Health Risk Assessment of Volatile Organic Compounds for Children in Indoor Air, Ulaanbaatar, Mongolia

Oyun-Erdene Otgonbyamba 1,2, Gantuya Ganbat 3, Ser-Od Khuyag 4, Enkhjargal Altangerel 5, Bilguun Ganbold 1, Altangadas Bayanjargal 6, Altangerel Bat-Erdene 6, Bataa Chuluunbaatar 7, Burmaajav Badrakh 2, Suvd Batbaatar 1,2 *

1 National Center for Public Health, Ulaanbaatar, Mongolia
2 “Ach” Medical University, Ulaanbaatar, Mongolia
3 German-Mongolian Institute for Resources and Technology (GMIT), Ulaanbaatar, Mongolia
4 Mongolian National University of Medical Sciences, Ulaanbaatar, Mongolia
5 Academy of Medical Professionals, Ulaanbaatar, Mongolia
6 “Green Crown” laboratory LLC, Ulaanbaatar, Mongolia
7 United Nations Children’s Fund, Ulaanbaatar, Mongolia

ABSTRACT

This study presents levels of volatile organic compounds (VOCs) measured indoors for the first time in Ulaanbaatar, Mongolia, and quantifies the health risk for children emphasizing the urgent need to improve control for indoor VOCs sources. The 583 samples collected at 144 sites, including new buildings, old apartments, schools, workplaces, kindergartens, baishin, and Mongolian traditional gers, hospitals, schools, and shopping centers are analyzed. Formaldehyde was detected in 95.7% of the samples, while benzene was in 24.2%. The levels of benzene, toluene, and xylene in new and old buildings and apartments exceed the recommended values of AGÖF for volatile organic compounds in indoor air. The probabilistic Monte Carlo simulation method was used to estimate the risk exposure of four types of VOCs (benzene, formaldehyde, toluene, and m,p-xylene) to the health of the study population. The risk of cancer for benzene and formaldehyde is high in the age group of 7 months–4 years, m,p-xylene, and toluene show non-cancer risk in this age group.

Keywords: Volatile organic compounds, Indoor air, Health risk assessment, Children, Ulaanbaatar

1 INTRODUCTION

People spend 87% of their lives indoors (Klepeis et al., 2001) where the concentrations of some pollutants are found to be 2–5 times higher than outdoors (Kim et al., 2012; Wallace et al., 1986). The major indoor air pollutants include carbon monoxide; volatile organic compounds (VOCs) which include formaldehyde and benzene other compounds emitted from sources such as solid fuels, smoking, gas-fired building materials; and furniture. These indoor air pollutants pose cancer and non-cancer risks to human health and the risk of death from acute carbon monoxide poisoning (Chaiklieng et al., 2021; Lai et al., 2004; Lee et al., 2018; Oyun-Erdene et al., 2023, 2021; WHO, 2014; WHO/Europe, 2014).

The International Agency for Research on Cancer has classified benzene and formaldehyde as Group 1 carcinogens, and short-term exposure can cause eye, nose, and throat irritation, headache, cough, and asthma (Cogliano et al., 2005; Wei et al., 2013). People are exposed to pollutants through inhalation, ingestion, and skin contact, and VOCs (benzene, xylene, and aldehydes) in indoor air have been found to enter the human body primarily through inhalation (Azuma et al., 2016; Bradman et al., 2017; Jiang et al., 2022; Kang et al., 2017; Rajasekhar et al., 2020). Population
groups spending long hours indoors are exposed to VOCs. For example, in a study of exposure to VOCs, cancer risk was highest among housewives (Guo et al., 2004). A study in Argentina found that the lifetime risk of cancer from exposure to benzene exceeded the limit set by the United States Environmental Protection Agency (U.S. EPA). Furthermore, it is possible to influence relapses and exacerbations of asthma in children exposed to indoor pollutants (Chin et al., 2014). VOCs are emitted from various solvent liquids, paints, pressed wood, and plastic materials and pollute the indoor air affecting human health, and causing cancer (Cogliano et al., 2005; Wei et al., 2013).

Children are more vulnerable and sensitive to the harmful effects and environmental toxins of air pollutants than adults. Children are more seriously affected, due to their higher breathing volume per body weight, and due to the fact that their pulmonary system is still under development (Stamatelopoulou et al., 2019; U.S. EPA, 2008). With age, children like adults, become exposed through inhalation, dermal absorption, and endogenous exposures, when toxins stored in tissue are released as a result of physiological changes such as eating disorders, pregnancy, lactation, osteoporosis, menopause, or calcium deficiency (Abadin et al., 2007).

