

POLLUTION REDUCTION POTENTIAL BY IMPLEMENTING ELECTROSTATIC DUST PRECIPITATORS ON MONGOLIAN SMALL-SCALE STOVES (A PILOT STUDY IN ULANBAATAR)

Daniel Karthe^{1,*}, Tim Hafer^{2,1}, Byambasuren Battulga^{3,1}, Lodoysamba Sereeter¹ and Gunther Stehr^{4,1}

¹Engineering Faculty, German-Mongolian Institute for Resources and Technology – GMIT, Nalaikh, Ulaanbaatar, Mongolia

²Faculty of Georesources and Materials Engineering, RWTH Aachen University, Germany

³Department of Mineral Processing and Engineering, School of Geology and Mining, Mongolian University of Science and Technology – MUST, Ulaanbaatar, Mongolia

⁴Faculty of Mechanical Engineering, Hochschule für Technik und Wirtschaft – HTW, Dresden, Germany

*Corresponding author: karthe@gmit.edu.mn

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ABSTRACT. The Mongolian capital of Ulaanbaatar experiences some of the world's worst air pollution during the winter months, most of it being caused by small coal- and wood-fired stoves which are used for heating and cooking purposes in peri-urban parts of the city. A recent pilot study in Songinokhairkhan District of Ulaanbaatar City evaluated the feasibility of electrostatic dust precipitators (ESP) for reducing particulate matter (PM) emissions from small stoves. This paper focuses on the pollution reduction potentials that would result from a large-scale implementation of ESPs. Using a locally developed low-cost ESP system (which is currently in the process of further improvement), reduction rates ranging between 10 to 50% of the PM emissions (depending on the fuel and combustion conditions) could be achieved. Fitting all or at least a major fraction of the small stoves with such ESPs could reduce PM emissions by an order of several thousand tons per heating season for the whole city. The avoided particle emissions would simultaneously prevent atmospheric pollution by various trace metals and metalloids including As, Cd, Pb and Zn, which are known to be major soil and water pollutants locally, and several other toxic substances. However, this also means that safe disposal strategies must be developed for the fly ash precipitated during ESP operation.

KEY WORDS: air pollution, particulate matter, heavy metals, stoves, electrostatic precipitator (ESP), Mongolia

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INTRODUCTION

In many parts of the world, small-scale combustion systems pose particular challenges for air pollution control: despite their limited size, high unit numbers may result in significant emissions into the atmosphere. Moreover, producers and customers tend to focus more on low unit costs than on efficiency or flue gas treatment, which is disproportionately expensive as compared to similar techniques applied to larger combustion systems. Small-scale stoves, heaters or furnaces fired by solid fuels such as coal or biomass are therefore important sources of pollutants ranging from particulate matter to various gaseous compounds (Özdoğan 1997; Kim Oanh et al. 2005; Jerret 2015; Lelieveld et al. 2015; Hrdlička et al. 2016).

Globally, air pollution is estimated to lead to around 3.3 million premature deaths annually, most of which occur in Asia (Lelieveld et al. 2015). In Mongolia, air pollution has become a massive problem since its democratization in the early 1990s (Fan et al. 2016; Karthe et al. 2019), causing at least 10% of the mortality in Ulaanbaatar (Allen et al. 2013). One key reason is largely uncontrolled urban growth, which mostly took place in the peri-urban 'ger' districts, where people live in simple houses or the traditional Mongolian felt tents (which are locally referred to as gers). It is estimated that more than half of Ulaanbaatar's population lives in ger areas (Tsutsumida et al. 2015; Krüger et al. 2019). Until recently, estimates on the number of ger households in Ulaanbaatar ranged between 81,600 (Huang

et al. 2013) and 140,000 to 160,000 (Luvsan et al. 2012; Lim et al. 2018). According to the latest reports, this number appears to have increased further, putting the number of ger households and thus small stoves in Ulaanbaatar at approximately 200,000 (Warburton et al 2018; UNDEP 2019). Today, Ulaanbaatar is one of the worst affected cities worldwide in terms of air pollution. High concentrations of particulate matter (PM) are a major problem, with PM₁₀ (and often also PM_{2.5}) concentrations reaching several hundred $\mu\text{g}\cdot\text{m}^{-3}$. In highly polluted localities (i.e. ger areas), concentrations on some winter days exceed 1,000 $\mu\text{g}\cdot\text{m}^{-3}$ (Davy et al. 2011; Hasenkopf et al. 2016; Cavanaugh 2017), which is significantly above Mongolian and international air quality standards (table 1). A particular threat for public health is caused by the enrichment of the particles with toxic elements such as As, Cu, Pb and Zn (Nishikawa et al. 2011).

The predominant emission sources for PM are simple stoves used for heating and cooking in the city's ger areas. Even though they account for only about 13% of Ulaanbaatar's coal consumption (Batmunkh et al. 2013), stoves are responsible for about 30 to 40% of the total PM emissions (Guttikunda et al. 2013; Huang et al. 2013; WHO 2018) and up to 87% of PM_{2.5} emissions (World Bank 2009). Until the winter of 2018/2019, most of the

