



Biomonitoring potentially toxic elements in atmospheric particulate matter of greater Dhaka region using leaves of higher plants

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Abstract In this study, four different plant species, namely *Artocarpus heterophyllus*, *Mangifera indica*, *Psidium guajava*, and *Swietenia mahagoni*, were selected from seven different locations to assess the feasibility of using them as a cost-effective alternative for biomonitoring air quality. Atmospheric coarse particulate matter (PM₁₀), soil samples, and leaf samples were collected from residential, industrial, and traffic-congested sites located in the greater Dhaka region. The heavy metal concentrations (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) in the leaves of the different species, PM₁₀, and soil samples were analyzed. The highest Pb (718 ng/m³) and Zn (15,956 ng/m³) concentrations were found in PM₁₀ of Kodomtoli which is an industrial area. On the other hand, the highest Fe (6,152 ng/m³) and Ni (61.1 ng/m³) concentrations were recorded in the PM₁₀ of Gabtoli, a heavy-traffic area. A significant positive correlation ($r=0.74$; $p<0.01$) between Pb content in plant leaves and PM

fraction was found which indicated that atmospheric PM-bound Pb may contribute to the uptake of Pb by plant leaves. The analysis of the enrichment factor (EF) revealed that soils were contaminated with Cd, Ni, Pb, and Zn. The abaxial leaf surfaces of *Psidium guajava* growing at the polluted site exhibited up to a 40% decrease in stomatal pores compared to the control site. Saet's summary index (Z_c) demonstrated that *Mangifera indica* had the highest bioaccumulation capacity. The metal accumulation index (MAI) was also evaluated to assess the overall metal accumulation capacity of the selected plants. Of the four species, *Swietenia mahagoni* (3.05) exhibited the highest MAI value followed by *Mangifera indica* (2.97). *Mangifera indica* and *Swietenia mahagoni* were also found to accumulate high concentrations of Pb and Cr in their leaves and are deemed to be good candidates to biomonitor Pb and Cr contents in ambient air.

Keywords Air pollution · Particulate matter · Biomonitoring · Potentially toxic elements (PTEs)

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Introduction

Air pollution is the greatest external threat to human life expectancy on the planet. Outdoor air pollution causes mortality of 4.2 million annually, with over 2 million of those fatalities occurring in South-East Asia (Bulto et al., 2017). Due to the presence of several contaminants, particulate matter (PM) in

the atmosphere is of great concern for public health. Furthermore, it facilitates the amalgamation of potentially toxic elements (PTEs), including but not limited to cadmium (Cd), chromium (Cr), iron (Fe), lead (Pb), nickel (Ni), and zinc (Zn). These elements pose significant risks to human well-being, particularly in relation to neurological functioning and the cardiovascular, respiratory, and dermatological systems (Apte et al., 2018; Pope et al., 2004).

It is obvious that unrestrained industrial growth and persistent disregard for laws meant to preserve the quality of the air are the main causes of Dhaka's quick rise to rank among the most polluted metropolitan areas in the world (Gulshan et al., 2021; Moniruzzaman et al., 2022). Exposure to air pollution caused the premature death of about 24,000 people in Dhaka between 2005 and 2018, the highest among the 46 cities studied (Vohra et al., 2022). Monitoring urban air pollution is a vital research area in discovering existing risks and formulating new planning decisions. It is imperative to develop a sufficient monitoring system that will enable accurate evaluations of the pollution of the environment due to the presence of various contaminants in the air. Numerous studies have successfully shown that different plant species can monitor airborne heavy metals (HMs) contamination as effectively as high-tech instrumentation methods (Baldantoni et al., 2014; Chirantini et al., 2016; Shahrukh et al., 2023).

Plants are widely regarded as key bioindicators of pollution due to their continuous interaction with all environmental components (Schreck et al., 2020). Trees can filter 60 to 70 times more air pollutants compared to herbs and shrubs (McPherson et al., 1994). Plant parts, particularly leaves, trap and accumulate atmospheric pollutants. According to Fernández and Brown (2013), HMs can penetrate the leaves through a variety of structures, including stomatal pores, cuticular crevices, epidermal cell walls, aqueous pores, and lenticels. PM deposition on plant leaves is influenced by leaf properties such as shape and surface area of leaves, size, arrangement of petiole, and cuticular texture (Beckett et al., 2000; Dzierzanowski et al., 2011). The mechanisms of foliar transfer in plant tissues have been proposed by several researchers (Maisto et al., 2004; Sexton and Roberts, 1982). Heavy metal entry through the cuticle of a leaf consists mostly of four phases (Chamel et al., 1991), namely (1) adhesion to the cuticle, (2) penetration through the cuticle (perhaps via endocytosis),

