Urban Air Quality Studies in Mongolia: Pollution Characteristics and Future Research Needs

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ABSTRACT

For the last decades, Mongolia has seen an extensive escalation in population growth, urbanization, and industrialization, together with great increase in mining and usage of vehicles. As a result, a substantial increase has taken place in the types and number of emission sources of air pollutants, especially in urban areas. During the cold season, air pollution level in Ulaanbaatar, the capital of Mongolia, is frequently ranked as the highest in the world. However, due to the lack of air quality management, the country is suffering from a deterioration of air quality.

Despite the worse air pollution situation, due to insufficient research capacity of the country, to date, research works on characteristics of air pollution have mainly been based on current capability and/or collaboration with foreign institutes. The research gap in this area necessitates numerous investigations, which could have great importance in developing mitigating strategies and minimizing the adverse impact of air pollution on local and regional scales. This paper reviews previously available studies and reports in international scientific journals on air quality in Mongolia. Based on the existing research works, future needs of studies on ambient air pollution in Mongolia are suggested.

Keywords: Air pollution, Literature overview, Ulaanbaatar, Mongolia, Further research recommendations

1 INTRODUCTION

Asian countries have experienced substantial growth in development and urbanization coupled with increases in energy use and transportation in recent decades (Moran and Kanemoto, 2016; Bilgili *et al.*, 2017; Li *et al.*, 2017). A considerable increase has occurred in the number and types of emission sources of air pollutants in Asia (Moran and Kanemoto, 2016; Li *et al.*, 2017). As a result, air pollution has emerged as a significant threat to the environment, quality of life, and health of the inhabitants in Asia, especially in developing countries where emission control system and strategies are not usually well established (Liu *et al.*, 2016; Moran and Kanemoto, 2016). Mongolia is one of the most rapidly developing countries in the world. As an East Asian country located between China and Russia, it is known for pristine environments with largely empty grassland, cold winters, and nomadic traditional culture. After the transition from a socialist system during the Soviet Union to democratic system in the beginning of the 1990s, urbanization, population growth, industrialization, and transportation development accelerated and created various environmental stresses in both urban and rural areas in the country (Warburton *et al.*, 2013; Pfeiffer *et al.*, 2015; Fan *et al.*, 2016; Batsaikhan *et al.*, 2018). Especially in recent years, Mongolia has become known for one of the world's worst air in the winter months (Davy *et al.*,

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2011; Cousins, 2019). The most polluted air in Mongolia is found in the capital city of Ulaanbaatar, where 46% of the country's population resides (NSOM, 2021). Furthermore, other cities in rural areas of the country are also facing a high degree of air pollution up to and exceeding the World Health Organization (WHO) and permissible levels of national guidelines (MET, 2019). The defining characteristic of air pollution in Mongolia—as in many countries—is the high concentration of particulate matter (PM) (Davy *et al.*, 2011; Nishikawa *et al.*, 2011; Guttikunda *et al.*, 2013; Hasenkopf *et al.*, 2016). It has been considered that air pollution represents a major threat to public health in Ulaanbaatar, the capital city of Mongolia (Allen *et al.*, 2013).

In the last two decades, with worsening air quality in Ulaanbaatar, interest in addressing air pollution has been increased. A number of research works has been performed on the assessment of the ambient air quality by evaluating criteria (Luvsan *et al.*, 2012; Huang *et al.*, 2013) and trace (Byambaa *et al.*, 2019; Nirmalkar *et al.*, 2020) pollutants in Mongolia, chemical (Jung *et al.*, 2010; Davy *et al.*, 2011; Nishikawa *et al.*, 2011; Batmunkh *et al.*, 2013; Amgalan *et al.*, 2016) and physical characteristics (Jung *et al.*, 2011; Oyungerel *et al.*, 2012; Hasenkopf *et al.*, 2016) of atmospheric particulate matter, source apportionment of certain atmospheric pollutants (Davy *et al.*, 2011; Nishikawa *et al.*, 2011; Amgalan *et al.*, 2016) and other climatic and socioeconomic factors impacting urban air quality (Luvsan *et al.*, 2012; Ganbat *et al.*, 2013; Huang *et al.*, 2013; Ganbat and Baik, 2016). To date, there have been no systematic reviews of published studies on air pollution in Mongolia. In an effort to fill this gap in the literature, we aim to provide a systematic literature review of air pollution in Mongolia focusing on the source apportionment, physical and chemical characteristics of air pollutants, and identify areas for future research. The review is limited to articles and reports in the English language peer-reviewed scientific literature. Studies of health impacts including exposure and clinical symptoms resulting from indoor and outdoor air pollution are not discussed.

Section 2 introduces the study area and its climate, which constitutes the important factor affecting air pollution. Some characteristics of the air quality monitoring network are also described in Section 2. Section 3 presents an overview of air pollution studies in Mongolia and particularly in Ulaanbaatar. The paper recommends the directions for further research. Conclusions are given in Section 4.

2 STUDY AREA

Mongolia is a landlocked country in the East Asian region positioned between 41°40' to 52°15'N and 87°44' to 119°54'E (Fig. 1). Mongolia has a marked continental climate with a broadly latitudinal rainfall distribution, causing a steep climatic gradient from semi-arid conditions in the north, with a mean annual precipitation of up to nearly 400 mm, to arid conditions in the south, with only 100 mm (Wesche and Treiber, 2012). The climate supports three main rangeland types: meadow steppe or forest steppe in the north, true steppe in the center and desert steppe in the south. The highest temperatures can reach 45°C in the Gobi region, which is in the southern part of the country and covered by sandy desert. Very cold and dry winters occur in the Central Northern and Northwestern mountain regions in Mongolia, with decreases in temperature to −45°C (Wesche and Treiber, 2012). This cold weather is attributed to the Siberian high-pressure system, which extends southeastward across the Eurasian continent in winter. Wintertime Siberian high-pressure system is also responsible for both weak winds that prevent air from mixing near the surface and clear skies, causing the formation of temperature inversion. This condition plays a significant role in winter air pollution (Ganbat and Baik, 2016).

Mongolia is the least densely populated country in the world, with a total population of only 3.36 million in an area of 1.56 million square kilometers, and is the 18th largest country worldwide (NSOM, 2021). The administrative division of Mongolia consists of twenty-one provinces and a capital city. Mongolia's population has undergone rapid urbanization since the mid-1990s, and this shift has had a major impact on the capital city, Ulaanbaatar, which is now home to 1.57 million people, equaling 45.4% of the nation's total population (NSOM, 2021). In addition to the capital city, each province has a city as its center, where the most populated areas within the provinces have a population of 10.7–103.7 thousands (NSOM, 2021). Two main industrial cities, Erdenet (#23 and #24 in Table 1 and Fig. 1) and Darkhan (#7 in Table 1 and Fig. 1), which are the centers

Fig. 1. Mongolia's geographic administrative boundaries and air quality monitoring sites in province centers and Ulaanbaatar. Site identifications are mentioned in Table 1.

of Orkhon and Darkhan-Uul provinces, respectively, are the most populated and industrial hub regions outside the Ulaanbaatar. The populations living in cities, both centers of provinces and the capital, have increased dramatically in recent decades (Warburton *et al.*, 2013). The urban population occupied 57% (1.226 million) of the total population of 2.153 million in 1990, and as of 2020, it had increased by a factor of two, reaching 69% (2.316 million) of the total population of the country (NSOM, 2021).

Ambient air pollution is the main environmental issue in the cities of Mongolia. Because of its high population and air pollution emission rate coupled with geographical and climatic conditions, air pollution is the most serious in Ulaanbaatar (Cousins, 2019). Other cities (the centers of the provinces including major industrial cities—Darkhan and Erdenet) have also been experiencing a high degree of ambient air pollution in recent years, especially during the winter season (MET, 2019).