coal used in Ulaanbaatar's ger areas was subbituminous coal produced in small-scale mines in Nalaikh and the state-owned open-pit mine of Baganuur, two district of Ulaanbaatar which are located around 35 km southeast and 131 km of the city center (Erdenetsogt et al. 2009). The coals from Nalaikh and Baganuur have calorific values of approx. 4,200 kcal·kg⁻¹ and 4,000 kcal·kg⁻¹, an average moisture content of 10.1% and 11.4%, an ash content of approx. 18% and 14%, and a typical sulfur concentration of 0.2 to 1.1% and 0.3 to 0.5%, respectively (Erdenetsogt et al. 2009; JICA 2017). The combustion of 1 kg of such coal in traditional stoves releases about 5 to 10 g of PM into the atmosphere (Guttikunda et al. 2013). During a single heating season (which lasts approx. 240 days; World Bank 2009), one household burns about 5 t of coal and 3 m³ of wood for heating and cooking purposes (Luvsan et al. 2012). A combination of simple stoves, low combustion temperatures, inferior fuels and the absence of filter technologies cause high specific emissions (Guttikunda et al. 2013; Sorokina et al. 2013), which are released via short chimney stacks (about 3 m) and remain in the atmosphere close to the ground (Sorokina et al. 2013; Lim et al. 2018). For 2010, it was calculated that the stoves in Ulaanbaatar's ger areas emit about 39,000 tons of PM₁₀ (Guttikunda et al. 2013).

Table 1. Mongolian and international air quality standards

	Maximum PM ₁₀ concentration	Maximum PM _{2.5} concentration
Mongolian Air Quality Standard	50 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean)	25 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean)
WHO Air Quality Guideline	20 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean) 50 $\mu\text{g}\cdot\text{m}^{-3}$ (daily mean)	10 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean) 25 $\mu\text{g}\cdot\text{m}^{-3}$ (daily mean)
National Ambient Air Quality Standard of US-EPA («Primary standard»)	150 $\mu\text{g}\cdot\text{m}^{-3}$ (daily mean; not to be exceeded once per year over 3 years)	12 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean over 3 years) 35 $\mu\text{g}\cdot\text{m}^{-3}$ (daily mean)
European Air Quality Directive	50 $\mu\text{g}\cdot\text{m}^{-3}$ (daily mean with maximum 35 exceedances per year) 40 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean)	25 $\mu\text{g}\cdot\text{m}^{-3}$ (annual mean)

Sources: WHO 2006; EU 2008; World Bank 2011; US-EPA 2020

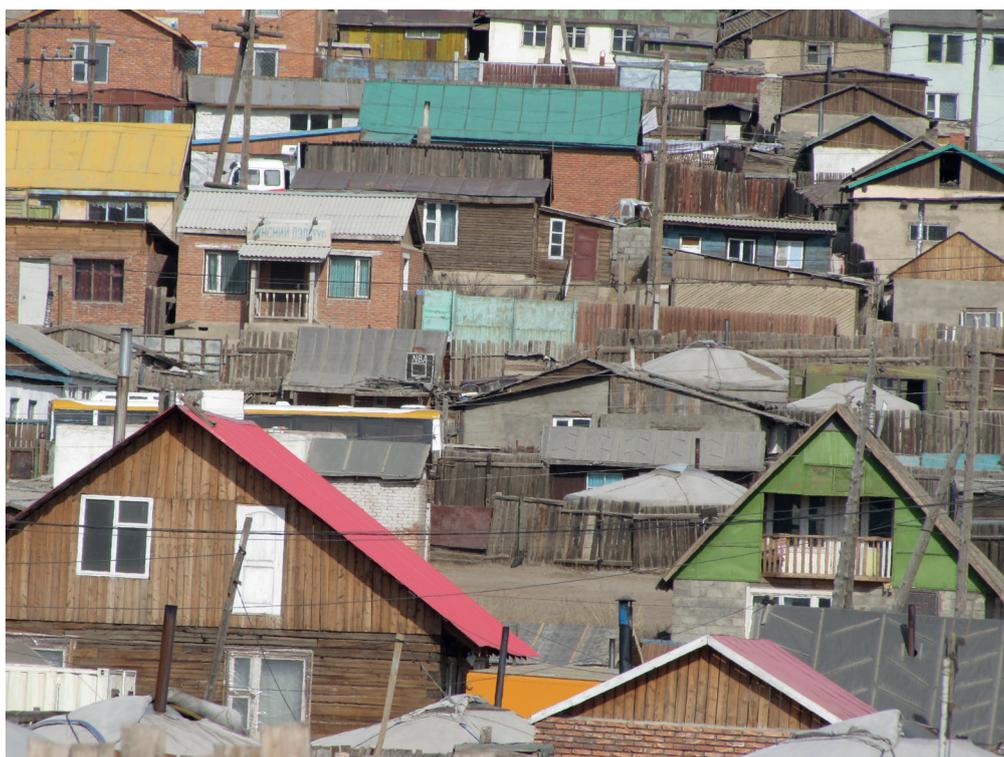


Fig. 1. Ger area in Ulaanbaatar. Both the traditional Mongolian gers (felt tents) and small houses are heated by simple stoves, which are the main source of PM emissions in the city (photo by Daniel Karthe)

Air pollution in Ulaanbaatar is a major cause of morbidity and mortality. One recent study showed that the lung function of adults living in Ulaanbaatar is about 35% below normal (Dashdemberel et al. 2012). During the cold season, rates of cardiovascular diseases increase with $PM_{2.5}$ pollution levels (Enkhjargal and Burmajav 2015). According to conservative estimates, at least 29% of cardiopulmonary deaths and 40% of lung cancer deaths are caused by outdoor air pollution (as compared to approx. 10 to 15% in Western countries), causing about 10% of the city's total mortality (Cohen 2003; Allen et al. 2013; Lelieveld et al. 2019). Children and pregnant women living in the city's ger districts tend to be at particular risk. According to Enkhmaa et al. 2014 and Dorj et al. 2016, air pollution levels with fine particulate matter, SO_2 and NO_2 correlate with pregnancy losses, premature birth and low birth weights. The prevalence rate of pediatric asthma in Ulaanbaatar is estimated to be above 20% in 6 to 7 year-olds, almost double the world average level (Yoshihara et al. 2016).

