

## Research article

# First measurement report for volatile organic compounds characteristics during winter in Ulaanbaatar, Mongolia

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## ABSTRACT

In this study, 34 volatile organic compounds (VOCs) were analyzed using an online VOCs instrument at 30-min intervals from November 16 to November 23, 2023, in Ulaanbaatar (UB), the capital of Mongolia for the first time. The average concentration of the 34 VOCs was  $13.0 \pm 11.1$  ppb, with the top 10 compounds, such as benzene, toluene, ethylbenzene, and xylenes (BTEX), constituting 80 % of the total. The concentrations of n-hexane, n-heptane, and undecane tended to increase significantly during high-concentration episode period (HEP). Compared to other studies, BTEX concentration levels in UB were higher than those in Seoul and Beijing, but lower than in Southeast Asian cities. Positive matrix factorization (PMF) identified four VOCs sources: vehicle exhaust (33.8 %), industrial/coal combustion (25.3 %), secondary formation precursors (21.3 %), and solvent usage (19.6 %). Vehicle exhaust and industrial/coal combustion sources increased during rush hours and were strongly correlated with nitrogen oxides. During HEP, stagnant air mass led to increased contributions from vehicle exhaust and industrial/coal combustion sources, indicating a significant local impact. Solvent usage appeared to be influenced by building materials and exterior painting which increased with high relative humidity. Secondary formation precursors increased in concentration during daytime and were highly correlated with ozone. Among the measured compounds, benzene was assessed for lifetime health risk, showing that adults with the prolonged exposure exhibited higher risk than infants and children. However, during HEP, children were also at increased risk, despite their shorter exposure duration. Based on the concentration levels of VOCs and the associated health risks, the results highlight that the need for a policy on ambient VOCs management in UB, with a particular focus on local source management.

## 1. Introduction

Volatile organic compounds (VOCs) encompass hundreds of organic species that contain carbon and hydrogen and have a high

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vapor pressure, making them easily emitted into the atmosphere [1]. VOCs can be emitted from a variety of sources, including anthropogenic activities such as vehicular emission, industrial process, household fuel use, and solvent use, as well as natural sources such as plant photosynthesis, volcanic eruption, and wildfire [2]. The rapid industrialization and urbanization of the modern world are the main reasons for the increase of the concentration of VOCs in the atmosphere, which is associated with deteriorating air quality.

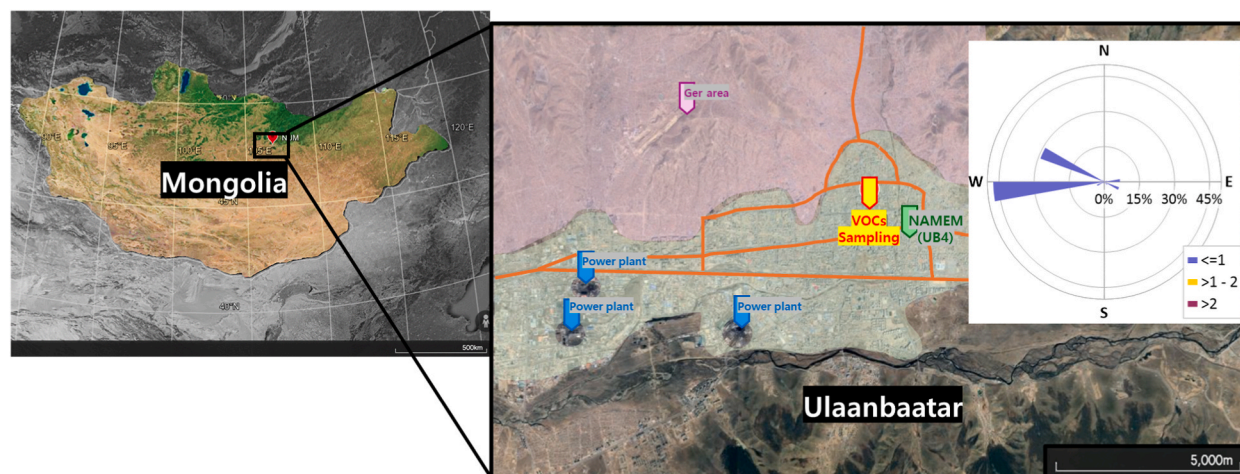
VOCs play a significant role in the formation of secondary organic aerosol (SOA) through photochemical reactions with nitrogen oxides and tropospheric ozone precursors [3]. In addition, some of the VOCs such as benzene and formation products from them such as ozone and SOA are harmful to humans. Air pollution is the fourth leading risk factor for mortality worldwide, with pollutants such as ozone, particulate matter, and VOCs posing significant health risks through inhalation, ingestion, and dermal exposure [4,5]. VOCs can have various effects on human health, including respiratory, neurological, cardiovascular, and skin diseases [6]. Efforts are being made globally to reduce the harmful effects of benzene, which is the most hazardous VOC component, by establishing a specific standard value to mitigate this risk [7]. According to Sekar et al. [7], numerous countries in Asia, including India, Iraq, Japan, South Korea, and Vietnam, along with all 28 member states of the European Union and Australia, have established their own ambient air quality standards and are striving to meet them. Moreover, countries such as Hong Kong (Occupational Safety and Health Council, <https://www.oshc.org.hk>), the United States (The National Institute for Occupational Safety and Health, <https://www.cdc.gov/niosh>), and South Korea (Ministry of Environment-Indoor air quality control act, <https://eng.me.go.kr>) are actively working to reduce exposure to benzene by implementing standards for workplace and indoor air.