Researchers point out that air pollution is rapidly increasing in Mongolian cities due to urbanization, poverty, coal combustion, and vehicle emissions, especially in Ulaanbaatar, which is highly polluted. The negative impacts (Allen et al., 2013; Enkhjargal et al., 2020; Guttikunda, 2008; NCPH, 2018) of outdoor and indoor air on health appear to be strongly related (Enkhjargal et al., 2008). As of 2020, 4 out of 10 people of the Mongolian population live in Ulaanbaatar; 77% of them live in baishins (free-standing structures unattached to any infrastructure such as central heating, proper sanitation, electricity) and apartments, and 22% live in Mongolian traditional gers (yurts) (NSO, 2021).

In recent years, the impacts of air pollution in Ulaanbaatar on public health have been examined in various research studies (Barn et al., 2018; Enkhbat et al., 2021, 2016; Galsuren et al., 2022; Suvd et al., 2020; Tsogtbaatar et al., 2017); however, there has been little attempt to systematically identify VOCs in various indoor environments in Ulaanbaatar and assess the health risks. VOCs such as formaldehyde, benzene, toluene, ethylbenzene, m,p-xylene, and o-xylene were found in the indoor air of offices, schools, kindergartens, hospitals, and houses (Davaalkham et al., 2019; Oyun-Erdene et al., 2019).

In 2020, the Mongolian Ministry of Health and the “Green Crown” environmental laboratory jointly tested 8 types of products, such as paints, tiles, solvents, and emulsions, to determine the level of VOCs released into the indoor environment. According to the tests, benzene, ethylbenzene, m, x-xylene, and toluene were 1.3–117.2 times the permissible levels in Mongolia. It should be noted that outdoor air quality standards exist in Mongolia (MASM, 2016), but there are no national standards requirements, controls, or monitoring of indoor air quality. As of 2022, in Mongolia about 10 percent of the population are children aged 0–6-year-old (MSIS, 2022). In general, children aged 0–3 years spend 8–9 hours per day at home with caregivers, while children aged 3–5 years spend 8–9 hours in kindergarten per day during the work week (World Bank, 2017); the rest of the time at home. According to a study (Naransukh et al., 2018) children aged 6–13 years in Ulaanbaatar spend 81% of their time (19.4 hours day⁻¹) at home, 16% (3.9 hours day⁻¹) at school, and 3% (0.7 hours day⁻¹) on their way to class or home.

It is also necessary to calculate the lifetime risk of cancer from benzene and formaldehyde since spending long periods indoors such as at home, school, or kindergarten with VOCs exceeding acceptable values would likely have a negative impact on health. Thus, in this study, we aimed to quantify VOCs in different indoor locations in Ulaanbaatar, Mongolia, and conduct an assessment to estimate children’s health risks. To the authors’ knowledge, this is the first study to define the level of indoor environment VOCs, and to evaluate its cancer and non-cancer risk for Mongolian children who inhabit these spaces. This evidence can be used for the next actions to be taken by the Government of Mongolia, to prevent children’s exposure to VOCs in the surrounding indoor environment.

2 MATERIALS AND METHODS

2.1 Sampling of Sites and Method of Analysis

In this study, a total of 583 samples of indoor air were collected from 144 sites which consisted of new buildings (n = 380), old apartments (n = 144), offices (n = 38), kindergartens (n = 20), baishins
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(n = 16), Mongolian traditional gers (n = 15), hospitals (n = 14), schools (n = 9), and shopping centers (n = 7) from November 2019 to July 2020 in Ulaanbaatar. The sample collection criteria is as follows: 1) samples from newly constructed buildings and apartments were obtained 28–30 days after completion of the construction, based on complaints from owners who complained of a strong smell, 2) samples from households and all other sites were obtained with approval from the inhabitants/owners.

In this study, 67% of the total samples were from residential buildings such as apartments, and baishins, while the remaining samples included other sites such as offices and educational institutions. All surveyed apartments, kindergartens, schools, hospitals, baishins, some office buildings, and Mongolian traditional gers have conventional ventilation, very few office buildings support central air conditioning. In winter, windows were typically closed due to outdoor air pollution and cold weather. Approximately 93.1% (543) of the samples were taken from buildings with central heating and 6.9% (40) from baishins with no central heating. The average room area was 27.5 ± 23.2 m² (22.3 ± 4.7 m² for apartments with partial heating and 27.8 ± 25.4 m² for apartments and offices with central heating). During the measurement, the mean indoor air temperature was 20.1 ± 3.6°C and the average atmospheric pressure was 983.62 ± 69.7 kPa.