Because of the severity of these public health impacts, Mongolian authorities, local interest groups and international donors have undertaken various efforts to mitigate the current air pollution crisis. Approaches included the introduction of 'improved' (i.e. fuel-saving) stoves, cleaner fuels and filter systems. More radical approaches considered the transition to electrical or hybrid heating systems, or even resettlement of people from ger areas to apartment houses (Lobscheid et al. 2015; Fuhrmann 2019). Building up particularly on past experiences with improved stoves and the installation of filter systems, a pilot study conducted in 2018/2019 developed an electrostatic precipitator (ESP) system for small stoves used in ger area households. The system, which was developed in a research and development project called GLEAR (Clean Air for Gers), is described in more detail by Stehr (2018). Core objectives of this project were safety, robustness and affordability rather than maximum pollution reduction efficiency of the ESP system. The evaluation of the pollution reduction potential presented in this manuscript is based on a pilot-scale trial of the above-mentioned system in 2018/2019. However, it is important to note that future improvements in the system are likely to improve PM removal rates (as well as those of associated toxic trace elements). Moreover, the system can be combined with improved stoves and/or cleaner fuels, which could in the future maximize the benefits. The aim of the study is to document the already massive emission control potential for simple ESP systems, with the perspective of even greater reduction potentials in the future.

MATERIALS AND METHODS

The following experiments were conducted to assess the performance of the ESP system described by Stehr (2018):

- Measurement of PM concentration in the flue gas (with/without ESP)
- Collection of precipitates in the ESP system and subsequent quantification/chemical analysis of residues

Flue gas analyses with/without ESP

The PM concentration in the flue gas was measured using the suspended particulate analyzer SM 500 (Wöhler, Bad Wünnenberg, Germany). The system can measure PM concentrations, temperature, pressure as well as O_2 and CO concentrations in the flue gas; volumetric flow or velocity of the flue gas cannot be determined. Due to low ambient temperatures during the measurements (conducted in November/December 2018), an auxiliary probe heater was used, to prevent condensation on or around the sampling probe. Measurements were conducted in an uninhabited

laboratory ger (47.770531° N, 107.243373° E) on the campus of the German-Mongolian Institute for Resources and Technology in Nalaikh District of Ulaanbaatar, Mongolia. Besides having a more controlled test setup, longer measurements in inhabited homes would have been relatively intrusive to people's privacy. In all other aspects (construction materials, size and height, stove types and placement), the 'laboratory ger' resembled the traditional Mongolian felt tents which are a common form of housing in peri-urban districts.

The probe of the particle analyzer was inserted into the chimney stack through a small hole about 2.5 m above the ground (2.1 m above the top of the stove, and 0.8 m above the top of the ESP system). For the experiments, 2 kg of raw subbituminous coal from a nearby small-scale mining area was used; this was the coal which was commonly used to heat stoves in Nalaikh as well as other districts of Ulaanbaatar at the time of writing. For lighting the fire, 20 sheets of commercially available paper (A4 size) and 1 kg of dried wood of Siberian elm (*Ulmus pumila*), which was chopped into pieces of 2 to 3 cm thickness, were used. Such procedures are common ways of lighting and firing small stoves in Mongolia, even though other inflammables (e.g. dried animal dung) are also used for this purpose. Following the ignition of the fire, PM concentrations were observed over a period of 40 minutes as they tended to stabilize within a few minutes after lighting the stove.

Experiments were conducted in two types of stoves, which can be categorized as traditional and improved. The improved stove was produced by Royal Ocean LLC (Ulaanbaatar, Mongolia) and had a maximum thermal power output of



Fig. 2. Experimental setup for the suspended PM monitoring in a laboratory ger (photo by Gunther Stehr, annotations by Daniel Karthe)

6.6 kW. According to the manufacturer, the stove can be loaded with up to 8 kg of fuel. Traditional stoves are typically made in small workshops and do not have clearly marked producers. Technical data are not specified by the producers; local governmental reports mention a typical power output of 14 kW (Ulaanbaatar Area Project 2013). The main difference between traditional and improved stoves is not their power output (improved stoves exist in different sizes, of which the 6.6 kW version is very common) but their fuel efficiency. Placement and lighting of fuels in the combustion chamber was done in the following order: (1) large coal pieces were placed on the grate at the bottom of the combustion chamber, with wood and paper on top; (2) improved stoves were lit from the top, whereas traditional stoves were lit from the bottom (as recommended by the manufacturers); (3) after approximately 60% of the wood has turned into ember, about 200 g of small coal pieces (about 2 to 5 cm in size) were placed on the top of the fire in order to achieve a more homogenous combustion of the fuel below.