Through the air quality (AQ) monitoring network, which constitutes of the National Agency for Meteorology and Environmental Monitoring (NAMEM) and the Air Pollution Reduction Department of Ulaanbaatar city (APRD), a total of 42 sites are operating across the country (Fig. 1). At the site, sulfur dioxide (SO₂), nitrogen dioxide (NO₂), and particulate matters (PM₁₀ and PM_{2.5}) are monitored

Table 1. List of the air quality monitoring sites with measured parameters in Mongolia.

Site name (ID)	Measuring parameters						
	WP	SO ₂	NO _x	CO	O ₃	PM _{2.5}	PM ₁₀
Ulaanbaatar city							
Uildver (UB1)	○	○	○	○	○	-	○
Baruun 4 zam (UB2)	○	○	○	○	-	○	○
1-r horoolol (UB3)	○	○	○	○	○	○	○
Zuun 4 zam (UB4)	○	○	○	○	○	○	○
Zuun ail (UB5)	○	○	○	○	○	-	○
Mongol gazar (UB7)	○	○	○	○	-	-	○
Urgakh naran (UB8)	○	○	○	○	○	-	○
Selbe 5 buudal (UB12)	-	○	○	-	-	○	○
Hailaast (UB11)	-	○	○	-	-	-	○
Bogdkhaanii ordon museum (UB13)	-	○	○	○	-	○	○
Tolgoit (APRD1)	○	○	○	○	○	○	-
MNB (APRD2)	○	○	○	○	○	○	-
Amgalan (APRD3)	○	○	○	○	○	○	-
Nisekh (APRD4)	○	○	○	○	○	○	○
Dambadarjaa (APRD5)	-	○	○	○	-	○	○
Bayankhoshuu (APRD6)	○	○	-	-	-	○	○
Other cities (province centers)							
1-Altai	△	○	○	-	-	-	-
2-Arvaikheer	△	○	○	-	-	-	-
3-Baganuur	△	○	○	-	-	-	-
4-Baruun-Urt	△	○	○	-	-	-	-
5-Bayankhongor	△	○	○	-	-	-	○
6-Bulgan	△	○	○	-	-	-	-
7-Darkhan-1	△	○	○	-	-	-	○
8-Dalanzadgad	△	○	○	-	-	-	-
9-Zuunmod	△	○	○	-	-	-	-
10-Zuunkharaa	△	○	○	-	-	-	-
11-Mandalgobi	△	○	○	-	-	-	-
12-Murun	△	○	○	-	-	-	○
13-Ulgii	△	○	○	-	-	-	-
14-Undurkhaan	△	○	○	-	-	-	-
15-Sainshand	△	○	○	-	-	-	-
16-Ulaangom	△	○	○	-	-	-	-
17-Uliastai	△	○	○	-	-	-	-
18-Khovd	△	○	○	-	-	-	-
19-Tsetserleg	△	○	○	-	-	-	-
20-Choibalsan	△	○	○	-	-	-	-
21-Choir	△	○	○	-	-	-	-
22-Shariin gol	△	○	○	-	-	-	-
23-Erdenet-1	△	○	○	-	-	-	○
24-Erdenet-2	△	○	○	-	-	-	-
25-Sukhbaatar	△	○	○	-	-	-	-

WP: weather parameters; ○ Measure; - Not measure; △ Measure at local weather station.

regularly. Only a few sites in Ulaanbaatar measure ozone (O₃) and carbon monoxide (CO) concentrations. The numbers of measuring parameters vary between the sites. The AQ monitoring sites of Mongolia with the measured parameters is listed in Table 1. Sixteen air quality monitoring sites are operated in Ulaanbaatar and located in—industrial (UB1 and UB7), residential (UB4, UB5 and UB13), ger area (UB3, UB11, UB12, APRD1, APRD2, APRD3, APRD4, APRD5, and APRD6), roadside (UB2), and remote areas (UB8). The current national air quality standard (MNS 4585:2016)

designating the maximum permissible levels of pollutants in ambient air was last amended in 2016. The pollutant levels in the national standard are high in comparison with those in the WHO guidelines (UNDP, 2019). For example, the national standard for 24-hour $\text{PM}_{2.5}$ is $50 \mu\text{g m}^{-3}$, while the WHO standard is $25 \mu\text{g m}^{-3}$ (Table 2.2 from UNDP (2019)). The air quality index is used to report the air quality situation to the public and has been revised and implemented in 2018 based on the effects of air pollutant concentrations on human health (MET, 2018).

3 RESULTS AND DISCUSSION

3.1 Pollutant Sources

For decision-makers, accurate and up-to-date knowledge of the source apportionment is essential in developing an optimal air quality management program. There is a lack of studies focusing on the source apportionment of air pollution and emission inventory except for Ulaanbaatar. Several published reports and studies on the air pollution sources in Ulaanbaatar are available. For the first time, Guttikunda (2008) presented the sources of particulate matter emissions for 2006. A local source predominates over the long-range transport (Nishikawa *et al.*, 2011). The PM emitters were reported to be from power plants (36%), followed by household stoves (25%) and heat-only boilers (17%). At the ground level in the city, it was calculated that stoves and HOBs (heat-only boilers) contribute the most to air pollution. The largest source of PM_{10} is household stoves and HOBs, which were indicated at ground level in the city (Guttikunda, 2008). It was mentioned that the PM source from vehicles is less important than that from power plants, stoves, and boilers, however, is increasing rapidly than the other sectors (Guttikunda, 2008).

The PM pollution source from combustion processes in stoves is also found to be significant (87%) from the analysis done in 2008–2009 (Lodoysamba and Pemberton-Pigott, 2011). The different averaging period and spatial location showed different contributions; for example, the difference between the contributions from combustion sources for $\text{PM}_{2.5}$ for 1-year and 5-year is ~35%, and locations near ger (Mongolian traditional felt tent) areas showed the highest contributions from combustion.

The emission inventory has been updated and reported within the Capacity Development Project for Air pollution control supported by the Japan International Cooperation Agency (JICA, 2017). The source contributions of individual PM, sulfate, and nitrate in Ulaanbaatar were identified. The pollution source contributions are likely to show spatial variations; for example, power plants in southern Ulaanbaatar show the largest contribution to PM_{10} emission sources, along with stoves, dust from roads and vehicle exhaust gas, while roads tend to show greater source contributions, followed by stoves in another part of Ulaanbaatar. Contributions from different sources may also depend on the emission height, e.g., stack height is 150–250 m for power plants, ~10–40 m for HOBs and ~3–6 m only for households' stoves.

3.2 Air Quality Studies in Small and Industrial Cities

In this section, ambient air quality studies in the central towns of the twenty-one provinces of Mongolia are considered. Within the framework of the National Environmental Monitoring System, criteria pollutants are monitored (Table 1) at the air quality (AQ) monitoring sites. Due to scattered sites of the national network, small and industrial cities have difficulty in getting detailed information on air quality. Nevertheless, according to the observation results, the main pollutants that show comparably higher concentrations and risks for human health overall in Mongolia are SO_2 , NO_2 , and PM, while CO and O_3 are below the national standard levels.

3.2.1 Gaseous pollutants

Fig. 2 shows the comparison of monthly mean concentrations for December of SO_2 and NO_2 for 2013–2015 and 2017–2019 periods measured at the AQ monitoring sites in non-capital locations. December month is chosen because it is the second coldest and polluted month of the year in the region. The concentrations of air pollutants vary across the country which are likely to be associated with various factors, such as pollutant sources, geographical and climate conditions, and socioeconomic factors. The mean SO_2 concentrations for December varied in the range of

Fig. 2. Monthly mean concentrations for December of (a) SO₂, (b) NO₂, and (c) PM₁₀ at the air quality monitoring sites.