Samples of VOCs (toluene (C₇H₈), benzene (C₆H₆), M-p-o-xylene (C₈H₁₀)), and formaldehyde (CH₂O) were collected according to NIOSH 1501, ISO 16017 using method (NIOSH)3501 and analyzed in an environmental laboratory accredited by MNS ISO/IEC 17025:2018. All interior doors and windows were closed and any air conditioners were shut down for 8 hours before sampling. The active sampling tube (SKC pocket pump210-1002, SKC Ltd., USA) was pre-adjusted to a rate of 0.01–0.2 L min⁻¹ for 40 min in solution (SKC absorbent charcoal tube. SKC Ltd., USA), at a height of 1–1.5 meters. Samples were taken from kitchens, bedrooms, living rooms of baishins and apartments, offices frequently occupied by people, classrooms in schools and kindergartens, and examination and treatment rooms of hospitals. The analysis was carried out by gas chromatography (GC) with a flame induction detector (FID) by extraction with an organic solvent—methanol. Formaldehyde samples were treated with chromotropic and sulfuric acids and analyzed on a spectrophotometer in a visible range at 580 nm. Using methanol as a solvent, VOC samples were analyzed by a GC-FID (Thermofisher Trace 1310). The oven temperature, vaporization temperature, and detector temperature were set to 40°C, 250°C, and 250°C, respectively. The H₂ flow rate was set to 30 mL min⁻¹, and the carrier gas (He) flow rate was 300 mL min⁻¹. The VOCs were identified according to the retention times of chemicals. In this study, five VOCs including benzene, toluene, m-xylene, and p-xylene were identified. The calibration curves of all chemicals were generated before and after the analysis. The method detection limit (MDL) for formaldehyde, benzene, and toluene is 0.5 µg m⁻³ and for m-xylene and p-xylene is 0.7 µg m⁻³ (NIOSH, 1994, 2003).

### 2.2 Probabilistic Health Risk Assessment

A health risk score based on the probabilistic health risk assessment method is used in this study (U.S. EPA, 2005). The EPA Respiratory Health Risk Assessment Method has been used to assess the potential health effects of indoor volatile organic compounds (U.S. EPA, 2005a). In cancer risk assessment, the potency factor (PF) and the reference concentration (RfC) values for benzene, toluene, m-xylene, p-xylene, and formaldehyde were obtained from the Integrated Risk Information System (IRIS) database released by U.S. EPA (Table 1).

The cancer risk score is calculated using the following equation:

$$\text{CR}_i = \text{LADD}_i \times \text{PF}_i$$

(2)

where LADDi (Lifetime average daily dose) is the exposure to benzene and formaldehyde [mg (kg-day)⁻¹], CAi is the concentration of benzene and formaldehyde in the air (mg m⁻³), IR is the inspiratory rate (m³ h⁻¹) of a person living indoors, depending on age, ET is the exposure time (hours days⁻¹), EF is the exposure frequency (days year⁻¹), ED is the exposure duration (years), BW is the body weight (kg), LT is the lifetime (days), CRi (Cancer Risk i) is the cancer risk of benzene,
Table 1. Potency factor and reference concentration of VOCs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Benzene</th>
<th>Toluene</th>
<th>m-xylene</th>
<th>p-xylene</th>
<th>Formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td>mg (kg-day)^{-1}</td>
<td>0.027</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.045</td>
</tr>
<tr>
<td>RfC</td>
<td>mg m^{-3}</td>
<td>-</td>
<td>5</td>
<td>0.1</td>
<td>0.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: Slope factor inhalation (kg-day) mg–1 – Inhalation factor for contaminant (see Table 1 in U.S. EPA (2003, 2005b, 1989)).

and PFi ((Potency factor) or SF-Slope Factor)) is the pollutant cancer risk [(mg (kg-day)^{-1}]. The critical value for cancer risk recommended by the EPA is 1 × 10^{-6} (U.S. EPA, 2005a). According to the evaluation, a health risk value of less than 1 × 10^{-6} is defined as no risk, and a value greater than 1 × 10^{-6} is defined as a cancer risk.