Chemical characterization of aerosol precipitates

In order to further characterize the pollution reduction potential of the ESP system, fly ash which aggregated on the collection electrode surface was removed thoroughly and collected at least twice a week. In this case, samples were taken from stoves operated under real-life conditions in Songinokhairkhan District, Ulaanbaatar, during January and February 2019. Songinokhairkhan is one of the capital city's 9 districts located in the northwest of Ulaanbaatar at the foot of a mountain, the Songino Khairkhan Uul. Its population of approx. 260,000 people overwhelmingly lives in gers and simple houses, and is one of the city's worst affected areas in terms of air pollution. Sampling was conducted in the context of a pilot trial of 70 prototype units as further described by Stehr (2018). Following the determination of the weight, mixed samples were prepared and sent to two independent and certified laboratories for chemical analysis. At ALS Global Geochemical Laboratory, Ulaanbaatar, Mongolia a 70 g subsample was pulverized so that > 85% of the particles were reduced to $\leq 75 \mu\text{m}$ in diameter. The pulverized sample was digested with aqua regia ($\text{HNO}_3 + 3 \text{HCl}$) and subsequently analyzed for 35 trace elements by inductively coupled plasma atomic emission spectroscopy (5110 ICP-AES, Agilent, Santa Clara, CA, USA). At SGS IMME Laboratory, Ulaanbaatar, Mongolia, a subsample of $\approx 98 \text{ g}$ was wet-screened to a size of $75 \mu\text{m}$ and subsequently

prepared by sodium peroxide (Na_2O_2) fusion. The sample was then analyzed for 35 trace elements using inductively coupled plasma mass spectrometry (NexION 300Q ICP-MS, PerkinElmer, Walton, MA, USA) and for another 18 trace elements using inductively coupled plasma optical emission spectrometry (OPTIMA 8300 ICP-OES, PerkinElmer, Walton, MA, USA). Following the chemical analyses, results were compared to Mongolian and German soil quality standards, and enrichment factors were calculated to compare samples with average elemental concentrations in the upper continental crust (Wedepohl 1995; Batmunkh et al. 2013). The rationale behind this approach was to quantify not only the air pollutants trapped by the ESP system, but also the potential toxicity of the residues, which is an important consideration in order to prevent soil and water pollution as a consequence of disposal.

Enrichment factors (EFs) for trace elements in aerosols were calculated as proposed by Hoffman et al. (1972) and as applied by Batmunkh et al. (2013) for aerosols during winter haze events in Ulaanbaatar: $\text{EF} = (X_p / R_p) / (X_c / R_c)$, where X_p – concentration of an element in a precipitate sample, R_p – concentration of a reference element in a precipitate sample; in case of this study Al, X_c – concentration of an element in the earth crust, R_c – concentration of a reference element in the earth's crust. Based on the calculated enrichment factors, elemental concentrations are then classified as follows: $\text{EF} < 10$: natural to near-natural; $10 \leq \text{EF} < 100$: moderate anthropogenic enrichment; $\text{EF} \geq 100$: strong anthropogenic enrichment (Koulousaris et al. 2009). In this paper, an additional category is used for very strong enrichment ($\text{EF} \geq 1,000$).

RESULTS

Flue gas analyses with/without ESP

Four test runs of 40 minutes were conducted to compare suspended PM concentrations in flue gas with or without ESP system. PM concentrations were measured at 1 s resolution and subsequently averaged over full minutes. Mean values and other statistical data refer to the variation observed between the test runs and within the test runs. The results of suspended particle concentration measurements in the flue gas over a period of approximately 40 minutes are shown in figure 1. Results were achieved under the optimum configuration of the ESP, which was, however, still at a prototype stage.

PM concentrations in the flue gas peaked during the first few minutes following the ignition. With activated ESP, relatively high PM removal rates could be achieved during

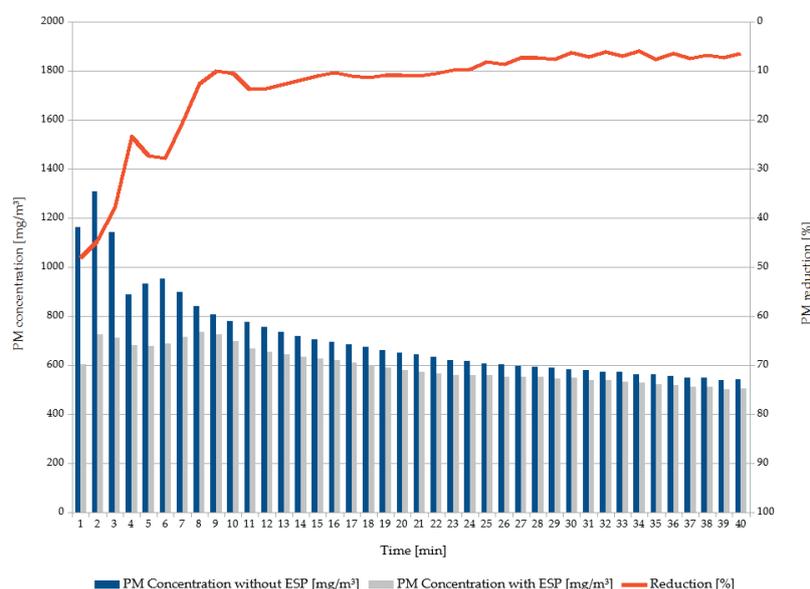


Fig. 3. Suspended PM concentrations without and with activated ESP, and reduction rates in the flue gas

Table 2. Comparison of observed PM concentrations with vs. without ESP during the first 40 minutes (based on n = 4 test runs and 60 measurements per minute)

Time from start	Suspended PM concentration without ESP [mg·m ⁻³]	Standard deviation [mg·m ⁻³]	Suspended PM concentration with ESP [mg·m ⁻³]	Standard deviation [mg·m ⁻³]
First minute	1164.1	± 563.5	603.6	± 105.1
First five minutes	1065.2	± 575.6	679.3	± 32.7
Minutes 6 to 10	850.4	± 465.7	712.5	± 16.7
Minutes 11 to 15	737.4	± 349.8	644.6	± 4.5
Minutes 16 to 20	672.4	± 277.8	599.5	± 5.1
Minutes 21 to 40	583.3	± 204.4	538.5	± 4.7
Entire observation period	691.5	± 309.5	599.0	± 9.7

this period. Both with and without ESP, PM concentrations first increased, then fluctuated during the first 5 to 6 minutes, and subsequently decreased. During the first 5 minutes of the combustion process, the ESP system led to a mean concentration reduction of 385.9 mg·m⁻³; between minutes 21 and 40, the mean reduction decreased to 44.8 mg·m⁻³. Interestingly, emissions observed with the ESP in operation exhibited much lower standard deviations than test runs without ESP (table 2). Relative reduction rates show that the ESP system is capable of reducing PM concentrations by approx. 36% during the first 5 minutes after lighting the stove; a maximum of up to 60% was observed at this time. Reduction efficiencies then gradually declined to approximately 10% during the first twenty minutes, and slightly further afterwards (table 3).