Benzene, toluene, ethylbenzene, and xylenes (known as BTEX) are arguably the most studied of the VOCs due to their various anthropogenic sources and associated health effects. Previously, emission sources were estimated using the benzene/toluene and ethylbenzene/xylene ratios [8–10]. However, in recent years, with the development of instruments for real-time measurement and analysis of multiple compounds, studies have been conducted to classify pollution sources using receptor models [11–14]. Additionally, studies have been undertaken to identify the potential for ozone and SOA formation based on measured data, as well as to assess hazardous effects through hazard assessment. However, no studies on characteristics of VOCs in the atmosphere have been reported in Mongolia until now.

Mongolia is identified as one of the regions sensitive to alterations in air pollution concentration, primarily attributed to rapid changes in economic structure since the mid-1990s. On top of that Mongolia's climate is noted to contribute to this sensitivity [15]. Mongolia's climate is characterized by long, dry winters from mid-September to mid-May, while summers are relatively short and humid, with most of the annual precipitation falling in the summer [16]. About 50 % of Mongolia's population lives in the capital city of Ulaanbaatar (UB) [17], with approximately half of the residents residing in apartments and receiving central heating and hot water from combined heat and power stations [16]. The rest of the population lives in gers, traditional Mongolian tents, and small private houses [18]. These dwellings mostly use stoves for heating and cooking that mainly rely on coal and wood [19].

The main sources of air pollutants in UB are coal combustion and road traffic [20]. The geographical characteristics and meteorological conditions of Mongolia's arid climate, vast pastures, high altitudes, rapid urban expansion, and the rapidly increasing number of vehicles are expected to influence the distribution and transformation of VOCs. Therefore, understanding the dynamic changes of atmospheric VOCs in Mongolia is essential for assessing the serious impacts on the environment and human health.

This study is the result of the first investigation of VOCs measuring using a continuous measurement instrument in UB, Mongolia, which has not been previously studied. We aimed to investigate the characteristics of VOCs in UB during the winter through VOCs concentration and source apportionment using the positive matrix factorization (PMF) receptor model. This study assesses the potential risk of VOCs concentrations in Mongolia to air quality and human health. Therefore, we hope that this study will serve as a starting point for developing sustainable environmental protection and health policies in Mongolia.



**Fig. 1.** Sampling location of this study provided by Google Earth. The VOCs (yellow pin) and gas-phase components (green pin) sampling point was located in a residential and industrial area (light green), surrounded by a major road (orange line). To the north situated the Ger area (light pink), and to the southwest is a large thermal power plant (blue pin). The figure includes the wind rose for the sampling site.

## 2. Methods

### 2.1. Sampling information

Sampling was conducted from 16 to November 23, 2023 at the National University of Mongolia (NUM, 47.92°N, 106.92°E), located in UB, the capital of Mongolia (Fig. 1). The sampling site is located in the central area of UB, characterized by heavy traffic and frequent congestion during the measurement period. In 2022, UB had around 700,000 registered vehicles, out of approximately 1.2 million in Mongolia, with passenger automobiles constituting the largest portion, exceeding 70 % [21]. As noted by Huang et al. [22], a significant portion of vehicles in Mongolia consists of used cars imported from South Korea and Japan. In UB, more than 70 % of vehicles are over 10 years old [15]. UB is situated in a valley within the mountains to the northeast and south [16]. The area features flat terrain predominantly composed of residential and industrial facilities. Furthermore, within 5–10 km to the south-western of the measurement point in UB, there are three large coal fired power plants. In addition, to the north of the measurement point, there are extensive ger areas where coal and wood is used for individual heating and cooking. A detailed map of ger area is presented in Guttikunda et al. [23].

Meteorological and real-time gaseous components data were provided by the National Agency for Meteorology and Environmental Monitoring (NAMEM) in UB, and the data are shown in Fig. S1. In UB, there are currently 19 operational air quality measurement sites, and real-time readings are publicly available on the website (<http://agaar.mn/>). For this study, the data from Bukhiin Urguu (residential and industrial area), a nearby site situated 1.4 km away from the measurement site, were utilized. The dataset included concentrations of gaseous components such as nitrogen oxides, carbon monoxide (CO), ozone (O<sub>3</sub>), and sulfur dioxide (SO<sub>2</sub>), as well as particulate matters such as PM<sub>2.5</sub> and PM<sub>10</sub>. However, only the gaseous components had appeared in this study. The data for the gas-phase components were recorded at 1-h intervals. O<sub>3</sub> was measured using the LED based, UV photometric ozone analyzer (O342e, ENVEA, France), while CO was measured with the CO12e (ENVEA, France), a non-dispersive infra-red carbon monoxide analyzer. For sulfur dioxide, the AF22e (ENVEA, France), a UV fluorescent sulfur dioxide analyzer, was employed, and nitrogen oxides (NO, NO<sub>x</sub>, and NO<sub>2</sub>) were measured using the AC32e (ENVEA, France), a chemiluminescent analyzer. The hourly temperature, wind speed, wind direction, relative humidity (RH), and insolation data were downloaded from the Weather Underground website (<https://www.wunderground.com/dashboard/pws/IULAAN7>) at the point closest to the sampling site. The provided data recorded at 5-min intervals were averaged into hourly data. The temperature and wind speed data were converted to Celsius (°C) and meters per second (m s<sup>-1</sup>), respectively. The wind direction was measured in 32 directions, the prevailing wind direction was determined as the direction with the highest frequency of occurrence as hourly. The mixing depth of Atmospheric Administration (NOAA) Air Resources Laboratory's (ARL) HYSPLIT model, which is based on meteorological data from GDAS 1.0 was used as the mixing layer depth.