(3) desorption in the apoplast, and (4) absorption by the adjacent cells. Birbaum et al. (2010) reported that coarse particles are adhered to surface wax and diffused into the leaves, while fine particles are taken up by the leaves. Diffusion of HMs in plants is influenced by several variables, including cuticle maturity, leaf shape, and surface area, physicochemical forms of the adsorbed metal, surface texture of the leaves, exposure time to the metal, and environmental factors like gas exchange (Beckett et al., 2000; Nair et al., 2010). Kozlov et al. (2000) obtained a linear relationship between HM concentration in leaves and HMs in the atmosphere, suggesting that the uptake of HMs by foliage may be dose dependent. As various metals accumulate on tree leaves simultaneously, the overall metal accumulation on the leaves of the studied tree species is likely to provide valuable information vis-à-vis their potential as bioindicators (Shahrukh et al., 2023). Consequently, the metal accumulation index (MAI) can be employed to evaluate the overall efficiency of heavy metal accumulation in plants (Hu et al., 2014; Liu et al., 2007; Monfared et al., 2013).

Biomonitoring is an inexpensive and environmentally benign technology that can substitute for expensive and aggressive physical and chemical analytical methods generally used in air pollution monitoring systems (Jashim et al., 2021; Kulkarni et al., 2014). Many higher plants have been employed as biomonitors for evaluating the quality of the environment with respect to pollution from PTEs (Alahabadi et al., 2017; Bilo et al., 2017; Madejón et al., 2013; Majolagbe et al., 2010; Mataruga et al., 2020; Mohammadi et al., 2018; Ozturk et al., 2017; Piczak et al., 2003; Popek et al., 2017). The advantages of utilizing trees as biomonitors include the ease of collection and identification of biological materials, the profusion of biological materials for analysis, and the presence of high biomass for PTE accumulation (Bilo et al., 2017; Sawidis et al., 2011). The danger associated with exposure cannot be sufficiently determined by physical or chemical means, whereas biological techniques directly evaluate exposure risk (Calzoni et al., 2007). The broader goal of this study was to evaluate the performance of some tropical common tree species in urban settings in biomonitoring the concentration of heavy metals in the air. We aimed to identify the metal accumulator higher plants whose metal concentration can best represent the HM concentration in the ambient air. The specific objectives were (i) to determine the concentration of

potentially toxic elements (PTEs) in PM₁₀, soil samples, and leaves of four different plant species, (ii) to observe if there are any linear relationships between HM concentration of PM₁₀ of ambient air and that of plant samples, (iii) to compare the stomata pore of epidermis of leaves collected from the control and polluted sites, and (iv) to assess the metal accumulating capacity of the selected plant species using metal accumulation index (MAI).

Materials and methods

Study area

Dhaka, the main study area of this investigation, is the largest city in Bangladesh and home to 21.74 million people (Shahruckh et al., 2023). Numerous motor vehicles, including both public and private transport, ply the roads in the city and serve as a source of air pollutants (Ahmed et al., 2012; Nargis et al., 2022; Rahman et al., 2019). To make the matters worse, the construction of buildings and roads is a common sight in the city (Islam et al., 2015; Rahman et al., 2021). The sampling locations were selected to include traffic-congested sites, industrial sites, and residential sites (Fig. 1). Modonpur, Narayanganj (site 2) and Kodomtoli, Dhaka (site 3) were surrounded by a variety of enterprises. Thus, these two places were categorized as industrial areas. Due to severe traffic on the neighboring roads, Farmgate (site 6) and Gabtoli (site 7) in Dhaka were regarded as traffic-congested areas. Both Doyel Chattar, Shahbag (site 4), and Pallabi, Mirpur (site 5) were chosen

as semi-residential and residential areas, respectively. A remote location with limited pollution sources, Hashadah, Chuadanga (site 1) was selected as a control and reference site.

Sampling

PM and soil samples were collected from seven different locations in three replicates. Four different plant species were also selected from those seven locations. For each species, leaf samples were collected from three separate plants. Therefore, a total of 21 PM samples, 21 soil samples, and 84 leaf samples were collected for analysis.