2.2–117 $\mu\text{g m}^{-3}$ (not shown here) at the AQ monitoring sites and exceeded the permissible level (50 $\mu\text{g m}^{-3}$, the daily mean) in Bayankhongor (#5 in Fig. 1 and Table 1) and Dalanzadgad (#8 in Fig. 1 and Table 1) in 2018 (Fig. 2(a)). The mean NO_2 concentrations for December of each year at the AQ monitoring sites varied in the range of 6.4–112 $\mu\text{g m}^{-3}$ (not shown here). In Bayankhongor and Erdenet, high levels of NO_2 were observed, exceeding the national permissible level (50 $\mu\text{g m}^{-3}$, daily mean) (Fig. 2(b)). Air quality monitoring sites in Bayankhongor and Erdenet are located on roadside and the numbers of automobiles in the cities are dramatically increased in recent years. According to the National Statistical Office of Mongolia, the numbers of automobiles are increased by factor of ~ 1.8 in Orkhon province (96% of population lives in the Erdenet city) for the last eight years (NSOM, 2020). During the period from 2017 to 2019, the mean concentration of SO_2 for December clearly increased for the most sites in comparison with period from 2013 through 2015 (Fig. 2(a)). Luvsan *et al.* (2012) discussed regular monitoring data of SO_2 from 10 AQ monitoring sites in cities (Khovd, Ulaangom, Murun, Tsetserleg, Arvaikheer, Mandalgobi, Darkhan, Sukhbaatar, Erdenet, and Choibalsan) and four AQ monitoring sites (UB1 to UB4) of Ulaanbaatar for the period 1996–2009 to determine the source area of sulfur dioxide in Mongolia. Clear seasonal variations in SO_2 associated with heating demand in harsh winter and increased emissions from urbanization and industrialization were seen and the annual mean concentrations of SO_2 are likely to rise with increasing population and industrial development (Luvsan *et al.*, 2012). Moreover, the steel industry, mining, and/or other industrial activities can be major contributors to air pollution in Darkhan, Erdenet, and Sukhbaatar (Luvsan *et al.*, 2012).

3.2.2 Particulate matter

As mentioned, particulate matter is the most common polluting parameter in Mongolia due to emissions from incomplete coal combustion in households and soil resuspended dust. Fig. 2(c) shows December mean concentration of PM_{10} at three local sites—Erdenet, Darkhan, and Murun for the period of 2015–2019. As shown in Fig. 2(c), the PM_{10} concentration exceeds the national permissible level at the sites (100 $\mu\text{g m}^{-3}$, daily mean), with monthly average concentrations ranging between 89 $\mu\text{g m}^{-3}$ (in Erdenet in 2015) and 230 $\mu\text{g m}^{-3}$ (in Murun in 2019) in winter. Bolor-Erdene *et al.* (2011) conducted an analysis of PM_{10} and $\text{PM}_{2.5}$ mass concentrations and their elemental compositions in ambient air in the cities of Erdenet and Ulaanbaatar, but detailed information about the sampling period and concentration for the Erdenet cities was not provided (Bolor-Erdene *et al.*, 2011).

3.2.3 Trends of air quality in small cities

According to a report from the Ministry of Environment and Tourism (MET, 2020), the air quality in many cities of Mongolia is getting worse each year. Variations in the yearly mean concentrations of SO_2 at three sites (Bayankhongor, Darkhan, and Arvaikheer, Fig. 2(a)) illustrate a dramatic increase of 50–90% for the 2009–2011 period. In addition to the continuous increase in the pollution level of ambient air in many small and industrial cities of Mongolia, detailed research works on both criteria and trace pollutants—spatial and temporal variations, risk assessment, source characteristics, and socioeconomic, geographical, and climatic condition impacts were not yet systematically investigated or published in international scientific journals. Only two works (Bolor-Erdene *et al.*, 2011; Luvsan *et al.*, 2012) considered a few air pollution parameters outside of the capital city Ulaanbaatar. Both studies noticed clear seasonal variations in pollution levels in ambient air at all investigated sites, with the greatest variations occurring from December to February. The major sources are household and heat power stations' fuel burning for heating, which impacts the seasonal frequency of these air pollutants in Mongolia (Luvsan *et al.*, 2012). Moreover, mining waste dump can have a significant contribution to ambient PM pollution in Erdenet city (Bolor-Erdene *et al.*, 2011). Air pollution from SO_2 in small cities of Mongolia is becoming worse as urbanization (Luvsan *et al.*, 2012) and energy use increase.

3.3 Air Quality Studies in Ulaanbaatar City

Ulaanbaatar, Mongolia, is known as one of the most severely polluted cities in the world (Cousins, 2019). Ulaanbaatar's air pollution has become of increasing concern in recent two decades. Table 2 summarizes international publications focusing ambient air pollution and related

Table 2. Compilation of published studies on ambient air quality in Mongolia.

Study	Study area (number of sites)	Focus	Considered pollutants and data collection	Study period
Guttikunda <i>et al.</i> (2013)	UB	<ul style="list-style-type: none"> General discussion of PM pollution 	<ul style="list-style-type: none"> Emission inventory of PM, SO₂, NO_x, CO₂ for 2010; forward trajectory modeling to estimate PM concentration 	2010
Amarsaikhan <i>et al.</i> (2014)	UB	<ul style="list-style-type: none"> General discussions of air pollution 	<ul style="list-style-type: none"> Recall of previously reported studies 	Recall studies covering 2007–2013
Lodoysamba and Pemberton-Pigott (2011)	UB	<ul style="list-style-type: none"> Emission inventory 	<ul style="list-style-type: none"> PM measurement Multi-element analysis using the ion beam method Source apportionment 	2008–2009
Ganbat and Baik (2016)	UB	<ul style="list-style-type: none"> Weather and topographic condition 	<ul style="list-style-type: none"> Meteorological condition analysis Numerical weather modeling 	2013
Wang <i>et al.</i> (2018)	UB	<ul style="list-style-type: none"> Impact of meteorological condition on air pollution 	<ul style="list-style-type: none"> Analysis of meteorological, air quality (PM), ground based LIDAR, and radiosonde data 	2008–2016
Wang <i>et al.</i> (2017)	UB	<ul style="list-style-type: none"> Impact of meteorological condition on air particulate pollution 	<ul style="list-style-type: none"> Analysis of meteorological and LIDAR data 	2010
Prikaz <i>et al.</i> (2018)	UB (1)	<ul style="list-style-type: none"> Source area of SO₂ by HYPPLIT model 	<ul style="list-style-type: none"> NO_x, NO, NO₂, O₃, CO, PM₁₀, PM_{2.5}, PM₁ from National monitoring network 	Over 2017
Luvsan <i>et al.</i> (2012)	UB (4) Provinces (10)	<ul style="list-style-type: none"> Influence of sources and meteorological conditions on SO₂ pollution by multiple regression models 	<ul style="list-style-type: none"> SO₂ data from National monitoring network 	Multiyear (1996–2009)
Bolor-Erdene <i>et al.</i> (2011)	UB (1) Erdenet (1)	<ul style="list-style-type: none"> Mass concentration Elemental composition of PM_{2.5} and PM_{2.5-10} 	<ul style="list-style-type: none"> PM_{10-2.5}, PM_{2.5} sampling Elemental analyses by XRF 	No information provided
Huang <i>et al.</i> (2013)	UB (38)	<ul style="list-style-type: none"> Source contributions for SO₂ and NO₂ using land use regression model 	<ul style="list-style-type: none"> SO₂, NO₂ by 2 weeks passive sampling, analyses 	Three different seasons (Sep. 2011–Mar. 2012)
Amgalan <i>et al.</i> (2016)	UB (2)	<ul style="list-style-type: none"> Elemental composition, Source contributions PMF model 	<ul style="list-style-type: none"> Sampling of PM_{0-2.2}, PM_{2.2-10} Elemental analyses by XRF 	Over 1 year (Sep. 2012–Aug. 2013)
Batmunkh <i>et al.</i> (2013)	UB (1)	<ul style="list-style-type: none"> Chemical characteristics of atmospheric aerosol during winter 	<ul style="list-style-type: none"> PM_{2.5} sampling mass concentration chemical analyses for ions, metals, OC, EC 	One season (Jan. 2008–Feb. 2008)
Byambaa <i>et al.</i> (2019)	UB (5)	<ul style="list-style-type: none"> Source contribution prediction of PAHs in ambient TSP Health risk assessment based on concentrations 	<ul style="list-style-type: none"> 15 priority PAHs 	1-week sampling at three seasons (Jan. 2017, Mar. 2017, Sep. 2017)
Hasenkopf <i>et al.</i> (2016)	UB (1)	<ul style="list-style-type: none"> Elemental composition of PM_{2.5} Physical characterization of PM_{2.5} 	<ul style="list-style-type: none"> PM_{2.5} mass concentration Elemental analyses Determination of particle size, shape, and ice nucleation 	Nine months (Jun. 2012–Feb. 2013)

Table 2. (continued).