### 2.2. VOCs measurement

For measurements, 34 VOC compounds were continuously analyzed every 30 min using a gas chromatograph (GC955-611, Synspec, Netherlands). 34 VOCs, corresponding to C<sub>6</sub>-C<sub>12</sub>, include 16 aromatics and 18 alkanes. GC955-611 is an online GC that collects samples in a pre-concentration tube for 30 min and automatically injects them into the GC every 0 and 30 min. Nitrogen gas produced in a gas generator (NITROSTATION 50RC, Synspec, Netherlands) was used as a carrier gas, and the compounds were separated using a SY-1 column (30 m in length, 0.32 mm in diameter, Synspec, Netherlands) made of 100 % dimethylpolysiloxane. The analytical conditions applied were as follows: the column oven temperature was maintained at 60 °C for 4 min and then gradually raised to 110 °C, with the column flow rate varied from 1.5 ccm to 3.5 ccm starting at 17 min among the 30-min analysis time. It was detected with a Photoionization Detector (PID) type detector. In a PID, compounds that have passed through a column are ionized as they pass through a UV lamp and are detected by a sensor. For calibration, 57 mixed standard gases (RIGAS, Korea) with a concentration of 1 μmol mol<sup>-1</sup> were diluted to 1.0, 2.5, 4.0, 6.0, 8.0, 10, and 12 nmol mol<sup>-1</sup>, and the R<sup>2</sup> values for 34 compounds were above 0.99. Concentrations below LDL were calculated for individual compounds by halving the concentration of LDL, and the sum of the 34 individual compounds was named as 34VOCs. Detailed information regarding VOC measurement using online GC-PID can be also found from Lee et al. [13].

### 2.3. Data analysis

#### 2.3.1. PMF model

The US EPA PMF 5.0 model (<https://www.epa.gov/air-research/positive-matrix-factorization-model-environmental-data-analyses>) was used to allocate pollution sources in this study. The PMF model was developed by Paatero and Tapper [24] and has been used in many studies for source apportionment of VOCs [25]. Before running the model, the input data must be processed. Uncertainty values were obtained by multiplying the LDL for each species by 5/6. Uncertainty above the LDL was calculated using the following equation:  $[(\text{error fraction} \times \text{measured value})^2 + (0.5 \times \text{LDL})^2]^{0.5}$ , and error fraction of 0.1 was applied. The uncertainty for 34VOCs multiplied 400 % of values and used as total variable in the model. The LDL, below LDL ratios, category settings and signal-to-noise ratios (S/N ratios) of individual species are shown in Table S1. When entering the data into the PMF program, 34VOC was set as the "total variable (weak)", and compounds with LDL less than 80 % were classified as "bad". Species with LDL less than 60 % or an S/N ratio of 2 or less were classified as "weak". The extra modelling uncertainty was fixed at 20 %, the same as in Lee et al. [13]. The PMF models and processed data are described in greater detail by Paatero and Tapper [24] and Lee et al. [13].

By adjusting the number of factors, optimal number of sources was determined based on Q/Qexp, maximum individual column

mean (IM), and maximum individual column standard deviation (IS) values for each factor, as well as verification methods like displacement (DISP) and bootstrapping [26,27].

### 2.3.2. Health risk assessment

Among the 34 VOCs measured in this study, benzene is the only one with a human health hazard rating in the Integrated Risk Information System (IRIS). Benzene is classified as a "known" human carcinogen (Category A) under the 1986 Risk Assessment Guidelines. Inhalation exposure to benzene is known to cause leukemia [28]. The excess cancer risk (ECR) for the benzene exposure scenario can be calculated using Eq. (1) and Eq. (2) from US EPA [29], Won et al. [30] and Zahed et al. [31]:

$$EC = \frac{C_{Air} \times ET \times EF \times ED}{AT} \quad (\text{Eq. 1})$$

$$ECR = EC \times IUR \quad (\text{Eq. 2})$$

where EC represents the exposure concentration via the inhalation route and  $C_{Air}$  represents the airborne contaminant concentration (95th percentile and mean concentration in this study). Since breathing volume is not directly proportional to body weight, body weight was not considered a variable in the inhalation exposure assessment [32]. ET, EF, ED, and AT represent exposure time (hours per day), exposure frequency (days per year), exposure duration (years), and average time (hours), respectively. In this study, AT was assumed to be the lifetime average daily exposure over the life expectancy at each age. Life expectancy for men and women in UB is 67.5 and 75.6 years, respectively [33]. In this study, a life expectancy of 71.6 years was used, representing the average lifespan of both males and females without distinguishing between the genders. The inhalation unit risk (IUR) is defined as the carcinogenic risk associated with continuous exposure to  $1 \mu\text{g m}^{-3}$  of a pollutant [34]. The IUR of benzene required to calculate the ECR represents the carcinogenic risk from inhalation exposure and is  $2.2 \times 10^{-6}$  per  $\mu\text{g m}^{-3}$  [35]. The IUR was consistently applied in this study, with the EC serving as the primary determinant of risk by utilizing different exposure scenarios for infants, children, and adults. For benzene,

**Table 1**

Volatile organic compound (VOC) concentrations (ppb) during the study period in Ulaanbaatar, Mongolia.