PM sampling

PM samples were collected by a respirable PM₁₀ sampler (model TEI -108 NL) on a 24-h basis. The sampler utilizes inbuilt cyclone separator technology to gather PM from the surrounding air. Particles from 10 μ down to 0.1 μ are deposited on the filter paper mounted on the filter paper holder. The particles collected from the filter paper were further used to analyze the concentration of PM in the ambient air. From the difference between the mass of the empty and loaded filter paper, the mass of the collected particles was measured. After measurement, the filter papers were stored in a desiccator at room temperature.

Leaf sampling

Fully expanded leaves of *Artocarpus heterophyllus*, *Mangifera indica*, *Psidium guajava*, and *Swietenia mahagoni* were collected from the selected locations. The collected leaves were washed thoroughly with DI water and air-dried. The air-dried leaves were further dried in an oven for 5 min at 105 °C followed by drying at 70 °C for 48 h until they reached a constant weight (Kachenko & Singh, 2006; Zhang et al., 2014). Following weighing, the desiccated leaves were ground in a grinder.

Soil sampling

From each sampling site, soil samples were collected at a depth ranging from 0 to 15 cm using an auger. The collected soil was kept in zip-lock bags and marked properly. Each of the collected soil

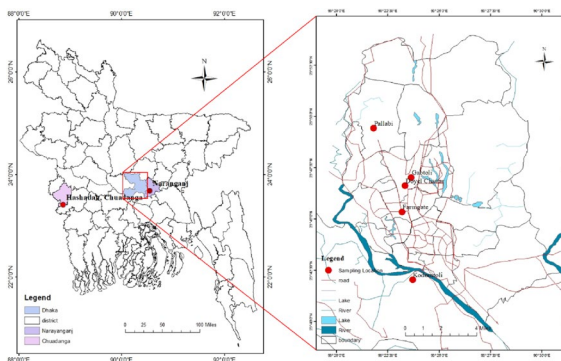


Fig. 1 Geographical representation of the study area

samples was dried in the air for 7 days. After crushing the aggregates, a portion of the ground samples were subjected to screening, passing through a sieve with a 2-mm aperture and mixed thoroughly. The soil samples were preserved in plastic containers with appropriate labeling.

Morphological analysis of PM

The morphological study of airborne particles was conducted using a scanning electron microscope (SEM) (model JEOL, JSM 6490LA), as depicted in Fig. 2. Double-sided adhesive carbon tape was used to mount 1 mm² dry and particle-loaded filters on aluminum stubs. Samples were examined and photographed at different magnifications on a stereo SEM with 30 tilt and 10 kV. Four photos at different magnifications were captured for each sample to highlight the morphological features.

The National Institute of Health in Maryland's ImageJ program was used to analyze the particles. Calculations were made for morphological characteristics such as count, surface area, aspect ratio (AR), circularity, equivalent spherical diameter (ESD), roundness, and solidity.

Measurement of stomatal pore size

Collection of stomatal imprints (nail varnish method)

The stomatal aperture can be measured using the microscope imaging of epidermal imprints of leaf samples by the nail varnish method (Wu & Zhao, 2017). Transparent nail varnish was painted in two places covering an area of about 2 cm² on the underside of a leaf. It was then allowed to dry out thoroughly for about 5 min over the leaf to avoid denaturing of the imprint. A piece of clear sticky cellophane tape was placed over the painted area to remove the imprint. The cellophane tape was then fully pressed and peeled off. When the sticky tape was peeled off it brought the varnish which had an imprint of the surface of the leaf. It was then taped to a microscope slide, labeled, and taken to the laboratory for microscopic observation. To ensure the validity of this experiment, the test was carried out on leaves with different maturities. Samples of the stomatal pore imprints were taken at the seven sites in question.