Study	Study area (number of sites)	Focus	Considered pollutants and data collection	Study period
Davy <i>et al.</i> (2011)	UB (1)	<ul style="list-style-type: none"> PM mass concentration Elemental composition, source contributions by PMF model 	<ul style="list-style-type: none"> PM_{10-2.5}, PM_{2.5} sampling Elemental analyses by XRF 	Multiyear (Oct. 2004–Apr. 2008)
Gunchin <i>et al.</i> (2019)	UB	<ul style="list-style-type: none"> PM mass concentration Elemental composition, source contributions by PMF model 	<ul style="list-style-type: none"> PM_{10-2.5}, PM_{2.5}, sampling Elemental analyses by XRF 	Multiyear (Jan. 2014–Jan. 2017)
Nishikawa <i>et al.</i> (2011)	UB (1)	<ul style="list-style-type: none"> Two seasons chemical composition of PM₁₀ Monitoring PM_{2.5} and PM₁₀ 	<ul style="list-style-type: none"> PM₁₀ sampling and analyses for ions, elements, OC, EC, C isotope composition in OC PM_{2.5}, SO₂, PM₁₀ 	<ul style="list-style-type: none"> PM₁₀ sampling: 1-week each season (Jan. 2008; Jun. 2008) PM_{2.5}, SO₂, PM₁₀–Over a year (Jun. 2009–May 2010)
Oyungerel <i>et al.</i> (2013)	UB (12)	<ul style="list-style-type: none"> Particle sizes and their distributions of roadside aerosols 	<ul style="list-style-type: none"> Particles in snow samples 	January 2011 (total accumulated snow)
Jung <i>et al.</i> (2010)	UB (1)	<ul style="list-style-type: none"> Composition of water-soluble organic acids in atmospheric fine PM during winter haze period 	<ul style="list-style-type: none"> PM_{2.5} sampling Analyses of 40 water soluble organic acids 	Dec. 2007
Jung <i>et al.</i> (2011)	UB (1)	<ul style="list-style-type: none"> Hydrophobic property of water-soluble organic rich aerosols 	<ul style="list-style-type: none"> Determination of shape and hydrophobic property of PM_{2.5} samples 	Dec. 2007
Lee <i>et al.</i> (2018)	UB (2)	<ul style="list-style-type: none"> Comparison size and chemical composition of < 2.5 µm of road dust in Ulaanbaatar and in Gwangju, Korea. 	<ul style="list-style-type: none"> Size and chemical composition of < 2.5 µm dust; metals, ions, carbonaceous compounds 	Jan. 2016
Morino <i>et al.</i> (2008)	UB (2)	<ul style="list-style-type: none"> VOC concentration in ambient air 	<ul style="list-style-type: none"> 12 VOC in ambient air 	No information provided
Ganbat <i>et al.</i> (2020)	UB (12)	<ul style="list-style-type: none"> Improvement in air quality 	<ul style="list-style-type: none"> Reduction of PM_{2.5} and PM₁₀ concentrations 	Multiyear (2014–2020)
Batbold <i>et al.</i> (2021)	UB (57)	<ul style="list-style-type: none"> Source apportionment of heavy metals from ground surface 	<ul style="list-style-type: none"> Determination of heavy metal source from settled dust samples 	Jan. 2020
Nirmalkar <i>et al.</i> (2020)		<ul style="list-style-type: none"> Biomass burning contribution OC in PM_{2.5} 	<ul style="list-style-type: none"> PM_{2.5} sampling and analyses of biomass burning markers (levoglucosan/mannosan), EC, OC, water soluble ions Data analyses for contribution of biomass burning and non-biomass burning sources in OC 	Jan.–Feb. and Apr.–May 2017
Gunchin <i>et al.</i> (2021)	UB (1)	<ul style="list-style-type: none"> Chemical speciation of Zn and Cr in PM 	<ul style="list-style-type: none"> PM sampling and analysis by XANES 	Jun. 2016–Jan. 2017
Yamamoto <i>et al.</i> (2020)	UB (1)	<ul style="list-style-type: none"> Chemical characteristics of suspended PM and sources contributions 	<ul style="list-style-type: none"> PM analyses for OC, metals, ions, n-alkanes and PAHs 	Jan. 2014–Apr. 2015

topics mentioned above in Mongolia. Almost all studies conducted on the Ulaanbaatar's air pollution (Table 2), while only two works considered the air pollution in other cities (Bolor-Erdene *et al.*, 2011; Luvsan *et al.*, 2012). To date, ambient air quality and its related topics including chemical composition for both critical and trace (emergent) pollutants, toxicity, physical properties, source characteristics and apportionment, and distribution have been insufficiently studied (see also Fig. 1 of Hasenkopf *et al.*, 2016) (Hasenkopf *et al.*, 2016).

3.3.1 Impacts of climate and topographic conditions

Geographical and weather conditions are important factors affecting air pollution in Ulaanbaatar (Guttikunda *et al.*, 2013). Considering how weather conditions affect air pollution may help understand the essence of air pollution and is important for appropriate reduction measures. Studies attempting to explain the weather and geographical impacts on air pollution in Ulaanbaatar have applied different methods. The city of Ulaanbaatar is located in the valley of Tuul River and surrounded by high mountains (Amarsaikhan *et al.*, 2014). Due to complex topography, the pollutant dispersion is complex in Ulaanbaatar. The valleys, for example the Selbegol valley located to the north of the city, play an important role in transporting the pollutants over/toward the city (Lorentz *et al.*, 2019). In summertime, when the fair condition for the development of local winds is met, urban breeze circulation, mountain/valley winds are well developed (Ganbat and Baik, 2015). Well-developed winds and deep convective boundary layers are capable to transporting pollutants far away from their emission sources. Weather conditions and air circulations on a local scale in summertime (Ganbat and Baik, 2015, 2016) are very different from those in wintertime. In winter, weak local winds are developed in a stable boundary layer (Ganbat and Baik, 2016) where the motion is suppressed resulting in trapped pollutants in the shallow boundary layer. With extreme climate, Ulaanbaatar is the coldest capital of the world; the average temperature of January is -33°C , but the temperatures can drop below -40°C (Pillarisetti *et al.*, 2019). Temperature inversions are frequently observed in mountainous urban areas and can cause severe air pollution problems, especially in wintertime (Luvsan *et al.*, 2012).

During winter periods, the effects of temperature inversion are enhanced because of lower mixing layer heights (Whiteman *et al.*, 1999). Air pollutants emitted from various sources tend to be concentrated within the valley area under the temperature inversion condition, and a layer of cooler air is trapped near the ground by a layer of warmer air above that prevents any dispersion of pollutants (Baumbach and Vogt, 2003). The low wind speed within the atmospheric boundary layer accompanied by the temperature inversion condition due to the Siberian high-pressure system contributes to the increase in air pollutants in winter in Mongolia (Wang *et al.*, 2018; Lorentz *et al.*, 2019). Ganbat and Baik (2016) conducted a numerical modeling experiment to investigate wintertime weather conditions that are favorable for bad air quality in Ulaanbaatar. It was revealed that the air is very stable and windless within the temperature inversion layer, which leads to the stagnation of air pollutants. Spatial and temporal variations of temperature inversion in Ulaanbaatar for the chosen case are clearly presented in the numerical modeling study (Ganbat and Baik, 2016). The numerical study reveals that the temperature inversion is strong and deep in the valleys compared to that over the mountains and mountain slopes. The temperature inversion weakens in the daytime as surface heats.