	A.M. <sup>a</sup>	S.D. <sup>b</sup>	Min.	Median	Max.
34VOCs	13.0	11.1	1.00	9.42	67.5
Alkanes	3.99	4.13	0.39	2.41	26.9
2-Methylpentane	0.50	0.53	0.05	0.41	4.55
3-Methylpentane	0.20	0.10	0.03	0.18	0.65
n-Hexane	1.15	1.31	0.01	0.77	7.70
2,4-Dimethylpentane	0.13	0.11	0.02	0.11	0.57
Cyclohexane	0.20	0.21	0.01	0.13	1.29
2-Methylhexane	0.30	0.38	0.07	0.07	2.31
2,3-Dimethylpentane	0.06	0.10	0.02	0.02	0.64
3-Methylhexane	0.27	0.31	0.02	0.18	1.94
2,2,4-Trimethylpentane	0.09	0.12	0.02	0.02	0.60
n-Heptane	0.33	0.57	0.03	0.03	3.55
Methylcyclohexane	0.12	0.11	0.01	0.10	0.58
2,3,4-Trimethylpentane	0.01	0.01	0.01	0.01	0.10
2-Methylheptane	0.08	0.16	0.02	0.02	1.07
3-Methylheptane	0.07	0.11	0.02	0.02	0.60
n-Octane	0.24	0.21	0.02	0.25	1.79
n-Nonane	0.03	0.05	0.02	0.02	0.32
n-Decane	0.03	0.09	0.01	0.01	0.69
Undecane	0.18	0.78	0.03	0.03	7.85
Aromatic VOCs	8.97	7.15	0.52	7.12	42.0
Benzene	1.57	1.54	0.09	1.04	9.80
Toluene	4.44	3.13	0.26	4.00	18.1
Ethylbenzene	0.38	0.35	0.01	0.27	2.07
m,p-Xylene	0.78	0.67	0.02	0.57	3.99
o-Xylene	0.56	0.50	0.01	0.40	2.77
Styrene	0.07	0.08	0.01	0.04	0.47
iso-Propylbenzene	0.01	0.01	0.01	0.01	0.05
n-Propylbenzene	0.05	0.05	0.01	0.04	0.29
m-Ethyltoluene	0.21	0.23	0.01	0.13	1.30
p-Ethyltoluene	0.13	0.15	0.01	0.08	0.83
1,3,5-Trimbenzene	0.09	0.09	0.01	0.06	0.54
o-Ethyltoluene	0.07	0.06	0.01	0.06	0.34
1,2,4-Trimethylbenzene	0.35	0.32	0.01	0.26	1.84
1,2,3-Trimethylbenzene	0.20	0.17	0.01	0.18	0.80
m-Diethylbenzene	0.04	0.03	0.01	0.04	0.15
p-Diethylbenzene	0.03	0.05	0.01	0.01	0.29

<sup>a</sup> A.M. arithmetic mean.

<sup>b</sup> S.D. Standard deviation.

Won et al. [30] reported that indoor and outdoor concentrations are similar. Therefore, assuming the same amount of exposure to benzene indoors and outdoors, exposure scenarios were created. These scenarios considered exposure to the lifetime cancer risk for 24 h and 350 days [36] up to the life expectancy within each age group to calculate the ECR. The study was divided into three groups: infants aged 0–1 years, children aged 2–18 years, and adults aged 19–70 years.

### 3. Results and discussion

#### 3.1. Characteristic VOCs concentration in Ulaanbaatar (UB)

The meteorological and gaseous components data along with VOCs during the sampling period are shown in Fig. S1. The average temperature during the measurement period was  $-9.77^{\circ}\text{C}$ , with lows reaching  $-27.0^{\circ}\text{C}$ . The wind was predominantly from the west, but there was very little wind, with a maximum wind speed of less than  $1\text{ m s}^{-1}$ . The average RH was around 70.4 %, and snowfall occurred on two occasions, although the amount was not significant. The mixed layer depth averaged 139 m, with a maximum of 972 m. In UB, situated at 1300 m above sea level [16], was characterized by a low mixing height. The average concentrations of gas-phase components in UB during the measurement period were  $15.0 \pm 9.77$  ppb for  $\text{SO}_2$ ,  $47.0 \pm 32.3$  ppb for  $\text{NO}_x$ ,  $1.84 \pm 1.27$  ppm for CO, and  $5.14 \pm 5.67$  ppb for  $\text{O}_3$ . Compared to cities such as Beijing, Seoul, Seosan, and Noto in Northeast Asia [37],  $\text{SO}_2$  concentrations were approximately 10 times higher,  $\text{NO}_x$  were 2 times higher, CO were more than 3 times higher, while  $\text{O}_3$  levels were more than 2 times lower.

The average 34VOCs concentration measured in UB during the winter of 2023 was  $13.0 \pm 11.1$  ppb and statistical information on individual compounds are shown in Table 1. By VOC group, aromatic VOCs accounted for 69.2 % and alkanes for 30.8 %, with toluene ( $4.44 \pm 3.13$  ppb) having the highest concentration among the individual compounds, representing 34.3 % of the 34VOCs. In Fig. 2, temporal trend of aromatic and alkane groups is shown. A clear diurnal trend with bimodal peaks was observed, high concentrations during rush hour in UB. A high-concentration episode period (HEP) was defined as when the concentration of 34VOCs is higher than the average concentration and lasts for more than 24 h. This was the case from 17:30 on November 19 to 20:00 on November 20. Conversely, a low-concentration episode period (LEP) was defined as the period when the 34VOCs concentration is below 50 % of the average concentration and persisted for more than 24 h. This was the case from 21:30 on November 21 to 07:30 on November 23, during which values below 50 % of the average concentration persisted for more than 24 h. During LEP, concentration of gaseous components and 34VOCs, except for  $\text{O}_3$ , experienced a significant decrease.