Measurement of area of stomatal pore

The imprints were observed using a microscope at a magnification of $\times 40$ (Fig. 2). The area of the stomatal pore was then measured in μm using the ImageJ

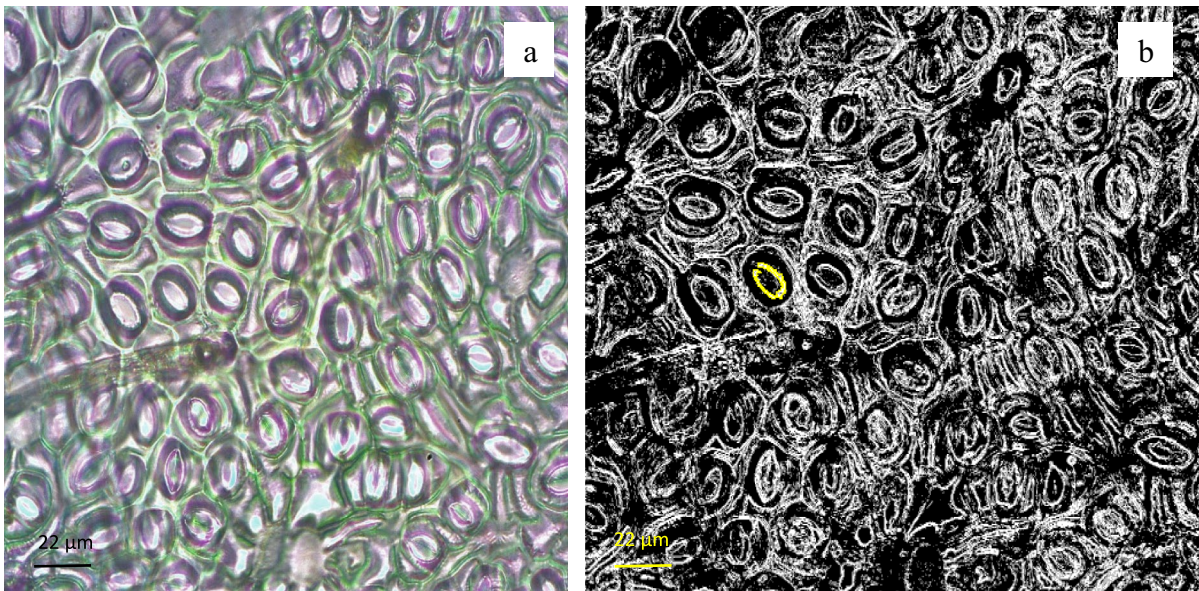


Fig. 2 Microscopic image of stomata of *Psidium guajava* leaf at $40\times$ magnification: **a** original image; **b** binary image

software. Ten stomatal measurements were recorded per strip attached to the microscopic slide within an hour of strip preparation. Five leaves from each sample location were observed. The image processing program ImageJ was used to analyze these pictures (Rasband, 1997). All data were recorded, and the mean values of pore size were calculated.

Heavy metal analysis

An atomic absorption spectrometer (AAS) (model VARIAN AA-240) was used to identify the HMs in the samples. Soil and plant samples under study were first digested using the wet digestion method (Estefan et al., 2013). Briefly, 1 g of the sample was taken into a 100-mL volumetric flask, and 10 mL of HNO₃ was added. The solution was allowed to stand for a few hours before being carefully heated over a sand bath until the brown fumes from the flask ceased completely. After allowing the flask to cool to ambient temperature, 10 mL of perchloric acid was added, and the flask was heated until it was almost dry. After that, it was filtered through a Whatman 42 filter paper, and 100 mL of DI water was added to make up the volume. The PM₁₀ samples were digested with aqua regia (1HNO₃:3HCl) (v/v) following Peña-Icart et al. (2011).

Enrichment factor

A common way to study environmental pollution is to look at the enrichment factor (EF) for metal concentration compared to uncontaminated background or reference levels (Callen et al., 2009). By convention, a trace element in PM with an average EF value of 10 comes from the crust, while an EF value greater than 10 means that a large part of the element comes from somewhere other than the crust (Chester et al., 1999). As a reference element, Fe was used to calculate the EF for Dhaka’s urban aerosol with respect to the composition of the earth’s crust.

Enrichment factor can be calculated with the following relationship.

$$EF = \frac{\left(\frac{X}{Fe}\right)_{\text{sample}}}{\left(\frac{X}{Fe}\right)_{\text{crust}}}$$

Geoaccumulation index

The geoaccumulation index (I_{geo}), proposed by Muller (1969), assesses the degree of pollution by comparing the heavy metal contents in the collected samples to the background values (upper continental crust or local soil). The index is determined using the following equation (Khuzestani & Souri, 2013).

$$I_{geo} = \log_2 \frac{C_n}{1.5B_n}$$

Here, C_n represents the concentration of the heavy metals in the soil that was measured. B_n represents the background concentration (upper continental crust) of heavy metal as stated by Wedepohl (1995). A multiplier of 1.5 was employed due to the reduction in background value fluctuations, which can be related to lithogenic differences in the samples.