In addition, the non-cancer risk score is calculated using the following equation (U.S. EPA, 2009):

\[
ADD_i = \frac{CA_i \times IR \times ED \times EF \times ET}{BW \times LT}
\] (3)

\[
HQ_j = \frac{ADD_j}{RfC_j}
\] (4)

where ADDi (average daily dose) is the daily dose of a non-cancerous pollutant [mg (kg-day)^{-1}], HQj refers to the non-cancer risk assessment of contaminants, and RfCj is the reference concentration (mg m^{-3}) of the inhaled non-cancerous pollutant.

The EPA’s recommended non-cancer risk thresholds range from 0 to 1 (U.S. EPA, 2005a). A non-cancer health risk score of less than 1 is an acceptable level for an individual, while a score above 1 indicates some risk of developing a non-cancerous disease.

2.3 Statistical Analysis

The normal distribution of the concentration of VOCs was studied both by histogram and by statistics (Shapiro-Wilk test). The Shapiro-Wilk test was applied to log-transformed concentrations, due to significant left skew, but the normal distribution assumption was rejected. Therefore, analyze of the VOC results was summarized using the geometric mean (GM) standard error, and the maximum and minimum values were determined.

All compounds were classified according to the recommendations of the German Association for Environmental Institutes and the recommendations of the German Federal Environmental Protection Agency (AGÖF, 2013). The combined effect of selected compounds was assessed using the Spearman correlation. Subgroup analysis was performed using the Mann-Whitney U-test to compare the mean levels of VOCs in the following subgroups: site (building, apartment, workplace, school, kindergarten, baishins, gers, hospital, shopping center); heat source (centralized and non-centralized heating); and period of use (new, old). Associations showing statistically significant p-values (p ≤ 0.05) were adjusted using the Spearman correlation method.

For calculating cancer and non-cancer risks, parameters were adopted from published ones, such as inhalation intensity and exposure time, which were taken from relevant international guidance, and from previously published research results (Batjargal et al., 2017; Health Canada, 2010; Munkhzaya et al., 2020) (Table 2), and the probability of health risk was calculated using

Table 2. Parameter values in the calculation model of the average daily dose in health risk.

<table>
<thead>
<tr>
<th>Age groups</th>
<th>Body weight (BW) (kg)*</th>
<th>Inhalation rate (IR) (m^3 day^{-1})**</th>
<th>Exposure time (ET) (h day^{-1})</th>
<th>Exposure frequency (EF) (day year^{-1})</th>
<th>Exposure duration (ED) (year)</th>
<th>LT year^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infant (0–6 months)</td>
<td>7.2</td>
<td>2.1</td>
<td>20</td>
<td>330</td>
<td>70</td>
<td>23100</td>
</tr>
<tr>
<td>Toddler (7 months–4 years)</td>
<td>13.7</td>
<td>9.3</td>
<td>20</td>
<td>330</td>
<td>66</td>
<td>21780</td>
</tr>
<tr>
<td>Child (5–11 years)</td>
<td>28.8</td>
<td>14.5</td>
<td>20</td>
<td>330</td>
<td>60</td>
<td>19800</td>
</tr>
<tr>
<td>Teen (12–19 years)</td>
<td>51.3</td>
<td>15.8</td>
<td>20</td>
<td>330</td>
<td>55</td>
<td>18150</td>
</tr>
</tbody>
</table>

Monte Carlo simulations with several random simulation repetitions of 10,000 and a 95% confidence level. All statistical analyses were performed using R v4.0.3 (R Foundation for Statistical Computing: Vienna, Austria) and RStudio v1.4.1103 (RStudio, PBC: Boston, MA, USA). We used the package EnviroPRA-Environmental Probabilistic Risk Assessment Tools (Barrio-Parra and Dominguez-Castillo, 2017).

3 RESULTS AND DISCUSSION

3.1 Concentrations of VOCs in Indoor Environments

Fig. 1 shows the percentage of VOCs in each type of indoor environment. A total of 562 samples containing formaldehyde were collected at 123 sampling sites; some baishins (n = 5) and Mongolian traditional gers (n = 16) were not measured. On the other hand, 583 samples containing benzene, toluene, m,p-xylene were collected at all 144 sampling sites (Table 3). Formaldehyde was detected in 538 samples (95.7%), benzene in 141 (24.2%), and m, p-xylene, and toluene were detected in 75 (12.9%) samples. Benzene was found in all samples from houses, and Mongolian traditional gers, and 2 (12.5%) samples were taken from the shopping centers. However, m,p-xylene, and toluene were not detected or the levels did not reach the measurement limit in the samples taken from the service centers (Fig. 1).