As shown in Fig. 3, the concentrations of 34VOCs during the HEP ( $26.7 \pm 14.7$  ppb) were more than 10 times higher than during the LEP ( $2.21 \pm 1.25$  ppb). During both episodes, toluene and benzene ranked 1st and 2nd highest, respectively, with xylene and ethylbenzene also among the top 10 species. For BTEX, the concentration in HEP was higher than in LEP by about 10 times, while the ratio of BTEX to 34 VOCs remained almost unchanged. However, for n-hexane, the concentration increased by about 20 times during HEP, and the ratio to 34VOCs increased more than 2 times, indicating that n-hexane is a significant contributor to HEP. Additionally, for undecane and n-heptane, which were the low concentrations in the LEP period, the concentration increased by more than 30 times during HEP, and the ratio to 34VOCs increased by 2–3 times during the HEP period. This indicates that they, similar to n-hexane, are significant compounds during HEP. n-Hexane, n-heptane, and undecane are known to be emitted from diesel vehicles and coal fired power plants [38–40]. This indicates that the influence of the large coal fired power plants and the impact from vehicles in UB are significant during the HEP. In UB, more than 70 % of vehicles are over 10 years old, and these older vehicles are reported to be major contributors to air pollution [15].  $\text{NO}_x$  and CO, the major emissions from vehicle exhaust [41], showed a rapid increase during HEP, similar to the trend observed for VOCs. On the other hand, the concentration of  $\text{SO}_2$ , which is known to be emitted from coal fired power plants and ger area in UB [16], increased when the southeast wind blew. However, the concentration of VOCs did not show a similar trend to  $\text{SO}_2$ . This indicates that the influence of vehicles at the measurement location is greater than the influence of power plants.

BTEX accounts for a large proportion of the 34VOCs regardless of the episodes. The levels of BTEX measured in this study are compared with those reported in other studies (Table 2). Compared to the most recent winter study results in Seoul by Lee et al. [13], benzene levels in UB were approximately 5 times higher, while toluene, ethylbenzene, and xylene were roughly twice as high. Except for benzene, the concentration of TEX in UB was higher than Beijing and other areas of China [11,42–45]. Xie et al. [45] reported that the benzene level in Hebei was about 2 time higher than UB during the heating season and they suggested that the benzene exposure

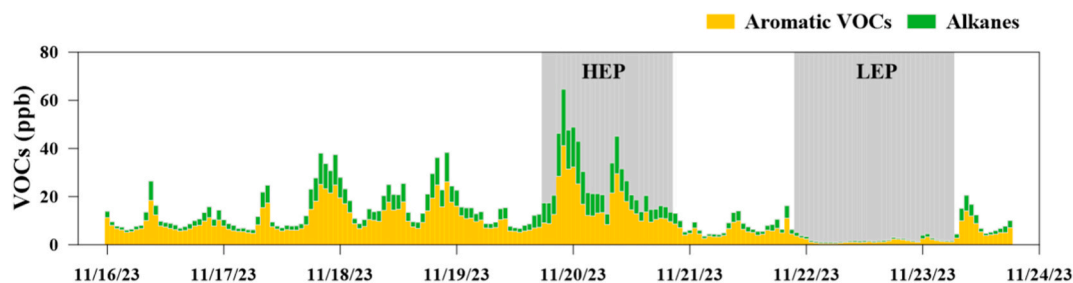


Fig. 2. Variation of concentrations for aromatic VOCs and alkane groups over the entire period.

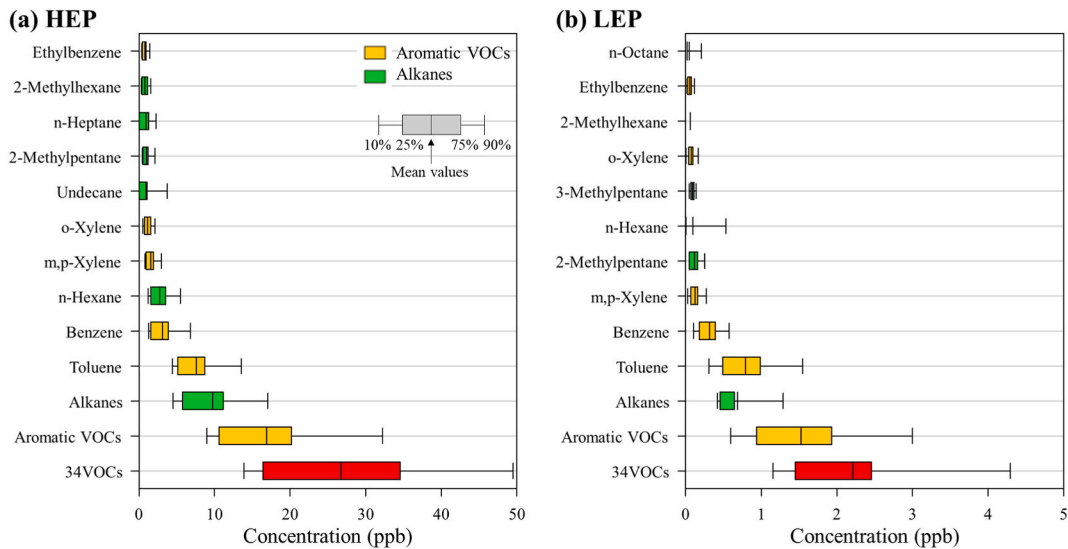


Fig. 3. Concentration of the top ten species, groups of VOCs, and 34VOCs by episodes, (a) HEP and (b) LEP.

would pose a high risk to human health. The health risk of benzene in UB is treated in detail in section 3.3. When comparing Seoul, Beijing, and UB in Northeast Asia, the concentration of VOCs in UB was approximately twice as high. Kim et al. [37] measured at these cities simultaneously during the winter of 2020, the levels of NO<sub>x</sub>, CO, and PM<sub>2.5</sub> in UB were 2–3 times higher than in Seoul or Beijing. However, the concentration of SO<sub>2</sub> in UB was about 50 times higher than in the other two cities [37]. In a previous study, the high SO<sub>2</sub> levels was attributed to the extensive coal combustion in the ger area and power plant during winter [15]. Therefore, UB had significantly higher SO<sub>2</sub> concentrations compared to Seoul or Beijing due to the large impact of uncontrolled coal combustion. Meanwhile, VOCs, NO<sub>x</sub>, and CO levels compared to SO<sub>2</sub> appeared to be not significantly higher than Seoul or Beijing. Although VOCs concentrations should be higher in UB due to the large number of old and used vehicles [15], it was likely due to the significantly smaller number of vehicles in UB compared to Seoul [46] and Beijing [47], and the slower volatilization of organic solvents due to the extreme cold in UB during winter.