The fact that the majority of users light their stoves 3 to 4 times per day, and up to 8 times in some cases, means that the system's maximum reduction rates may be achieved several times per day.

Geochemical characterization of aerosol precipitates

The chemical analyses of samples and reference values from Mongolian (Mongolian Agency for Standardization and Metrology 2008) and German soil standards (German Federal Ministry of Justice and Consumer Protection 2017) as well as mean concentrations of the respective elements in the upper continental crust (Wedepohl 1995) are presented in table 4.

It should be noted that the threshold values given for the Mongolian and German soil standards are the strictest

Table 3. Mean, minimum and maximum suspended PM reduction rates observed during different phases of the combustion process

Time from start	Maximum Reduction	Mean Reduction	Minimum Reduction	Standard deviation
First minute	-60.2%	-48.1%	-28.5%	± 6.4%
First five minutes	-60.2%	-36.2%	-22.1%	± 3.5%
Minutes 6 to 10	-29.2%	-16.2%	-6.3%	± 2.0%
Minutes 11 to 15	-15.0%	-12.6%	-10.0%	± 0.7%
Minutes 16 to 20	-12.4%	-10.9%	-9.0%	± 0.6%
Minutes 21 to 40	-12.9%	-7.7%	-5.0%	± 0.7%
Entire observation period	-60.2%	-13.4%	-5.0%	± 1.2%

Table 4. Chemical composition of aerosol precipitates. All concentrations refer to the total trace element content in mg·kg⁻¹

Chemical element	Analysis by			Mongolian soil standards	German soil standards	Mean concentration in the upper continental crust
	ICP-AES	ICP-MS	ICP-OES			
Ag	0.2	N/A	N/A	N/A	N/A	0.055
Al	3,700	N/A	3,900	N/A	N/A	77,440
As	287	236	N/A	2	0.4	2.0
B	40	N/A	N/A	15		17
Ba	160	N/A	197	N/A	N/A	668
Be	0.6	N/A	< 5 (BDL)	N/A	N/A	3.1
Bi	12	N/A	7.3	N/A	N/A	0.123
Ca	11,400	N/A	9,100	N/A	N/A	29,450

Cd	17.4	13.7	N/A	1	0.04	0.102
Ce	N/A	6.4	N/A	N/A	N/A	N/A
Co	10	8.7	N/A	30	N/A	11.6
Cr	51	N/A	41	60	200	35
Cs	N/A	1.2	N/A	N/A	N/A	N/A
Cu	42	N/A	16	60	1	14.3
Dy	N/A	0.48	N/A	N/A	N/A	N/A
Er	N/A	0.27	N/A	N/A	N/A	N/A
Eu	N/A	0.13	N/A	N/A	N/A	N/A
Fe	196,000	N/A	121,500	N/A	N/A	30,890
Ga	< 10 (BDL)	4	N/A	N/A	N/A	14
Gd	N/A	0.61	N/A	N/A	N/A	N/A
Ge	N/A	3	N/A	N/A	N/A	N/A
Hf	N/A	2	N/A	N/A	N/A	N/A
Hg	< 1 (BDL)	N/A	N/A	0.5	2	0.056
Ho	N/A	0.08	N/A	N/A	N/A	N/A
In	N/A	< 0.2 (BDL)	N/A	N/A	N/A	0.061
K	1,200	N/A	1,200	N/A	N/A	28,650
La	< 10 (BDL)	2.9	N/A	N/A	N/A	32.3
Li	N/A	N/A	< 10 (BDL)	N/A	N/A	22
Lu	N/A	< 0.05 (BDL)	N/A	N/A	N/A	N/A
Mg	1,100	N/A	900	N/A	N/A	13,510
Mn	632	N/A	378	N/A	N/A	527
Mo	8	6	N/A	2	N/A	1.4
Na	700	N/A	N/A	N/A	N/A	25,670
Nb	N/A	< 1 (BDL)	N/A	N/A	N/A	26
Nd	N/A	2.6	N/A	N/A	N/A	N/A
Ni	47	N/A	66	60	1.5	18.6
P	150	N/A	200	N/A	N/A	665
Pb	222	287	N/A	50	0.1	17
Pr	N/A	0.69	N/A	N/A	N/A	N/A
Rb	N/A	6.5	N/A	N/A	N/A	110
S	31,400	N/A	N/A	N/A	N/A	953
Sb	21	32.5	N/A	N/A	N/A	0.31
Sc	1	N/A	9	N/A	N/A	7
Sm	N/A	0.5	N/A	N/A	N/A	N/A
Sn	N/A	12	N/A	30	N/A	2.5
Sr	128	N/A	113	600	N/A	316
Ta	N/A	< 0.5 (BDL)	N/A	N/A	N/A	N/A
Tb	N/A	0.05	N/A	N/A	N/A	N/A
Th	< 20 (BDL)	0.8	N/A	N/A	N/A	10.3
Ti	200	N/A	300	N/A	N/A	3,117
Tl	< 10 (BDL)	8.5	N/A	N/A	0.1	0.75
Tm	N/A	< 0.05 (BDL)	N/A	N/A	N/A	N/A