Wang *et al.* (2018) employed statistical methods using meteorological and air quality observations, LIDAR, and radiosonde data (Wang *et al.*, 2017; Wang *et al.*, 2018). They elucidated the formation and breakup timing of the temperature inversion layer capping the urban area of Ulaanbaatar. A stable atmosphere persists throughout winter (Fig. 6(c) in Wang *et al.* (2018)) and becomes thicker and stronger from September to January. A relatively shallow mixing layer ($< 300\text{ m}$), where the wind is weak and vertical convection is suppressed, allows the air pollutants to stagnate within it. Using observational data for the period 2008–2016, the authors presented a significant positive correlation ($R = 0.595$) between the temperature inversion intensity and $\text{PM}_{2.5}$ concentration in Ulaanbaatar (Wang *et al.*, 2017, 2018).

Statistical analysis of meteorological impacts on SO_2 concentration at 14 different sites in Mongolia was conducted by Luvsan *et al.* (2012). Linear regression model confirmed that SO_2 levels are negatively correlated with wind speed and temperature in Ulaanbaatar and SO_2 pollution has worsened since 2000s because of social impacts including urbanization and industrialization.

The authors mentioned the importance of wind directions in the increase in SO₂ levels due to coal consumption emissions in ger areas. SO₂ levels tend to be higher with winds from N–NNW (north–north northwest) than those from N–ENE (north–east northeast) (Luvsan *et al.*, 2012). Considering the studies on relationship between air pollutant concentrations and several meteorological conditions are insufficient, more sophisticated numerical modeling approach should be applied to understand the complex mechanisms.

3.3.2 Particulate matter

3.3.2.1 Mass concentration

The concentration of inhalable particulate matter (PM₁₀ and PM_{2.5}) in Ulaanbaatar is the highest in the country, making Ulaanbaatar city one of the most polluted cities in the world for several years (Guttikunda *et al.*, 2013; Cousins, 2019). Due to incomplete combustion in traditional low-efficiency stoves in ger area of Ulaanbaatar, high-concentration particulate matter is emitted from stacks of those stoves. These emissions (from 25% (Guttikunda, 2008) to 87% (Lodoysamba and Pemberton-Pigott, 2011)) result in extremely high concentrations of particulate matter in the urban atmosphere.

Fig. 3 shows the daily mean PM₁₀, PM_{2.5}, SO₂, and NO₂ concentrations for 2014–2021 averaged over the AQ monitoring sites in Ulaanbaatar. Prominent seasonal variations are clearly seen having the greatest concentration in cold seasons due to high pollutant emissions resulting from fuel consumption and weather condition with temperature inversion (discussed in Section 3.3.1). The PM_{2.5} concentration is greatest in winter exceeding many times the national permissible level (50 µg m⁻³) while it is likely to be below/near the permissible level most of the time during warm, non-heating seasons. Ganbat *et al.* (2020) reported the daily (hourly) maximum PM₁₀ and PM_{2.5} concentrations of 833.6 (2505) µg m⁻³ and 511.4 (1413) µg m⁻³ for the period, respectively (Ganbat *et al.*, 2020).

Many studies indicated that emissions from coal burning in ger area are the main reason for Ulaanbaatar's pollution problem (Guttikunda *et al.*, 2013; Lodoysamba and Pemberton-Pigott, 2011; JICA, 2017). Over the last decade, a variety of efforts have been made to reduce emissions from polluting sources, special attention has been paid to reduce emissions from ger areas because of coal combustion. A city-wide substitution of raw coal with upgraded briquette coal has been effective in reducing particulate matter pollution and largely reduced the PM_{2.5} and PM₁₀ concentrations in winter. In the past two winters, the air quality was improved in Ulaanbaatar to some extent which was first documented in Ganbat *et al.* (2020). For winter 2019–2020, the daily mean concentrations of PM_{2.5} and PM₁₀ during the heating season were reduced by 36% and 40% compared to the heating seasons in 2014–2018, respectively. The improvement was mainly by the city-wide substitution of raw coal with upgraded briquette fuel since 15 May 2019 according to Governmental resolution No. 62 adopted in 2018. Despite the progress in reductions in PM concentrations, the PM concentrations are still well above the WHO guideline values and the national standard levels.

3.3.2.2 Chemical composition

a) Elemental composition

Various organic and inorganic toxic substances can be present on particulate matter emitted from coal combustion as soot and ash particles. The elemental compositions of fine particulate matter in Ulaanbaatar ambient air were previously investigated in several locations by separating two different sizes of fine (aerodynamic diameter less than 2.5 µm) and coarse (between 2.5 and 10 µm) fractions (Davy *et al.*, 2011; Amgalan *et al.*, 2016; Hasenkopf *et al.*, 2016; Gunchin *et al.*, 2019). The main discussions were conducted on the source contributions of atmospheric particulate matter in the atmosphere based on seasonal variation and PMF (positive matrix factorization) analyses. Based on an investigation of a multiseasonal long period between 2004 and 2008 (Davy *et al.*, 2011), the combustion sources, such as coal combustion, biomass burning, and motor vehicles, dominated the fine fraction of particulate matter in Ulaanbaatar, primarily from local emission sources, but forest fires in the north can be a significant contributor to biomass burning concentrations over time. Crustal dust sources were the primary contributors to the coarse particle fraction (PM_{2.5-10}). For the study period, at the site of city center (National University of Mongolia), the distributions of source contribution of the coarse particulate matter (PM_{2.5-10})

Fig. 3. Daily mean concentrations of (a) PM_{10} , $\text{PM}_{2.5}$ and (b) SO_2 , NO_2 for 2014–2021 averaged over the AQ monitoring sites in Ulaanbaatar.

were in the order: soil > road dust > combustion, while of the fine particulate matter ($\text{PM}_{2.5}$), more categories were separated and in the order: combustion > soil > road dust > motor vehicles > biomass burning. There was also an unknown source grouped with high Zn loading for fine aerosols (Davy *et al.*, 2011). In addition, the results of different studies on source contributions for particulate matter can differ depending on time and locations of the studies. In an investigation by Amgalan *et al.* (2016) using the same techniques as Davy *et al.* (2011), source contribution of

PM_{2.5} were observed at two suburban ger areas of the city over the period of Sep 2012–Aug 2013. In the ger area, the source contribution of PM_{2.5} aerosols were determined in the following order: combustion > road dust > motor vehicles > soil. At another site located in the eastern part of the city, the contribution of PM_{2.5} changed to the following order: soil > combustion > motor vehicle > road dust (Amgalan *et al.*, 2016).