In contrast, BTEX concentrations in Hong Kong, Bangkok, Kuala Lumpur, and Hanoi in Southeast Asia [48–51] showed high levels compared to those in UB. According to a report by IQAir [52], Thailand, Malaysia, and Vietnam (excluding Hong Kong) are among the world's most polluted countries in terms of PM<sub>2.5</sub> levels. Mongolia exhibited similar pollution levels to those countries. However, VOCs are sensitive to temperature, which may be due to the higher concentrations observed in Southeast Asia compared to Northeast Asia.

3.2. Source apportionment by PMF

In the PMF model, various metrics are used to determine the optimal number of factors. To further validate the modelling results, DISP and bootstrapping analysis were performed. In the base run, while DISP met the criteria, bootstrapping did not reach the required

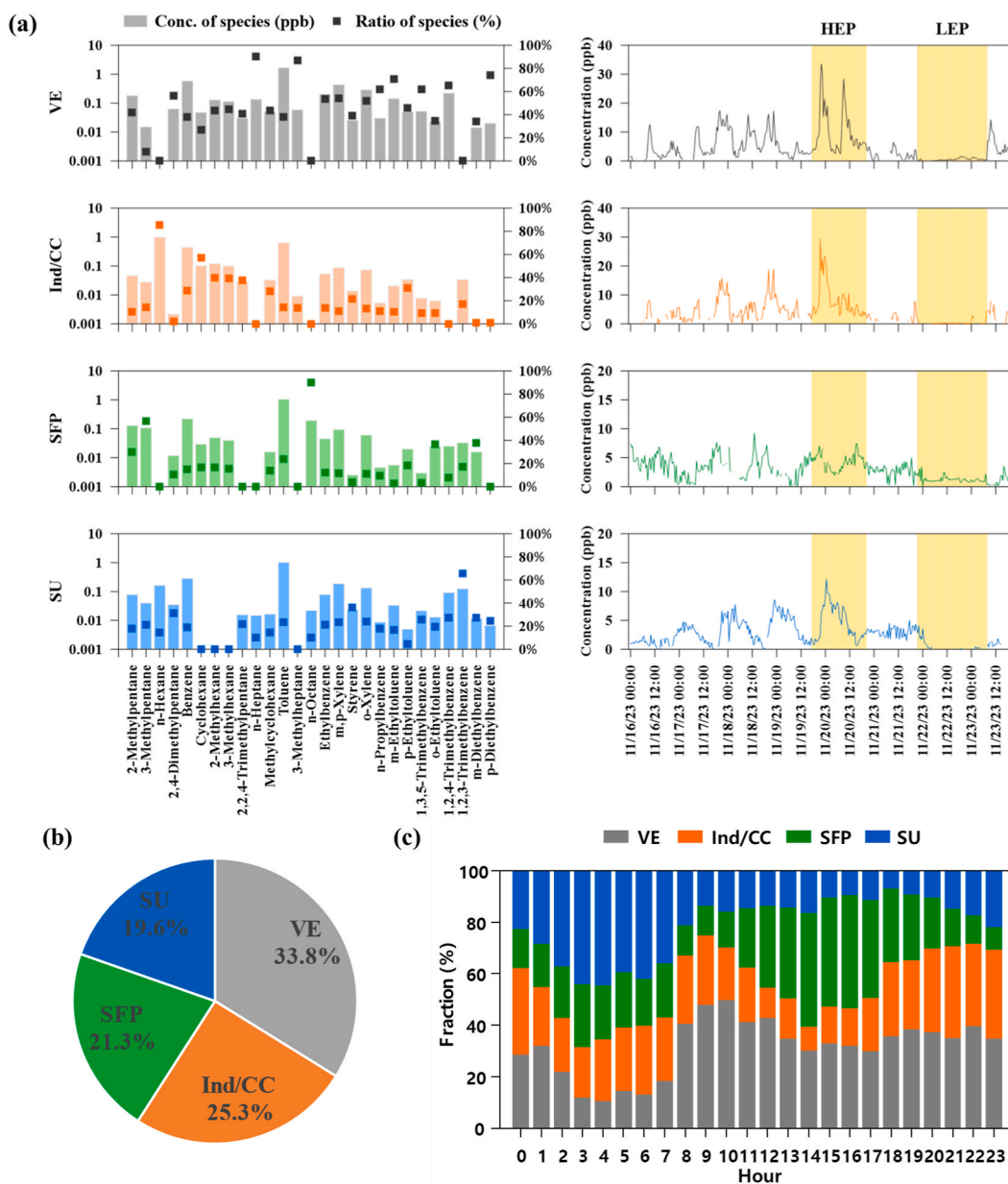
Table 2  
Comparison of BTEX concentration (ppb) from this study to the others.