Contamination factor

The contamination factor (CF) is determined by dividing the concentration of each heavy metal found in soil by the concentration of the same heavy metals found in the background. The calculation of CF was performed using the following equation.

$$CF = C_n/B_n$$

C_n represents the concentration of heavy metals present in the analyzed soil, while B_n represents the background value of heavy metals (Wedepohl, 1995). The categorization of CF is defined as follows: $CF < 1$ is classified as ‘low contamination’, $1 < CF < 3$ is classified as ‘moderate contamination’, $3 < CF < 6$ is classified as ‘considerable contamination’, and $CF > 6$ is classified as ‘very high contamination’ (Gope et al., 2017).

Pollution load index

To evaluate the quality of soil vis-à-vis the concentration of hazardous elements, an integrated method called the pollution load index (PLI) of the eight hazardous elements was employed, as described by Tomlinson et al. (1980). Assigned to the nth root of the multiplication of the contamination factor of metals,

the PLI was calculated. A PLI of 1 signifies the presence of baseline levels of pollutants, while a PLI greater than 1 indicates a decline in the quality of the site (Gope et al., 2017).

Metal accumulation index (MAI)

The overall effectiveness of heavy metal accumulation in the plants was evaluated using the metal accumulation index.

$$(\text{MAI}) = (1/N) \sum_{j=1}^N I_j$$

$$I_j = x/\delta x$$

I_j is the sub-index for variable j , and N is the total number of metals examined. To further define I_j , consider the following: x is the mean concentration of elements, and δx is its standard deviation (El-Amier et al., 2018; Liu et al., 2007).

Saet's summary index

Saet's summary index also known as the total pollution index (Z_c) was used as criteria for assessing the hazard classified by the hazard degree (Saet & Smirnova, 1983). It is calculated by the formula:

$$Z_c = \sum Kki - (n - 1)$$

where Kki is the correlation coefficient for each element. $Kki = Ci/Cib$, where Cib is the background concentration (concentration of heavy metals from the control site), Ci is the actual concentration of the i -th element in plant leaves, and n is the number of elements analyzed.

The following critical values enable the total contamination Z_c to be characterized by the degree of hazard. For $Z_c < 16$, the contamination is deemed non-toxic; $Z_c < 32$ is considered moderately hazardous; $Z_c < 128$ is considered hazardous; and $Z_c > 128$ is regarded as extremely hazardous (Vodyanitskii, 2010).

Quality assurance and quality control (QA/QC)

To reduce contamination, precautions were taken at every stage of sample collection. The sampler was maintained on a regular basis to ensure that it produced reliable readings. Each filter paper was

Table 1 Minimum detection limit (MDL) of the analyzed HMs

Elements	MDL ($\mu\text{g/mL}$)	Elements	MDL ($\mu\text{g/mL}$)
Fe	0.0200	Cd	0.0086
Cu	-	Zn	0.0100
Cr	0.0087	Pb	0.0506
Ni	0.0350	Mn	0.0600

desiccated and weighed before and after sampling with an analytical microbalance (Sartorius, ME5-F) with a sensitivity of 1 mg. Three plants from each species and nearly 30 leaves from each plant from different branches and heights were collected for homogenization of all leaf samples. Triplicate analyses were performed to verify the repeatability of the leaf sample digestion procedure. Table 1 provides the minimum detection limits of the AAS for the examined elements.

Statistical analysis

Microsoft Excel 2021 and Minitab statistical software (version 21) were used for statistical analysis. For every sample, triplicate analyses were conducted. The concentrations of HMs (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) in PM_{10} , soil, and leaf samples were subjected to correlation analysis.

Results and discussion

Physical characterization of PM_{10}

The majority of the particles were not fully spherical, as seen by the circulatory effects, which varied from 0.71 to 0.83 (less than one) (Chang et al., 2022). Irrespective of the size of the particles, the factor of roundness is crucial in defining them. The particles' roundness ranged from 0.6 to 0.71 (< 1), indicating a range in shape from nearly spherical to irregular (Fig. 3).