While numerous studies of approaches on elemental composition and organic compounds (described in the next section) in PM have been carried out, the only study was recently conducted on chemical speciation of zinc (Zn) and chromium (Cr) in aerosols. Gunchin *et al.* (2021) introduced a chemical speciation analysis of two elements in fine (PM_{2.5}) and coarse (PM_{2.5-10}) particulate matters based on the results of X-Ray Absorption Near-edge Structure Spectroscopy measurements. According to the results, chromium (Cr) was dominant in the form of tri-valent chromium sulfate (Cr₂(SO₄)₃) and chromium oxide (Cr₂O₃) for both PM_{2.5} and PM_{2.5-10} fractions. Relative abundances of those forms were varied between the samples, but no direct relation was observed with Cr and S concentrations in aerosol. Two abundant speciation of Zn—sulfate (ZnSO₄) and silicate (Zn₂SiO₄) were identified for both fine and coarse PM fractions. Zn oxalate (ZnC₂O₄) was determined in fine particles, while Zn chloride (ZnCl₂) in the coarse particles and the relative abundances of the species of Cr and Zn were also had no direct relation with the concentrations of Zn, S, Si, and Cl. The authors concluded that Cr and Zn were mainly originated from anthropogenic sources—combustion and resuspension of dust particles due to traffic (Gunchin *et al.*, 2021).

b) Combined approaches for chemical composition and sources

The chemical compositions of atmospheric fine aerosols (PM_{2.5}) in Ulaanbaatar city including water-soluble organic acids (Jung *et al.*, 2010) and ionic, elemental, and carbonaceous compounds (organic and black carbon) were investigated during winter haze events (Jung *et al.*, 2010; Nishikawa *et al.*, 2011; Batmunkh *et al.*, 2013) and compared with those of the warm season (Nishikawa *et al.*, 2011). According to these earlier studies performed decade ago, ionic, metallic, and carbonaceous compositions of particulate matter in Ulaanbaatar (PM_{2.5} and PM₁₀) are attributed mostly to coal combustion products in the winter (heating) period (Nishikawa *et al.*, 2011; Batmunkh *et al.*, 2013). Carbon components (OC and EC) are dominant in PM₁₀ for both heating (47%) and non-heating (33%) seasons in Ulaanbaatar air (Nishikawa *et al.*, 2011). Concentrations of OC (EC) were ranged between 45.4 µg m⁻³ and 119 µg m⁻³ (18.7 µg m⁻³ and 30 µg m⁻³) in heating season and between 10.1–27.3 µg m⁻³ (4.31–8.28 µg m⁻³) in non-heating season (Nishikawa *et al.*, 2011). During the same year in winter (2008), the organic mass carbon content in PM_{2.5} counted 62.7%, and the content of ammonium sulfate followed, with a 12.6% contribution (Batmunkh *et al.*, 2013). Elemental concentration and their ratios are clearly distinguished for different sampling periods due to their dominant sources, e.g., coal combustion in heating season, while soil dust resuspension in non-heating season. The research by Jung *et al.* (2010) firstly reported the dicarboxylic acids, ketocarboxylic acids, and α-dicarbonyls, and as well as soluble inorganic ions of PM_{2.5}. The most part of aerosols were composed from emissions from local sources and as well as weather/geographical condition is a key factor of occurrence of haze events. Distributions of dicarboxylic acids and related compounds were determined to have a predominance of terephthalic acid followed by oxalic, succinic, glyoxylic, and phthalic acids (Table 3), which indicated a significant contribution from the uncontrolled burning of plastic materials in home stoves for heating and waste incineration during the cold winter (Jung *et al.*, 2010).

Recently, Nirmalkar *et al.* (2020) conducted research on estimation of organic carbon emissions from biomass burning in Ulaanbaatar based on organic carbon (OC) and elemental carbon (EC), anhydrosugars (levoglucosan, mannosan, and galactosan), and water-soluble ionic composition. Biomass and coal burning and followed by soil dust and secondary aerosols formation were the major sources of PM_{2.5}. Similar to previous findings, in winter and spring, the OC was found to be a major component in PM_{2.5} constituting 64% and 56%, respectively, and 68% and 63% of the OC were emitted from biomass burning, respectively. The indicator compounds such as levoglucosan/mannosan and levoglucosan/K⁺ ratios revealed that the softwood burning aerosols in Ulaanbaatar is a major source of organic carbon in PM_{2.5}. Multivariate correlation analysis identified that non-biomass burning organic carbon is dominantly produced by coal burning and followed by vehicle and vegetative emissions (Nirmalkar *et al.*, 2020).

Table 3. Concentrations of dicarboxylic acids and related compounds in PM_{2.5} of Ulaanbaatar (Jung *et al.*, 2020).

Compounds	Concentration, ng m ⁻³	Percentage in total organic acids, %
Terephthalic acid	130 ± 51	19
Oxalic acid	107 ± 28	15
Succinic acid	63 ± 20	9
Glyoxylic acid	55 ± 18	8
Phthalic acid	54 ± 27	8

Soil dust contributions existed with almost the same contributions in two seasons, heating (January) and non-heating (June) (Nishikawa *et al.*, 2011). The meteorological conditions were determined to be the most impactful factor on the particulate matter concentration level in Ulaanbaatar (Jung *et al.*, 2010; Batmunkh *et al.*, 2013). During high-speed windy days with low atmospheric pressure (LP), the PM concentrations were lower by a factor of two or three than those on high-pressure days with a comparably stable stagnant atmosphere (Batmunkh *et al.*, 2013). Most of the air pollutants were directly emitted from local sources such as heat and power plants, home stoves, and automobiles during the winter season (Jung *et al.*, 2010).

c) Organic pollutants

Since the main producer of atmospheric pollution in the city is coal combustion (Guttikunda *et al.*, 2013; JICA, 2017), trace amounts of organic toxic compounds that are emitted by incomplete combustion (i.e., various types of PAHs) (Bari *et al.*, 2010; Sarigiannis *et al.*, 2015) are expected to be present at high concentrations in the air of Ulaanbaatar. However, very few research studies have been performed and published internationally on this topic. Total suspended particles (TSPs) collected from five different locations of the city for the heating and non-heating period of 2017 were investigated by Byambaa *et al.* (2019). The total PAH concentrations (15 priority PAHs) ranged between 131 and 773 ng m⁻³ in winter, 22.2 and 530.6 ng m⁻³ in spring, and 1.4 and 54.6 ng m⁻³ in autumn and showed a high risk for inhabitants, with the PAH levels exceeding the World Health Organization guidelines in winter (Byambaa *et al.*, 2019). In addition, a significantly higher concentration of 16 priority PAHs in inhalable particulate matter (PM_{2.5}) in the ambient air of the ger area in Ulaanbaatar was observed during the transition period between the heating and non-heating periods (Feb–Apr 2019) (Lorentz *et al.*, 2019). The risk level of PAHs bound to PM₁₀ was calculated to be extremely high (with a benzo[a]pyrene equivalent factor of 32 ± 17) and similar to that in the most polluted industrial city, Tianjin in China (29.7 ± 15.1 recalculated) (Jin *et al.*, 2018). Further detailed investigations on PAHs for fine atmospheric PM including size and molecular distributions as well as different source contributions and impacting parameters are urgently needed in Ulaanbaatar city to provide guidance to people to avoid exposure to such highly toxic carcinogenic compounds. It can also be noted that in addition to evaluation of the pollution level in ambient air, atmospheric transfer mechanisms, which depend on the climatic factors in the city air, as well as environmental fate and transfer through the geochemical cycle in certain conditions of the country can be important research topics.

d) Dust deposition

Lee *et al.* (2018) investigated size and chemical composition of a fine fraction (< 2.5 µm) of road dust collected from two locations in Ulaanbaatar and compared with those in Gwangju, South Korea. The authors found greater fractions of ultrafine fine (~30 nm) particles in UB road dust with comparably higher concentrations of As, SO₄²⁻, and Cl⁻ and is indicated significant impact of residential coal/biomass burning. In a recent study, application of chemical methods of atmospheric dry deposited dust is used to determine the sources for the seven potentially toxic metals (As, Co, Cr, Cu, Ni, Pb, and Zn) in heating season based on settled dust analyses sampled at 57 sites in Ulaanbaatar (Batbold *et al.*, 2021). The results showed that the metals composition in settled dust are attributed to coal combustion, vehicle exhaust emission, and soil particles. Southern part of the city is enriched with comparably high concentrations of As, Zn, Cu, and Cr when compared to other parts of the city and are mainly attributed to coal combustion sources.