Location	Sampling date	Benzene	Toluene	Ethylbenzene	Xylenes <sup>a</sup>	References
Hong Kong	2000.11–2001.02	1.59	7.02	0.60	1.09	Ho et al. [48] <sup>d</sup>
	2001.06–2001.08	0.93	6.96	0.73	1.62	
Bangkok, Thailand	2007.04–2007.08	1.82	9.58	0.94	3.39	Laowagul et al. [49] <sup>c</sup>
Kuala Lumpur, Malaysia	2013.12–2014.01	18.2	135	34.0	41.3 <sup>b</sup>	Hosaini et al. [50]
Tianjin, China	2014.11–2015.10	2.79	0.82	0.37	0.64	Liu et al. [43] <sup>d</sup>
Hanoi, Vietnam	2014.12–2015.01	12.8	27.4	4.80	21.9	Ly et al. [51]
Beijing, China	2016.03–2017.01	1.00	1.20	0.30	1.00	Li et al. [42]
Langfang, China	2016.04–2017.03	0.86	0.84	0.35	0.62	Song et al. [44]
Hebei, China	2018.11–2019.03	3.31	2.39	0.30	0.89	Xie et al. [45]
Lhasa, China	2019.05	1.65	1.21	0.29	1.05	Guo et al. [11]
Seoul, Korea	2020.12–2021.01	0.34	1.70	0.21	0.61	Lee et al. [13]
	2021.06	0.06	1.78	0.80	1.26	
Ulaanbaatar, Mongolia	2023.11	1.57	4.44	0.38	1.34	This study

<sup>a</sup> Combined value of m,p-xylenes and o-xylene.  
<sup>b</sup> Only p-xylene has data.  
<sup>c</sup> Converted units of concentration of VOCs in ambient air from  $\mu\text{g m}^{-3}$  to ppb, assuming a molar volume of 24.45 L at 25 °C and 760 mmHg.  
<sup>d</sup> Calculated mean of four-season values.

threshold of 80 out of 100 or higher. Consequently, the minimum dQ (−0.1) was selected through rotation to correspond to a bootstrapping value of 80 or more by sources. The optimum number of factors or sources during the winter in UB were four; vehicle exhaust (VE), industry/coal combustion (Ind/CC), secondary formation precursors (SFP), and solvent usage (SU).

VE accounted for the largest proportion (33.8 %) among the four sources, with high loadings of benzene, toluene, n-heptane, 3-methylheptane, and C<sub>9</sub>–C<sub>10</sub> aromatic VOCs as individual compounds (Fig. 4a and b). These compounds were also allocated to vehicle exhaust in the studies by Lee et al. [13], Liu et al. [43], and Xie et al. [45]. Additionally, Abbasi et al. [36] reported that if the benzene to toluene (B/T) ratio is lower than 0.5, the area is mainly affected by traffic emissions and if the B/T ratio is lower than 0.2, it is influenced by sources other than traffic. The B/T ratio for this factor was 0.35 (Table S2), indicating a close association with vehicular emission. Ho et al. [48] suggested that in Hong Kong, vehicle exhaust was the main source in winter due to reduced evaporation of fuel or additives at low temperatures. The diurnal variation in Fig. 4c shows a sharp increase in the VE source the rush hours, which correlates well with NO and NO<sub>x</sub> in Table S3 ( $R > 0.6$ ). Furthermore, this source clearly contributes to the rush hour during HEP (Fig. S2), indicating the need to regulate traffic on highly polluted days in UB. In Fig. S3, the VE was highest in the center and southwest, indicating local emissions from the roads surrounding the sampling point.



**Fig. 4.** Source apportionment by PMF model during winter in UB. (a) Source profile and time series, (b) source contributions, and (c) diurnal variation by sources.

The Ind/CC source contributed 25.3 % of the 34VOCs, with n-hexane, cyclohexane, 2-methylhexane, and 3-methylhexane being the main compounds. Cyclohexane is known as a marker compound in the petrochemical industry [53–55]. C<sub>6</sub>–C<sub>7</sub> alkanes, such as n-hexane and methyl hexanes, are classified as industrial emissions [43,45]. The ratio of m, p-xylene to ethylbenzene (X/E) is considered an indicator of the photochemical aging of BTEX compounds in urban areas. This is because xylenes are more reactive than ethylbenzene, with lifetimes of 11.8 h and 1.6 days, respectively [36]. As the photochemical reaction progresses, the X/E ratio gradually decreases, making it a useful indicator of air mass aging [11,13]. For Ind/CC, the X/E ratio was 1.66 (Table S2), which is significantly lower than other sources. In addition, this source showed the largest increase in concentration during the HEP corresponding to the low mixed layer depth (Table S3 and Fig. S4), suggesting a strong influence from the aging of the air mass. Meteorological conditions significantly influence the spread and dispersion of pollutants [56], which may explain the greater impact of power plants located in the southwestern region. Similarly, the Ind/CC source was highest in the southwest area (Fig. S3), suggesting a strong influence from the power plants, as shown in Fig. 1.

The third factor was mainly contributed by n-octane and 3-methylpentane, which are markers typically associated with asphalt and combustion, respectively [43,54,57]. However, in this case, they did not appear to be related to these activities due to their low correlation with other sources associated with vehicular emission and combustion. The third factor especially increased during daytime when examining the hourly pattern (Fig. 4c). Additionally, as shown in Fig. S4, when the sources were normalized to 34VOCs, the factor exhibits a trend very similar to O<sub>3</sub> (Fig. S1) with a higher correlation ( $R = 0.77$ ) than the other sources (Table S3). Moreover, this normalized source demonstrates a strong correlation between wind speed and the mixed layer depth (Table S3) which is particularly significant when atmospheric convection is active. Therefore, this source is identified as secondary formation precursors (SFP), contributing 21.3 % during the entire period and significantly increasing to 67.0 % during the LEP period (Fig. S2 and Fig. S4). The SFP was the only one characterized by a widespread distribution with no specific emission source (Fig. S3). To further confirm this factor, ozone formation contribution (OFC) was examined by the method shown in text S1. When aggregated by source, the largest contributor to OFC was SFP, contributing 33.0 % of ozone formation among the four sources. As well Ind/CC, SU, and VE contributed 28.0 %, 25.2 %, and 13.9 % of OFC, respectively. Sources from SFP contributed significantly more to ozone than other sources, indicating that they were clearly characterized as SFP.