All compounds are compared with guidance values provided by the German Association of Environmental Institutes and the German Federal Environmental Agency AGÖF Guidance values

![Fig. 1. Percentage of VOCs detected in samples in different kinds of indoor environments. *Formaldehyde was not collected in gers.](image)

Table 3. Averaged concentrations of VOCs (µg m⁻³).

<table>
<thead>
<tr>
<th>Category</th>
<th>Compound</th>
<th>n</th>
<th>GM</th>
<th>SD error</th>
<th>Max</th>
<th>Min</th>
<th>p25</th>
<th>p50</th>
<th>p75</th>
<th>p90</th>
<th>Guidance value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acyclic aliphatic aldehydes</td>
<td>Formaldehyde</td>
<td>538</td>
<td>8.7</td>
<td>1.2</td>
<td>225</td>
<td>0.5</td>
<td>2.8</td>
<td>8.4</td>
<td>27.3</td>
<td>54.3</td>
<td>30</td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td>Benzene</td>
<td>141</td>
<td>25.4</td>
<td>3.3</td>
<td>181</td>
<td>1.5</td>
<td>11.6</td>
<td>26.1</td>
<td>65.1</td>
<td>109.6</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>75</td>
<td>73.9</td>
<td>34.1</td>
<td>1379</td>
<td>3.1</td>
<td>36.6</td>
<td>59.9</td>
<td>135</td>
<td>592.7</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>m, p-xylene</td>
<td>40</td>
<td>75.9</td>
<td>12.1</td>
<td>345.2</td>
<td>3.8</td>
<td>50.9</td>
<td>65.2</td>
<td>111.2</td>
<td>179.9</td>
<td>29</td>
</tr>
</tbody>
</table>

Abbreviations: n: number of samples; GM: geometric mean; SD: standard error; p25–p90: percentiles; Guidance values according to the German Association of Environmental Institutes (AGÖF, 2013).
Table 4. The concentration of VOCs in different indoor environments (GM, [95% CI] μg m⁻³).

<table>
<thead>
<tr>
<th>VOCs</th>
<th>Kindergarten</th>
<th>School</th>
<th>New apartment</th>
<th>Old apartment</th>
<th>Office</th>
<th>Hospital</th>
<th>Baishins</th>
<th>Mongolian gers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formaldehyde</td>
<td>81.2</td>
<td>86.3</td>
<td>20.4</td>
<td>35.8</td>
<td>13.4</td>
<td>3.2</td>
<td>5.2</td>
<td>NA</td>
</tr>
<tr>
<td>Benzene</td>
<td>9.8</td>
<td>6.6</td>
<td>(16.3–55.4)</td>
<td>(10.4–100)</td>
<td>42.8</td>
<td>15.2</td>
<td>(2.6–19.82)</td>
<td>(5.6–22.3)</td>
</tr>
<tr>
<td>Toluene</td>
<td>87.9</td>
<td>6.6</td>
<td>(6.6–9.8)</td>
<td>(4.3–16.4)</td>
<td>10.4</td>
<td>175.1</td>
<td>(24.9–39.4)</td>
<td>(74.7–181.9)</td>
</tr>
<tr>
<td>Toluene (xylene)</td>
<td>87.3</td>
<td>87.9</td>
<td>(6.6–9.8)</td>
<td>(4.3–16.4)</td>
<td>10.4</td>
<td>175.1</td>
<td>(24.9–39.4)</td>
<td>(74.7–181.9)</td>
</tr>
<tr>
<td>m,p-xylene</td>
<td>87.9</td>
<td>87.9</td>
<td>(6.6–9.8)</td>
<td>(4.3–16.4)</td>
<td>10.4</td>
<td>175.1</td>
<td>(24.9–39.4)</td>
<td>(74.7–181.9)</td>
</tr>
</tbody>
</table>

Abbreviations: GM: geometric mean; [95% CI]: 95% Confidence interval; Guidance values according to the German Association of Environmental Institutes (AGÖF, 2013).

The geometric mean and the largest value for each pollutant, determined from the results of the study, were used to calculate the average daily dose of lifetime exposure, by age. For children aged 0–19: the dose of benzene is 0.006–0.017 mg (kg-day)⁻¹ for the lifetime average daily exposure, LADD is 3.2–38.3 times and was statistically significant (p = 0.001) across all types of indoor sites. The formaldehyde concentration in apartments with central heating (5.2 ± 1.2 μg m⁻³) is significantly lower than that in baishins with no central heating (203 ± 20.5 μg m⁻³). The formaldehyde concentration in baishins with no central heating is the greatest showing 6.7 times the guidance value, while it is below the Guidance values in new and old apartments and offices. However, in kindergartens and schools, the formaldehyde concentration is 2.7–2.9 times greater than the Guidance value. Benzene in baishins without central heating was found to be 4.7 times greater than in apartments with central heating, which is statistically significant (p = 0.003).