U	30	29.3	N/A	N/A	N/A	2.5
V	8	N/A	< 5 (BDL)	100	N/A	53
W	< 10 (BDL)	< 1 (BDL)	N/A	N/A	N/A	1.4
Y	N/A	2.6	N/A	N/A	N/A	20.7
Yb	N/A	0.2	N/A	N/A	N/A	N/A
Zn	1,280	N/A	1051	100	2	52

Notes. N/A – not available; BDL – below detection limit. In case of soil standards, the strictest precautionary value contained in the respective standard is mentioned (Mongolian standards differ depending on soil texture; in Germany, standards are defined for specific soil uses, with the strictest standards applying to agricultural soils and playgrounds).

limits defined by the respective standard. In case of the Mongolian soil standards, this refers to the limits for sandy soils; the respective limits for silty and clayey soils are up to 4 times higher depending on the specific pollutant. The German Federal Regulation on Soil Protection defines different types of tolerable limits. These include precautionary limits and intervention values, which are typically defined for specific uses. The strictest standards are defined for playgrounds and agricultural land; regulations are less strict for other land uses.

The wet and dry deposition of trace elements contained in coal-combustion by-products has been described as a source of soil and water pollution in many parts of the world (e.g. Landing et al. 2010; Wu et al. 2018). In order to identify elements of particular concern, enrichment factors (figure 4) were calculated using the methodology described by Batmunkh et al. (2013):

Fly ash samples are enriched in a large number of trace elements, including toxic substances which commonly occur in coal and combustion products (Nalbandian 2012; Unver and Terzi 2018). For 11 elements, enrichment factors are classified as 'strong', which is particularly problematic for substances known to harm the environment and human health. It is notable that 4 trace elements, namely Cd, As, Sb and Bi, were detected in concentrations indicating enrichment factors > 1000 and thus of particular relevance from the perspective of pollution control. A general assessment of the trace element concentrations found in the fly ash is presented in the matrix of table 5, where elements are rated according to their environmental concern (according to Nalbandian 2012; no immediate concern: 0, minor concern: 1, moderate concern: 2, major concern: 3) and their enrichment (near natural: 0, moderate: 1, strong: 2, very strong: 3).

Elements which received ratings of 3 or higher (table 5) can be considered priority substances because they are at least of some concern for the environment and public health, and they were found to have moderate or higher enrichment factors in fly ash. This can be interpreted in two ways: on the positive side, the removal of these trace elements from flue gas reduces atmospheric pollution and exposition of the local population via inhaling and atmospheric deposition. However, this also means that particular attention must be paid to these elements when developing disposal strategies for the collected fly ash.

DISCUSSION

The reduction rates achieved for PM concentrations in the flue gas indicate that the prototype ESP system tested still has a significant potential for improvement. ESP systems used for small combustion systems typically achieve a reduction in PM concentrations between 60 and 80% (Intra et al. 2010; Schmatloch and Rauch 2012). However, it is known from other applications that the efficiency of ESP systems tends to reduce over time due to the precipitation of particulate matter on the electrode (Caroll and Finnán 2017). The high particle emissions caused by the combustion of raw, subbituminous coal used in our experiments, the constant decline of in the system's efficiency over time, and the very large amounts of PM (about 100 g per day and ESP unit) collected all indicate that the accumulation of PM on the electrode had an insulating effect which led to decreasing removal rates over time. The ESP system tested here would therefore greatly benefit from a higher cleaning frequency of the collection electrode, e.g. via automatic mechanisms or an indication to users that cleaning is required. Nevertheless,

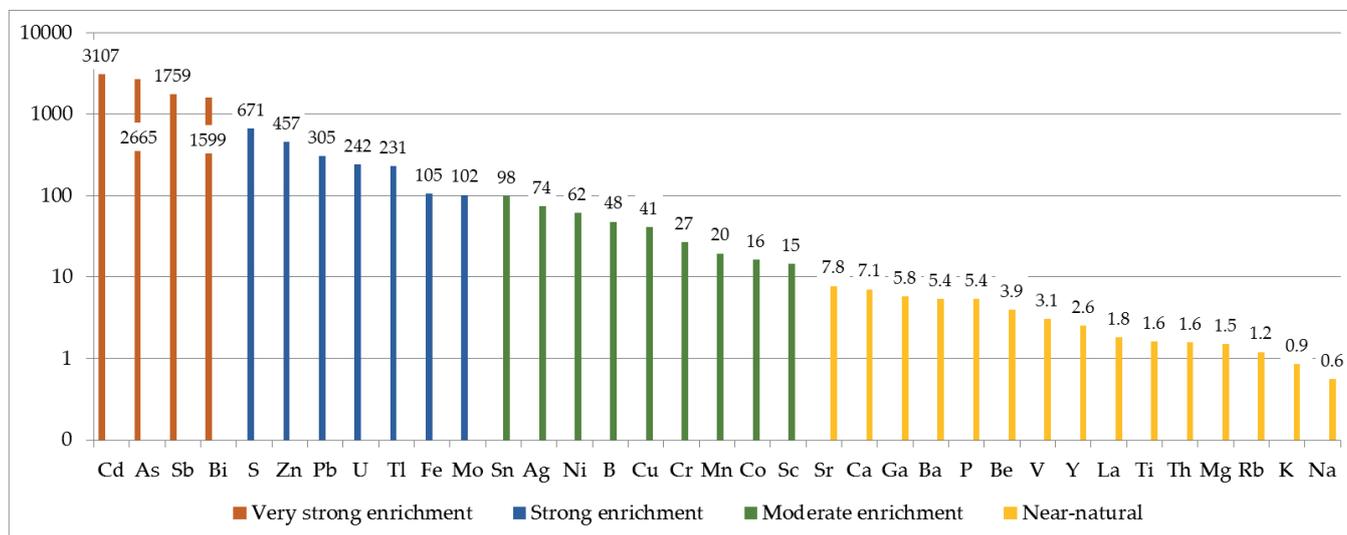


Fig. 4. Enrichment factors for trace elements in fly ash produced during the combustion of Nalaikh raw coal