3.3.3 Physical properties

The size distribution of the nanosized fraction of ambient air particulate matter along the roadside was investigated by Oyungerel *et al.* (2012). Snow samples collected from twelve locations of the city were used for particle size and size distribution analysis by photon cross-correlation spectroscopy. The particle mean diameters were found to be from 1.1 to 2.5 μm , ranging between 74 nm and 4.0 μm . Ultrafine particles or nanoparticles (0.02% volume percent) were found in the range of 74–100 nm, while 83.73% fine particles ($\text{PM}_{2.5}$) were found in the range of 100 nm–2.4 μm , and 16.25% coarse particles (PM_{10}) were found in the range of 2.4–4.0 μm . Aerosols along the road had a high content of $\text{PM}_{2.5}$ particles (Oyungerel *et al.*, 2012). Hasenkopf *et al.* (2016) studied the particle sizes, shapes, and ice-nucleating properties of particulate matter collected during different seasons. As a result, all particles are in the inhalable range, with almost all particles smaller than 2.5 μm , composed of minerals, soot, and sulfate-organic compounds. The particle concentration and sulfur content of particles increase in winter with lower ice nucleation activity (Hasenkopf *et al.*, 2016). Moreover, the hygroscopic property of water-soluble organic-enriched aerosols in Ulaanbaatar during the winter of 2007 was investigated by Jung *et al.* (2011). The authors found that hygroscopic growth of water-soluble organic matter (WSOM) in at RH 85% ($g(85\%)$) is ranged between 1.11 and 1.35 (avg. 1.23 ± 0.10), which are comparable to those of the biomass burning aerosols (Jung *et al.*, 2011).

3.3.4 Other pollutants

a) Sulfur dioxide (SO_2)

As expected, in Mongolia, SO_2 pollution in winter is more serious than that in the other three seasons. According to the observational data from 1996–2009 at the AQ monitoring sites in Ulaanbaatar (UB1, UB2, UB3, and UB4, see Table 1), the daily mean concentrations of SO_2 were $27.3 \pm 24.7 \mu\text{g m}^{-3}$ and increased dramatically during the study period (Luvsan *et al.*, 2012). The observed results are attributed to the use of raw coal in ger area for heat production over the years, where this coal without a washing pretreatment contains a significant amount of sulfur (Prikaz *et al.*, 2018). The main SO_2 emitters in Ulaanbaatar are combustion sources such as ger stoves, traffic and power plants. All seasonal fluctuations in SO_2 emissions are shown to be due to the increase in fuel consumption requirements in cold weather conditions (Luvsan *et al.*, 2012). Prikaz *et al.* (2018) investigated source areas of SO_2 in Ulaanbaatar based on whole-year data of air pollutants (NO_x , NO, NO_2 , O_3 , CO, PM_{10} , $\text{PM}_{2.5}$, and PM_1) measured at the APRD3 site (Fig. 1) and using HYSPLIT backward trajectory analyses (Prikaz *et al.*, 2018). According to the results, in 2017, the annual average concentration of SO_2 at the site was $32.43 \mu\text{g m}^{-3}$ and the hourly maximum concentration reached $233.2 \mu\text{g m}^{-3}$ in January. Back trajectory analyses showed that 78.8% of the total trajectories in Ulaanbaatar came from an area inside Mongolia.

Fig. 3(b) shows a noticeable variation of SO_2 with seasons and worsened SO_2 pollution in recent years in Ulaanbaatar city. The seasonal variation of SO_2 is similar to that of particulate matter showing a significantly higher concentration in winter than in summer. Compared with that in winters before 2018/2019, SO_2 increased by 41% in the following two winters, which has already elicited concerns. However, no study to date has yet elaborated and reported the recent increase in SO_2 concentration in Ulaanbaatar. Sulfur content in briquette fuel is $\sim 0.9\%$ (MNIA, 2019) and is not exceeding the National Standard (MNS 5679:2019, $< 1.0\%$ S), however, is approximately two times higher than that in Baganuur coal (0.42% S) (JICA, 2013), previously used as the main fuel of residences of Ulaanbaatar's ger area before the substitution to briquette in 2019. Thus, further investigation is needed by combining of fuel's characteristics (e.g., caloric values, compositions, and ash contents), emissions to propose adequate measures to reduce SO_2 pollution in Ulaanbaatar.

As shown in Table 2, the source apportionment studies for the SO_2 level and sulfur compounds in the particulate matter have not been sufficiently conducted in Mongolia. Spatial distributions of SO_2 and source characteristics across Ulaanbaatar were investigated by Huang *et al.* (2013). The authors collected multiseasonal passive samples from 38 locations in 2011–2012 and evaluated the impact of land use patterns on SO_2 and NO_2 distributions by multiple regression models. The SO_2 concentrations were $121.9 \mu\text{g m}^{-3}$ in the cold season and $46.62 \mu\text{g m}^{-3}$ in the moderate season (units were converted from ppb in original). Ger area sites showed significantly

higher SO₂ concentrations than non-ger area sites (60.09 µg m⁻³ and 32.78 µg m⁻³, respectively). These results also supported that the main source of atmospheric SO₂ in the winter season is coal combustion in ger areas (Huang *et al.*, 2013).

On the other hand, when considering the recent increase in vehicle and fuel consumption accordingly in the city due to an increasing population and number of vehicles, a high contribution from fuel combustion to the urban atmosphere is expected. This expectation is supported by the analytical results of fuels used in Mongolia. According to the Tables 1 and 2 of Bayasgalan *et al.* (2018), there are extremely high concentrations of sulfur in gasoline (117–400 ppm S) and diesel (1,135–1,165 ppm S) used in Mongolia, exceeding the Euro 4 standard (50 ppm S) by 2–8 times and 22–23 times, respectively (Bayasgalan *et al.*, 2018). So far, there have been no reported contributions of SO₂ from other sources related to industrial activities within the Ulaanbaatar city. Thus, detailed studies on the source contributions of SO₂ and sulfur compounds in the atmospheric particulate matter would have been one of the urgently needed research topics.

b) Nitrogen dioxide (NO₂)

As described in the previous sections, in addition to coal combustion, automobile emissions play a significant role in air pollution in cities (Davy *et al.*, 2011; Amgalan *et al.*, 2016). For the last ten years, the number of vehicles has increased in Ulaanbaatar by a factor of 4.5 and has reached ~540,000 (Bayasgalan and Matsumoto, 2017; NSOM, 2021). Approximately 72% of all vehicles were aged more than 10 years, and most of them were second-hand (Bayasgalan and Matsumoto, 2017). In connection with automobile emissions, NO₂ concentrations detected at roadside sites of NAMEM were in the range of 41–65 µg m⁻³ and exceeded national air quality guidelines for 97% of all measured days in 2014 (Bayasgalan and Matsumoto, 2017). The only study (Huang *et al.*, 2013) reported the seasonal variation in ambient NO₂ pollution, its spatial distribution, and the contributions of different sources in Ulaanbaatar. As described above, through two weeks of passive sampling at 38 locations in the warm, cold, and moderate seasons of 2011–2012, ionic analyses of the samples, and multiple regression models, ambient NO₂ pollution was explained by several land-use variables. As a result, the NO₂ concentrations at traffic road-side sites in the warm and moderate seasons (24.16 µg m⁻³ and 38.51 µg m⁻³, respectively, units were converted from ppb in original) were significantly higher than those at urban sites (14.3 µg m⁻³ and 27.06 µg m⁻³). Otherwise, during the cold season, significantly higher concentrations of NO₂ were observed, with an average of 66.9 ± 19.9 µg m⁻³ for all sites without a clear distinction between land use types (Huang *et al.*, 2013). Primarily, NO released into the air from the automobiles, and is converted to NO₂ in the atmosphere with the presence of oxidants (e.g., ozone). The conversion rate is increased in warm and moderate season when level of ozone concentration is higher. Thus, further evaluation for the variations of NO, NO₂ and ozone is needed to distinguish sources contributions for NO_x (NO and NO₂) over the year.