When calculating the Spearman correlation of VOCs, a strong positive correlation was observed between toluene (rs > 0.52, p > 0.009) and m,p-xylene. No correlation was found between other pollutants.

### 3.2 Probabilistic Health Risk Assessment

#### 3.2.1 Cancer risk assessment

The geometric mean and the largest value for each pollutant, determined from the results of the study, were used to calculate the average daily dose of lifetime exposure, by age. For children aged 0–19: the dose of benzene is 0.006–0.017 mg (kg-day)⁻¹ for the lifetime average daily exposure, LADD is 0.021–0.050 mg (kg-day)⁻¹ for the highest pollutant value; the formaldehyde dose is 0.008–0.023 mg (kg-day)⁻¹ for the highest pollutant value; and 0.009–0.055 mg (kg-day)⁻¹ is the potential impact.

Cancer risk from benzene and formaldehyde was determined according to the U.S. EPA-recommended criteria.
probabilistic assessment model according to Eq. (1) and Eq. (2); taking into account selected age characteristics (Table 2), the level of cancer risk is calculated for each age group, and the cancer risk value was $1 \times 10^{-6}$ (U.S. EPA, 2005a). According to the evaluation, a health risk value of less than $1 \times 10^{-6}$ is defined as no risk, and a value greater than $1 \times 10^{-6}$ is defined as a cancer risk.

Using an average indoor benzene exposure of 70 years (remaining lifetime) at a dose of 0.042 mg m$^{-3}$ approximates the risk of cancer in the population aged 0–19 years. For more clarity, we used box plots to indicate the value of the probability of the health risk graphically. In box plots from top to bottom, the health risk values with probabilities of 95%, 75%, 50%, 25%, and 5% are respectively represented. Fig. 2 presents the cancer risk levels for each group based on probabilistic health risk assessments, and the probabilistic results of health risks are shown in Table S1. At the 95th percentile, the average risk of leukemia would be $1.58 \times 10^{-6}$ associated with exposure to inhaled air containing 0.042 mg m$^{-3}$ of benzene, on average, in all living and study environments at approximately 70 years from birth. Children aged 0–6 months (1.38 $\times 10^{-5}$), 7 months–4 years (1.8 $\times 10^{-5}$), and 5 years–11 years (1.16 $\times 10^{-5}$) years have a risk for leukemia if they breathe air containing benzene for about 60 years. It can be seen from Fig. 2 and Table S1 that the 7 months–4 years have the greatest cancer risk, and the highest health risk value reached $1.8 \times 10^{-5}$ while the lowest health risk of benzene at the age group 12 years–19 years reached (5.68 $\times 10^{-6}$).

According to the calculations, for formaldehyde, an average dose of 0.02 mg m$^{-3}$ for 70 years of exposure affected a person's cancer risk. At the 95th percentile children aged 0–6 months (3.83 $\times 10^{-6}$), 7 months–4 years (4.72 $\times 10^{-6}$), and 5 years–11 years (2.76 $\times 10^{-6}$) have a cancer risk when breathing air containing formaldehyde at the above dose for about 70 years. In Fig. 3 and Table S1, it can also be seen that children aged 7 months–4 years have the highest risk of 4.18 $\times 10^{-6}$ and the lowest health risk of formaldehyde is at the age group 12 years–19 years is (1.24 $\times 10^{-6}$).

3.2.2 Non-cancer risk assessment

Non-cancer risk assessments of m,p-xylene, and toluene were performed using Eq. (3) and Eq. (4) provided by the U.S. EPA method. For the calculations, we used parameters as shown in Table 2 and probability estimates using RfC for each pollutant. The probabilistic non-cancer risk for children in each age group was calculated and the geometric mean and maximum values of m,p-xylene, and toluene pollutants were determined in air samples at the time of measurement. The U.S. EPA’s recommended non-cancer risk thresholds range from 0 to 1 unit (U.S. EPA, 2005a). A non-cancer health risk score of less than 1 is an acceptable level for an individual, while a score above 1 indicates some risk of developing a non-cancer disease. At the 95th percentile, for m,p-xylene of concentrations of 0.096 mg m$^{-1}$, there is a non-cancer risk of m,p-xylene for children aged 0–6 months (0.57), 5 years–11 years (0.86), and 12 years–19 years (0.52) except for 7 months–4 years (1.17) (Fig. 4).