Table 5. Relevance of trace elements according to their concern for environment and health, and their EF

Element	Environmental concern	Enrichment	Relevance						
			Priority substances				Minor relevance		
			6	5	4	3	2	1	0
Ag	Minor	Moderate					X		
As	Major	Very strong	X						
B	Major	Moderate			X				
Ba	Minor	Near natural						X	
Be	Minor (low concentration)	Near natural						X	
Bi	No immediate concern	Very strong				X			
Ca	No immediate concern	Near natural							X
Cd	Major	Very strong	X						
Co	Minor	Moderate					X		
Cr	Moderate	Moderate				X			
Cu	Moderate	Moderate				X			
Fe	No immediate concern	Strong					X		
Ga	No immediate concern	Near natural							X
K	No immediate concern	Near natural							X
La	No immediate concern	Near natural							X
Mg	No immediate concern	Near natural							X
Mn	Minor	Moderate					X		
Mo	Major	Strong		X					
Na	Minor	Near natural						X	
Ni	Moderate	Moderate				X			
P	No immediate concern	Near natural							X
Pb	Major	Strong		X					
Rb	No immediate concern	Near natural							X
S	Major	Strong		X					
Sb	No immediate concern	Very strong				X			
Sc	No immediate concern	Moderate						X	
Sn	Minor (low concentration)	Moderate					X		
Sr	Minor	Near natural						X	
Th	Major	Near natural					X		
Ti	No immediate concern	Near natural							X
Tl	Minor (low concentration)	Strong				X			
U	Major	Strong		X					
V	Moderate	Near natural						X	
Y	No immediate concern	Near natural							X
Zn	Moderate	Strong			X				

the experiments demonstrated that the system in principal has the potential to remove significant amounts of aerosols from the flue gas, particularly during the particularly dirty ignition phase. Moreover, the significantly lower standard deviations observed during test runs with ESP as compared to those without ESP indicate that the ESP appears to reduce fluctuations in the PM content of the flue gas, presumably by reducing short term peak concentrations.

The collected fly ash contained significant concentrations of trace elements. For As, B, Cd, Cr, Cu, Ni, Pb and Zn, at least one (and sometimes both) of the considered soil standards were exceeded. First and foremost, concentrating these substances in a precipitate removed from flue gas is positive in the sense of avoided emissions into the atmosphere. The potential for pollution mitigation by a large-scale introduction of ESPs throughout all ger

areas in Ulaanbaatar was calculated on the assumptions documented in table 6. It should, however, be noted that all values are approximations which may change in the future due to population growth as well as changes in the stoves and fuels used.

A wide (or full) scale implementation of electrostatic dust precipitators has the potential to avoid atmospheric emissions of undesired elements in orders of several tens of kilograms (Bi, Cd, Mo, Tl) to more than a hundred kilograms (B, Cr, Cu, Ni, U). The reduction potential for Al, As, Pb, S and Zn even has a magnitude exceeding one ton for each element (table 7).

Besides being promising in terms of air pollution control, the results indicate that the disposal of the collected fly ash as regular waste (or an application on soils, which is one of the common ways to dispose bottom ash collected in stoves) is highly problematic. Of particular concern are As and Cd, which are not only very strongly enriched in the precipitated PM, but which are also considered to be trace elements of major concern due to their high toxicity for the environment and people. The identification of appropriate disposal solutions would therefore be a high priority before a larger-scale introduction of ESP systems in Mongolia, particularly in the light of having to deal with quantities of several thousand tons of precipitated PM every year.

If safe disposal strategies can be identified, air pollution control by the implementation of ESPs on small stoves has the potential to reduce not only air pollution, but also the enrichment of toxic trace elements in other environmental compartments. Notably, some of the most relevant pollutants found in the urban environment of Ulaanbaatar are at least partially related to atmospheric deposition (table 8).

Since As, Cd, Pb and Zn are removed in significant amounts in ESP systems, widespread installation of such systems would help to reduce atmospheric deposition and resulting enrichment of these substances in urban soils and vegetation. In case of Pb, ESPs could also help to human exposition to Pb; this is particularly relevant for ger areas, where a significant part of the population has been shown to have elevated blood lead concentrations (table 8).