c) Volatile organic compounds

Volatile organic compounds (VOCs) are one group of components of air pollution comprising a complex mix of hundreds of carbon-containing gases. If VOCs occur in high concentrations in ambient air, exceeding permissible levels, then exposure can cause health risks (Han *et al.*, 2017; Barabad *et al.*, 2018; Kumar *et al.*, 2018). On the other hand, VOCs are the main precursors that form secondary air pollutants such as ozone through photochemical reactions in the atmosphere especially on hot and sunny days (Han *et al.*, 2017; Kumar *et al.*, 2018). The assessment of VOCs is not included in air quality network monitoring in Mongolia. Regarding the lack of analytical capacity, there have been almost no attempts made to identify, quantify, and characterize VOCs in urban or rural areas in Mongolia. Much earlier, Morimo *et al.* (2008) detected several VOCs in urban air and reported the results in conference proceedings, but no information about sampling sites or the duration of the study was provided. Significantly elevated concentrations of VOCs were detected in Ulaanbaatar air. The concentrations of 1,3-butadiene, chloroform, and benzene in the ambient air of Ulaanbaatar were much higher than those in the Japan Environmental Standards (Morimo *et al.*, 2008). More recently, the spatial distribution of VOCs at six sampling sites was determined within the framework of a collaborative project between German and Mongolia (Lorentz *et al.*, 2019). Three main VOCs, BTX (benzene, toluene, xylene), were detected by passive sampling in four weeks. Similar to those in other Asian cities, the VOC levels measured

in urban areas in Mongolia appear to be affected by automobile exhaust. The VOC concentrations near high traffic density were higher than those measured at other locations. Urban VOC emissions often represent a complex mix of traffic, industry, solvents, waste burning, and other sources (Barabad *et al.*, 2018).

d) Ozone (O_3)

Tropospheric ozone is a main secondary pollutant formed by photochemical reactions between oxides of nitrogen (NO_x) and volatile organic compounds (VOC). The precursors, NO_x and VOC, are primarily emitted by a various source in urban area including cars, power plants, industrial boilers, refineries, chemical plants, and other sources and chemically react in the presence of sunlight to produce ozone. Typically, ozone concentration is increased to unhealthy levels on hot sunny days in urban environments. Very scarce literature is available on ozone pollution in Ulaanbaatar. Dugerjav *et al.* (2013) analyzed ambient O_3 concentration for four measuring sites of Ulaanbaatar and indicated that the daily averaged O_3 were higher in summer season and were exceeded the national air quality permissible level (8-hour mean) at UB01 site and UB08 on some days (Dugerjav *et al.*, 2013). Dorligjav *et al.* (2014) studied temporal variation of ground level ozone over Ulaanbaatar by using surface observation, radiosonde, and air mass back trajectory analyses during 2014. The authors noted that there is a linear relationship between the ozone and sunshine duration. The ozone concentration also showed a logarithmic relationship with water vapor and a hyperbolic relationship with CO and NO_x (Dorligjav *et al.*, 2014). Based on the measurements at three AQ monitoring sites for 2020 (Fig. 4), O_3 level in Ulaanbaatar is not serious and is well below the permissible level ($100 \mu\text{g m}^{-3}$, 8-hour mean) for whole year in comparison to many other cities in the world, where the O_3 pollution is a serious problem. Higher level of O_3 concentration is possibly related to the high traffic emission density on weekdays.

4 FUTURE RESEARCH NEEDS

In reviewing the current state of knowledge for urban air quality studies and overviewing the urban air quality in Mongolia, we found a growing interest in reporting fundamental studies of concentrations and physical and chemical characteristics of air pollutants in Ulaanbaatar. The

Fig. 4. Diurnal, weekly, and annual variations of ozone in Ulaanbaatar for 2020.

frame of related scientific studies is still inadequate. Therefore, our review paper suggests several directions for future research.

To the authors' knowledge, there is no extensive scientific study reporting up-to-date emission inventory and its application in numerical modeling for scenario analysis. In addition, a better understanding of the air pollution sources and their chemical composition, stable and radiogenic isotopes and other tracer to identify source contributions and relevant studies coupled with modeling investigations are helpful for decision-makers to address the scope for policy interventions and take measures on controlling the pollutant emissions. Improvement in investigations on the source contributions of SO₂ and sulfur compounds in the atmospheric particulate matter should be feasible.

Further studies on air quality issues in other industrial cities/provinces such as Darkhan and Erdenet are recommended to systematically extend the current knowledge. The establishment of air quality monitoring sites and improvement in air quality investigations need continued emphasis to provide guidance in optimizing control measures.

Studies on size distribution using cascade impactors have not been reported, and size distribution in real-time size and composition distribution measurements are also not conducted up to date. Measurements and studies on VOC and organic trace gases are still limited in Mongolia. Further improvement on the investigation of the emission and formation of organic compounds are needed. Since there is a lack of control and management system on the usage and emission of hazardous volatile compounds in Mongolia (Barabad *et al.*, 2018; Bayasgalan *et al.*, 2018), further investigations through long-term and multiple-point observations are strongly needed to evaluate major sources, risks to inhabitants, and possible contributions to the regional atmosphere. Future research should aim to investigate the PAHs for fine atmospheric PM in details to provide a guidance to people to avoid exposure to toxic carcinogenic compounds.

Since the introduction of briquette fuel in Ulaanbaatar, current scientific knowledge on emission inventory and source apportionment is still limited; thus, further studies should address these uncertainties. Beyond knowledge in sources, a better understanding of the vertical structure of air pollution and the relationship with weather condition in Ulaanbaatar is important to explain air pollution more in-depth. In line with the necessity of society to prevent air pollution, further research area should be expanded into the comprehensive numerical modeling and dynamical forecast of air quality in cities of Mongolia. The efforts on air quality modeling techniques of computational fluid dynamics, urban air pollution and climate integrated modeling will greatly improve understanding of air pollution behavior and its environmental impacts and enable to run future scenarios. Apart from modeling activities, measurements of different parameters in different areas, especially in obviously high polluted areas, should be extended and intensified.

Study on contributions of human activities on pollutant characteristics and behavior, such as traffic related air pollution, is suggested to be conducted. Furthermore, since the surrounding environment of the monitoring sites affect the measurement, further identification of the influencing factors on measurement sites is necessary. Since the dust storm event, the biggest source of coarse particles in non-heating season, is frequent in Mongolia, the detailed investigations to differentiate the natural and anthropogenic sources of particulate matter should be conducted.

Finally, little is known regarding the impacts of air pollution on ecosystem and urban greening. A worthwhile future endeavor would include environmental impacts of air pollution and a next step is to identify environmental risks associated with long-term air pollution in Ulaanbaatar and other urban areas in Mongolia.

5 CONCLUSIONS

In this paper, we present a systematic review of the studies that have investigated air pollution in Mongolia, mainly focusing on air pollution studies in Ulaanbaatar since there is a lack of comprehensive studies on air pollution in other cities. As extremely high pollution appears and becomes a major concern in Mongolia, a significant body of research has addressed the problem.

Based on this systematic review of existing research works, particulate pollution is the most severe, and it is a primary pollutant in cities of Mongolia. Studies have been adequately reported the sources and composition of particulate matter in Ulaanbaatar. Most studies focused on mass

concentration and the chemistry (ions, metals, EC/OC) of the TSP, PM₁₀ and PM_{2.5} components, however, frequent updates are essential. It is already known that an increase in NO₂ is closely associated with an increase in the number of vehicles. Sulfur dioxide (SO₂) emission is mainly associated with coal combustion and partly with transport activities. Compared to a growing number of air quality studies in Ulaanbaatar, the air quality studies in other provinces are still limited. The findings on the urban air quality studies in Mongolia informs several directions for future research.

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