For toluene, at the 95th percentile, there is a non-cancer risk for children aged 0–6 months (0.03), 7 months–4 years (0.007), 5 years–11 years (0.05), 12 years–19 years (0.03) (Fig. 5).

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**Fig. 2.** Cancer risk of benzene.
Fig. 3. Cancer risk of formaldehyde.

Fig. 4. Non-cancer risk of m,p-xylene.

Fig. 5. Non-cancer risk of toluene.
3.2.3 Discussion

The present study measured and evaluated the levels of benzene, formaldehyde, toluene, and m,p-xylene in the indoor air of various sites in Ulaanbaatar, Mongolia, for the first time, using the U.S. EPA’s methodology to assess children’s cancer risk using Monte Carlo simulations (Alvarez-Vaca et al., 2022; Bruce et al., 2015; Huang et al., 2018). In Mongolia, research to monitor and determine VOCs in indoor air is just beginning, and conducting research to determine its health effects and risks has become important.

VOCs are defined as organic compounds whose boiling point is in the range of 50–100°C to 240–260°C (ISO, 2021) and they are the main indoor air pollutants. Many epidemiologic studies indicate that kindergarten and school indoor environments may contain environmental contaminants hazardous to children’s health, including VOCs such as benzene, toluene, m,p-xylene, and formaldehyde (Bradman et al., 2017; Jung et al., 2021; Quirós-Alcalá et al., 2016; Roda et al., 2011; Sofuoglu et al., 2011). In our study, VOCs in indoor environments such as new buildings, apartments, offices, kindergartens, schools, hospitals, shopping centers, houses, baishins and gers show levels that are likely to exhibit a negative impact on health, making our findings consistent with and these previous published studies.

The International Agency for Research on Cancer (IARC) has classified benzene as carcinogenic to humans. Positive associations have been observed for non-Hodgkin lymphoma, chronic lymphoid leukemia, multiple myeloma, chronic myeloid leukemia, acute myeloid leukemia in children and cancer of the lung (IARC, 2018). IARC has concluded that formaldehyde is "carcinogenic to humans" based on evidence that it can cause nasopharyngeal cancer and leukemia (Cogliano et al., 2005). The average risk of personal exposure to VOCs among New York City high school students was 666 per million, about 5 times higher than environmental exposure. In samples from Los Angeles, there was an average risk of developing cancer associated with personal exposure to VOCs of 486 per million, or 4 times the environmental risk. VOCs with the highest cancer risk include 1,4-dichlorobenzene, formaldehyde, chloroform, acetaldehyde, and benzene (Sax et al., 2006). Results in China over the last 20 years, the results show that indoor pollution due to benzene, toluene, and xylens has been more serious than in other countries. Moving into a dwelling more than 1 year after decoration and improving ventilation could significantly reduce exposure to indoor VOCs. Reducing benzene exposure is urgently needed because it is associated with greater health risks (4.5 × 10⁻⁴ for lifetime cancer risk and 8.3 for hazard quotient) than any other VOCs (Liu et al., 2022). Additionally, the concentration of benzene, which is associated with leukocyte cancer (Snyder, 2012), exceeded the Guidance values by 3.2–38.3 times and was statistically significant (p = 0.001) across all types of indoor environments. Hoang et al. (2017) defined child exposures for benzene, ethylbenzene, and/or naphthalene that exceeded California Safe Harbor Levels for cancer in all of the Early education center facilities tested and concludes more exposure research is needed on these compounds to clarify the long-term risks to children. These conclusions are similar with ours, that further research in this area is needed. According to our study, children are at risk (1.24 × 10⁻⁵ to 4.7 × 10⁻⁵) of cancer when they are exposed to an average concentration of 25.4 µg m⁻³ (min = 1.5, max = 181) of benzene and 8.7 µg m⁻³ (min = 0.5, max = 225) of formaldehyde in the indoor environment. This is consistent with the results of the above studies.

