increased average concentrations of limonene, α- and β-pinenes, and γ-terpinene by factors of 16, 19, 30, and 28, respectively in studio apartments of 25 volunteers as shown in Fig. 4. Before and after using a model scented candle, concentrations of limonene were highest, 20 and 320 μg m^{-3}, respectively. The *p*-values of the paired sample *t*-test for all target terpenes were lower than 0.00001 at the 95% confidence level. Increased indoor limonene, using a reference exposure concentration of limonene at 55 μg m^{-3} (Wallace, 1991), was correlated with an increasing wheezing and asthma, and these effects were more significant in children (Dales and Cakmak, 2019). In this study, limonene increased by approximately 1600% after using the scented candle in the studio apartments, 580 % greater than 55 μg m^{-3}. For other VOCs, increase of indoor concentrations by using scented candle were not statistically significant ($p > 0.05$), and the differences before and after product use were within a factor of two.

4. Conclusions

Burning incense for air freshening in studio apartment significantly elevated average benzene levels by a factor of 73. Considering that this panel study was conducted only for 3 h, a short exposure time, it is necessary to reduce the exposure to extraordinarily high benzene concentration from burning incense in limited indoor residential spaces. Since benzene emission strongly depended on product brand, it is required to set a safety standard based on the measured emission rate in a test chamber, especially for those products containing wood cores frequently used by consumers. Removing a wood core in incense products would be important modification of products to lower benzene emission. As a consumer-level mitigation measure, it is also important to

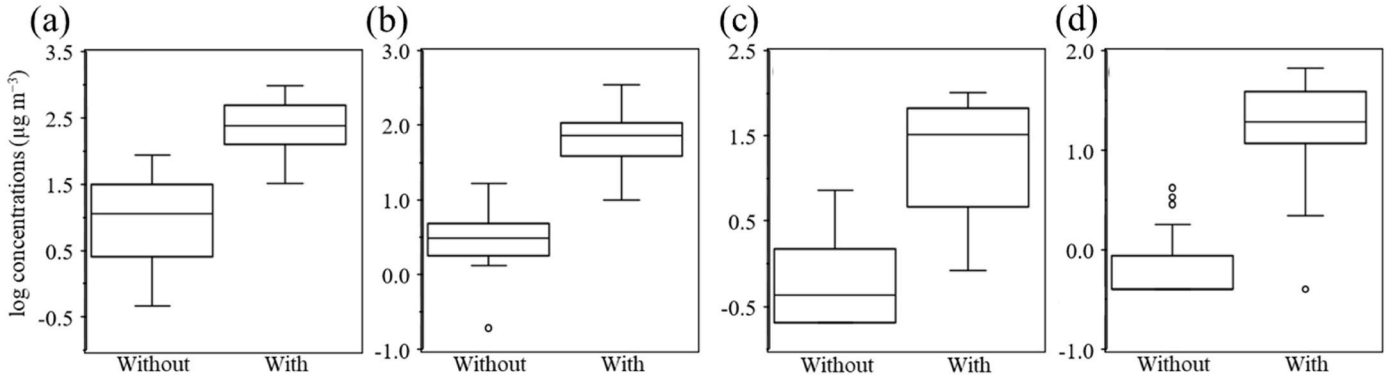


Fig. 4. Box-and-whisker plot showing the log concentrations (μg m^{-3}) of (a) limonene, (b) α-pinene, (c) β-pinene, and (d) γ-terpinene in studio apartments of 25 participants with and without the use of the scented candle. The median is shown as the vertical line splitting the box in two means. The 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.

ensure adequate ventilation when burning incense and not to overuse them. Because benzene is only emitted while burning of incense, it is recommended to reduce the duration of each incense-burning session.

The use of scented candles was observed to elevate indoor terpenes. Although the health risks associated with exposure to terpenes should be much lower than those of benzene, secondary products that might form from reactions of terpenes could be an important health concern. Considering the correlation between increased wheezing and asthma symptoms and elevated indoor limonene levels, cautious use of scented candles is necessary especially when they are used within a limited volume such as a studio apartment.

CRediT authorship contribution statement

Pil-Gon Kim: Writing – original draft, Methodology, Investigation, Conceptualization. **Arum Lee:** Methodology, Investigation. **Jaeho Shin:** Investigation. **Eugene Song:** Investigation, Conceptualization. **Yerim Koo:** Investigation. **Stefana Sochichiu:** Investigation. **Dana Fahad M. S. Mohamed:** Investigation. **Soobin Choi:** Investigation. **Yongseok Hong:** Writing – review & editing, Conceptualization. **Jung-Hwan Kwon:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2024.142344.

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