The fourth factor exhibited the highest loading of 1,2,3-trimethylbenzene, followed by ethylbenzene, xylene, and styrene as the next significant contributors. Many studies have classified aromatic VOCs such as ethylbenzene and xylene as sources due to the solvents used in building materials and paints [13,30]. The B/T ratio and X/E ratio were 0.28 and 2.35 (Table S2), respectively, both of which are lower than the values typically associated with vehicle emissions. This suggests that the impact of other pollutants, such as solvents, may be significant, indicating that the air mass was likely relatively fresher compared to the influence of other sources. Therefore, this factor is named SU in this study. Its contribution has remained stable at 19.6 % throughout the entire period and at 18.4 % during HEP. The SU source was found to be well correlated with RH (Table S3). Markowicz and Larsson [58] reported that indoor VOCs are released from building materials and surfaces when RH increases. In the case of UB, the RH increased during the nighttime after sunset, and the contribution of SU sources to the diurnal variation increased. This suggests that emissions from building exterior walls and paints are released when RH increases. SU exhibited high concentrations in the center source (Fig. S3), outside the influence of the power plant, clearly indicating localized emissions around the measurement site. Thus, the 34VOCs in UB were significantly indicated to influence by local sources.

### 3.3. Health risk assessments

The ECR via the inhalation route of benzene was evaluated throughout its lifetime cancer risk (Table 3). Since the measured concentrations of benzene were in ppb, units were converted using the average temperature and air pressure during the measurement period. The mean concentrations of benzene during the entire period and HEP were  $4.50 \mu\text{g m}^{-3}$  and  $8.87 \mu\text{g m}^{-3}$ , respectively, with 95th percentiles of  $13.4 \mu\text{g m}^{-3}$  and  $23.3 \mu\text{g m}^{-3}$ . Globally, countries have different benzene control levels, but many, including Korea, regulate benzene to be  $5 \mu\text{g m}^{-3}$  or lower annually [7]. The 95th percentile benzene concentration in UB during HEP had exceeded the guideline level ( $5 \mu\text{g m}^{-3}$ ) by a factor of 2–4. According to the US EPA IRIS, a cancer risk of 1 in  $10^6$  is generally considered an acceptable level of risk, and a cancer risk of 1 in  $10^5$  or more is considered a level of concern. Additionally, a cancer risk of more than 1 in  $10^4$  represents a high level of concern that warrants more stringent regulatory action [28]. The ECR to infants in this study was considered acceptable or negligible for infants even during the HEP due to the short exposure time. For both children and adults, the ECR throughout the entire period was higher than the acceptable risk level but lower than the  $10^{-5}$  threshold of concern. Therefore, they should be monitored continuously. However, the cancer risk levels for children and adults at the 95th percentile of the HEP were higher than the level of concern of  $10^{-5}$ . During HEP, the contribution of VE and Ind/CC sources increases, along with stagnant air mass and local emissions, leading to elevated concentrations of benzene in the air. The meteorological and topographical

**Table 3**  
Carcinogenic health effects of benzene in HEP and entire period.

	HEP				Entire period			
	Benzene ( $\mu\text{g m}^{-3}$ )	Infants	Children	Adults	Benzene ( $\mu\text{g m}^{-3}$ )	Infants	Children	Adults
Mean	8.87	$2.61 \times 10^{-7}$	$4.44 \times 10^{-6}$	$1.36 \times 10^{-5}$	4.50	$1.33 \times 10^{-7}$	$2.25 \times 10^{-6}$	$6.90 \times 10^{-6}$
95th percentile	23.3	$6.86 \times 10^{-7}$	$1.17 \times 10^{-5}$	$3.57 \times 10^{-5}$	13.4	$3.95 \times 10^{-7}$	$6.71 \times 10^{-6}$	$2.05 \times 10^{-5}$

characteristics of UB, including dry conditions, low wind speeds, and frequent temperature inversions in winter, led to more frequent high-concentration episodes, increasing health risks, even for children with shorter exposure duration. This indicates that while stringent exposure control measures may not be immediately necessary, benzene should be considered an air pollutant of concern in UB. Consequently, benzene concentrations should be monitored regularly, and if needed, local emission controls and measures to mitigate exposure to hazardous VOCs, including benzene, should be considered.

#### 4. Conclusions

This study is the first to measure 34 VOC compounds in Ulaanbaatar using an online instrument during the winter of 2023. BTEX compounds were dominant, with concentrations higher than in Northeast Asia but lower than in Southeast Asia. Despite the short measurement period, high and low concentration episodes (HEP and LEP) were identified. During HEP, the increase in n-hexane and n-heptane concentrations pointed to the influence of coal-fired power plants and heavy traffic. PMF source apportionment identified four main sources: VE, Ind/CC, SFP, and SU, with VE as the largest contributor, particularly during rush hours. VE and Ind/CC sources dominated during HEP, highlighting local emissions' strong impact. SFP was linked with ozone and increased during daytime, while SU increased with rising humidity, likely due to building materials and painting. Benzene posed a significant cancer risk to adults, emphasizing the need for continuous monitoring. Children also faced heightened risks during HEP, underscoring the importance of controlling local emissions. These findings provide crucial data for developing air quality policies in UB, particularly to mitigate benzene-related health risks and protect public health.

#### CRediT authorship contribution statement

**Soo Ran Won:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Yong Pyo Kim:** Writing – review & editing, Conceptualization. **Misheel Sainjargal:** Investigation. **Tseren-Ochir Soyol-Erdene:** Writing – review & editing, Supervision, Conceptualization. **Ji Yi Lee:** Writing – review & editing, Supervision, Conceptualization.

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#### 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.

#### Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.heliyon.2024.e40085>.

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