Our study defined children from 7 months to 4 years as being at the highest risk of cancer risk from formaldehyde and benzene, and non-cancer risks from toluene and xylene in indoor environments. The risks are due to the need for increased oxygen as the lungs enlarge during the increase in child’s body weight, which leads to higher doses of pollutants from the surrounding air penetrating the body through inhalation. According to the U.S. EPA, the average daily dose (ADD) of a chemical is usually equal to the average body weight of the exposed population, and if a child is exposed during childhood, the risk is calculated using the average weight of the child at the time of exposure (U.S. EPA, 1989). For instance, the average weight of children aged 0–6 months is approximately 4–7.4 kg, while a child aged 7 months to 3 years weighs an average of 9.2–14 kg (U.S. EPA, 2008, 2011). In addition, the frequency of breathing decreases from infancy to adolescence, and a sharp decrease (40%) is observed during the first 2 years of life. The metabolism of children during the resting period and oxygen consumption for infants and young children are high, and lung surface area per unit body weight is relatively large, and oxygen
consumption per unit body weight averages 5–9 per kg millilitres$^{-1}$ for infants during rest from week 1 to 1 year of age in children (Hill and Robinson, 1968; WHO, 1986).

An assessment of indoor air quality in 5,000 households in Japan found that indoor exposure to m,p-xylene and o-xylene was associated with neurodevelopmental delay in 3-year-old children with a 0.65 reduction [99% CI: 1, 14, 0.16] per 1 µg m$^{-3}$ increase in xylene (Madaniyazi et al., 2022). The results showed that high concentrations of toluene and m/n-xylene in the classroom tended to increase the number of overweight and obese children, while the number of children with nasal congestion was significantly higher (Paciência et al., 2019). In our study, the non-cancer risk of children spending time indoors, with lifetime exposure to 73.9 µg m$^{-3}$ (min = 3.1, max = 1379.8) average concentrations of toluene and 75.9 µg m$^{-3}$ (min = 3.8, max = 345.2) average concentrations of m-p-xylene was determined to be less than the EPA recommended value of 1.

In Mongolia, the average weight of the population is determined from surveys that track data such as early childhood growth and development, population nutrition, and identification of non-communicable risks. However, since no study has yet been conducted to determine the inhalation rate appropriate for the age of the population, the use of the reference rate established by Health Canada for health risk assessment is limited in directly determining health risks for Mongolians.

In addition, the results of the health risk assessment in this study may not reflect the risk status in all indoor sites. In our study, samples were collected only from indoor sites in the city of Ulaanbaatar, so the influence of outdoor air, which is highly polluted during the winter months in Mongolia (Ganbat et al., 2020) on the indoor environment was not taken into account.

Moreover, due to constraints such as time, human resources, laboratory capacity, research costs, and lockdown associated with the emergence of the COVID-19 pandemic, the sites where samples were obtained for this study are only a cross-sectional representation, and the results are thus preliminary.

As part of this study, we aimed to determine the levels of VOCs in various indoor environments and to assess the health risks for a vulnerable group of children. Indoor pollutant sampling was carried out during the COVID-19 pandemic and we included households, offices, and other sites, with permission from those who understood the importance of the study. Since the mean respiratory rate in children has not been studied in Mongolia, international guideline values were used to calculate the risk of developing tumors, taking into account EPA values (IR, PF, RfC, etc.), which limited the impact assessment. It should be noted that the samples obtained in field studies, were analyzed, and the results obtained in a facility with independent indoor air quality.

4 CONCLUSIONS

Volatile organic compounds are found in indoor environments such as Mongolian gers, baishins, workplaces, schools, kindergartens, and hospitals. The probabilistic health risk assessment shows that the average and $>95\%$ concentrations of benzene and formaldehyde in indoor air exceed the U.S. EPA value of $1 \times 10^{-6}$ by several times. The results of the cancer risk assessment of VOCs showed that m,p-xylene has a non-cancer risk at the highest dose level, whereas toluene has a non-cancer risk exceeding the U.S. EPA limit of 1. To control emissions of VOCs in indoor air, protect public health from risks, control indoor air quality, reduce pollution, and control health risks, we recommend establishing national standards or guidelines for the indoor environment based on the results of this study. In the future, taking into account the above limitations, it is necessary to conduct a more comprehensive step-by-step study to determine the sources of toxic substances in indoor environments. It is also necessary to develop and implement national standards, or guidelines, and an action plan, for import control and monitoring of materials containing VOCs used in indoor environments, especially carcinogenic VOCs. Regular monitoring of indoor air quality in homes, offices, schools, museums, hospitals, etc., needs to be part of an overall national program for improving and maintaining air quality standards, indoors as well as outdoors.

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SUPPLEMENTARY MATERIAL

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