Two main challenges could be identified regarding the ESP system and its operation. Firstly, operational monitoring in the laboratory showed that the system's efficiency decreases considerably over time. Following moderate PM removal rates of just below 50% just after the ignition of the stove, PM reduction rates fell to less than 10% within 40 minutes after the system's start. There are two plausible explanations for this behavior: (1) PM emissions are highest when the stove is lit and subsequently reduce; (2) the built-up of precipitates on the ESP electrodes has an insulating effect, thus reducing the system's efficiency. Whereas a high efficiency is desirable during the early phase of the combustion process (when emissions are highest), the second observation can be translated into future research and development needs; an automated cleaning of the electrodes could greatly improve the system performance after longer periods of usage. Secondly, significant concentrations of toxic trace metals in the precipitated PM imply that the ESP system does not only reduce air pollution with PM; it also contributes to avoiding emissions of harmful trace elements (particularly of As, Cd and Pb, which are known to be major environmental and public health concerns in Ulaanbaatar). This, however, means that a safe disposal strategy needs to be developed in order to avoid pollution of soils and water resources, and eventually

Table 6. Mean, minimum and maximum suspended PM reduction rates observed during different phases of the combustion process

Parameter	Value	Source(s)
Quantity of fly ash collected per ESP system and day	≈ 100 g	Own observations
Number of stoves in Ulaanbaatar's ger areas	200,000	Warburton et al. 2018; UNDEP 2019
Duration of heating period	240 days	World Bank 2009

Table 7. Avoided emissions based on mean suspended PM reduction rates for priority substances

Element	Concentration in precipitate [mg·kg ⁻¹]	Amount/day for a single ESP [g]	Amount/heating period for UB ger districts [kg]
Al	3,800	0.38	18,240
As	261.5	0.02615	1,255.2
B	40	0.004	192
Bi	9.65	0.000965	46.32
Cd	15.55	0.001555	74.64
Cr	46	0.0046	220.8
Cu	29	0.0029	139.2
Mo	7	0.0007	33.6
Ni	56.5	0.00565	271.2
Pb	222	0.0222	1,065.6
S	31,400	3.14	150,720
Tl	8.5	0.00085	40.8
U	29.65	0.002965	142.32
Zn	1,165.5	0.11655	5,594.4

Table 8. Relevance of trace elements related to the combustion of coal in the urban environment of Ulaanbaatar (UB)

Element	Known Problems	Source(s)
As	Two recent studies revealed that all tested soil samples (n=112) from UB exceeded the maximum permissible concentrations according to Mongolian soil standard (MNS 5850:2008)	Batjargal et al. 2010; Kasimov et al. 2011a
	A recent study from Nalaikh district, Ulaanbaatar, indicated that eolian transport of fly ash is an important pathway of As enrichment in soils and water.	Nottebaum et al. 2020
Cd	Above normal bioaccumulation of Cd has been detected in the urban vegetation of UB	Kasimov et al. 2011b
Cu	UB was identified as a source of Cu in the Tuul River, which is transported further into the Selenga River.	Lychagin et al. 2017
	Enriched in the snow cover of UB	Kasimov et al. 2019
Mo	Enriched in the snow cover of UB	Kasimov et al. 2019
	Above normal bioaccumulation of Mo has been detected in the urban vegetation of UB	Kasimov et al. 2011b
Pb	Elevated blood lead levels have been detected in children and the general population of UB, especially in ger areas	Olkhanud et al. 2014; Praamsma et al. 2016; Enkhbat et al. 2016; Erdenebayar et al. 2019
	Significant enrichment of UB soils with Pb; atmospheric depositions are the main contributor	Batjargal et al. 2010, Kasimov et al. 2011a, Tserenpil et al. 2016
	Enriched in the snow cover of UB	Kasimov et al. 2019
Zn	Significant enrichment of UB soils with Zn; atmospheric depositions are the main contributor	Kasimov et al. 2011a
	Above normal enrichment of Zn has been detected in the urban vegetation of UB	Kasimov et al. 2011b
	Enriched in the snow cover of UB	Kasimov et al. 2019

also bioaccumulation of these substances by plants, livestock and people.

Finally, it should be noted that according to new environmental regulations aiming at the reduction of air pollution in Ulaanbaatar, it is planned that raw coal from Nalaikh would be replaced by coal briquettes from Tavan Tolgoi mine. Theoretically, this coal has a significantly higher calorific value and most likely, a cleaner combustion. However, at the time of writing, some doubts remain regarding both the sufficient availability and affordability of briquettes. Moreover, a lack of experience using this higher quality coal in different stove types and under real-life conditions means that there is considerable uncertainty about how much this step could help to improve air pollution. In the future, it will certainly be meaningful to assess if a combination of the ESP system with higher quality coal is feasible and worth the double effort.

CONCLUSIONS

The extremely high levels of air pollution affecting Ulaanbaatar during the winter seasons are a major threat to public health and significantly reduce the life quality of the city's inhabitants. One priority among the urgently needed counteractions should be the reduction of emissions from the city's roughly 200,000 small stoves, which are used to heat dwellings in the city's peri-urban ger areas, thereby

causing about 30% to 40% of the total PM emissions (and up to 87% of the PM_{2.5} emissions) in the city. The well-established principle of ESP is one promising approach to combat this problem in a relatively cost-effective way; after the initial investment for the ESP system (about 100 US\$ to 200 US\$ for the system described here), operational costs are very low (power consumption of 30 watts, regular cleaning of the device). Pilot tests of an ESP system that was developed to work under the specific circumstances found in Mongolian ger areas demonstrated that the technology has the potential to significantly reduce air pollution. Based on the current prototype of the system, PM emission reductions of almost 4,800 tons per year would be possible if the system is deployed throughout the ger areas of Ulaanbaatar. The reduction of PM emissions would at the same time avoid atmospheric pollution by trace elements contained in fly ash particles, including significant amounts of Al, As, B, Bi, Cd, Cr, Cu, Ni, Mo, Pb, S, Tl, U and Zn.

The specific findings from Ulaanbaatar are not only of local relevance, but transferable to other urban settings where small combustion systems are important sources of particulate matter emissions. In particular, this includes neighboring regions of Central Asia, Siberia and Western China, where very cold winters create a need for heating and where significant parts of the population use simple and small stoves fired by coal or wood, usually without any flue gas treatment. ■

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