The proportionate relationship between an image's maximum width (W_{max}) and maximum height (L_{max}) is referred to as the aspect ratio. The cellular absorption of PM is significantly influenced by its aspect ratio. The higher the aspect ratio, the higher the activity of the particles. The diameter of a sphere with an equivalent volume is referred to as the equivalent

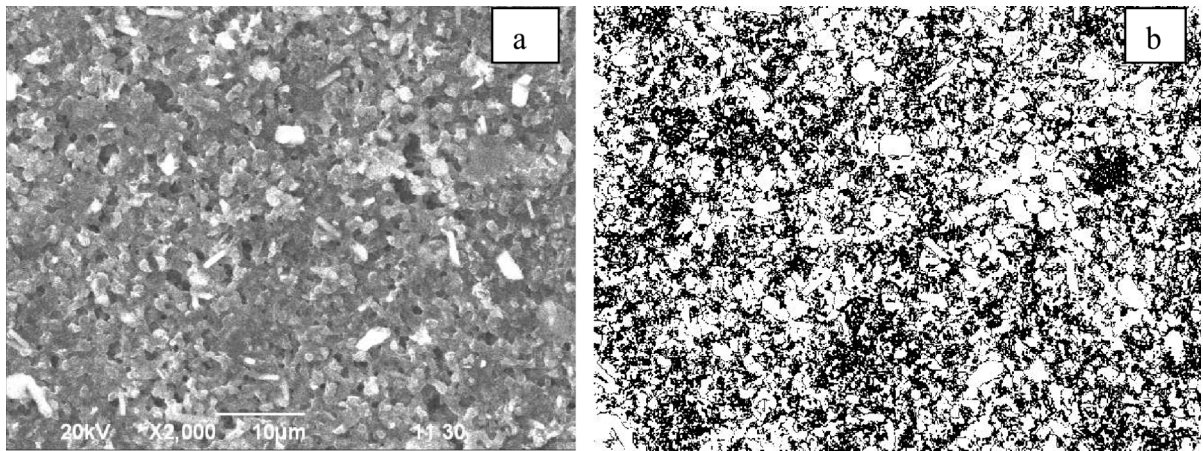


Fig. 3 SEM image of PM₁₀. **a** Original image; **b** binary image

Table 2 Morphological features of PM₁₀

Location	Count/mm ²	Circulatory	Aspect ratio (AR)	Roundness	Solidity	Equivalent spherical diameter (ESD)	Surface area (µm ²)
Chuadanga	99	0.79	1.31	0.62	0.85	0.73	1.67
Modonpur	3384	0.81	1.65	0.71	0.85	0.82	2.11
Kodomtoli	1747	0.83	1.77	0.69	0.86	0.85	2.25
Doyal Chattar	2217	0.77	1.80	0.66	0.82	0.86	2.32
Farmgate	1666	0.73	1.35	0.60	0.82	0.74	1.72
Gabtoli	1410	0.71	1.55	0.61	0.81	0.80	2.01
Pallabi	975	0.78	1.79	0.67	0.83	0.85	2.26

spherical diameter (ESD) of an irregularly shaped object (Parslow & Jennings, 1986). The respiratory deposition fraction is defined as an ESD value larger than 0.93 (McNaught & Wilkinson, 1997). ESD value (0.73–0.86) of the particles in the current study indicated that these particles were not respiratory fractions that could pass beyond the ciliated airways. No significant difference ($p > 0.05$) was found in the morphological aspects of PM₁₀ of the studied locations (Table 2).

Stomatal pore size

The morphology of abaxial leaf surfaces of *P. guajava* exposed to PM collected from different locations was studied. Microscopic examinations of the abaxial (lower) epidermis of leaves revealed that the stomatal pores and stomatal edges in the epidermis of the polluted leaves were clogged with particulate pollutants,

thereby preventing the easy exchange of gases. On the other hand, stomata in the control leaves were broadly open and slightly recessed (Fig. 4a). Leaves of the contaminated site had occluded stomatal openings (Fig. 4b).

In previous studies, specific leaf attributes, including the quantity and dimensions of stomata and the length of the leaf lamina, have exhibited their potential as bioindicators of industrial pollution. The length of the foliage was found to exhibit the highest degree of sensitivity (Dimitrova & Yurukova, 2005). In our study, stomatal pore size was decreased up to 40% (Table 3). When compared to the control site, the leaf surface of the plants growing at the contaminated site had smaller stomatal pores. Our results are consistent with the findings of Abdallah and Mejnun (2013), who stated that encrypted and somewhat sunken stomata were seen on the plant leaf in the polluted environment. Compared to healthier leaves, leaves

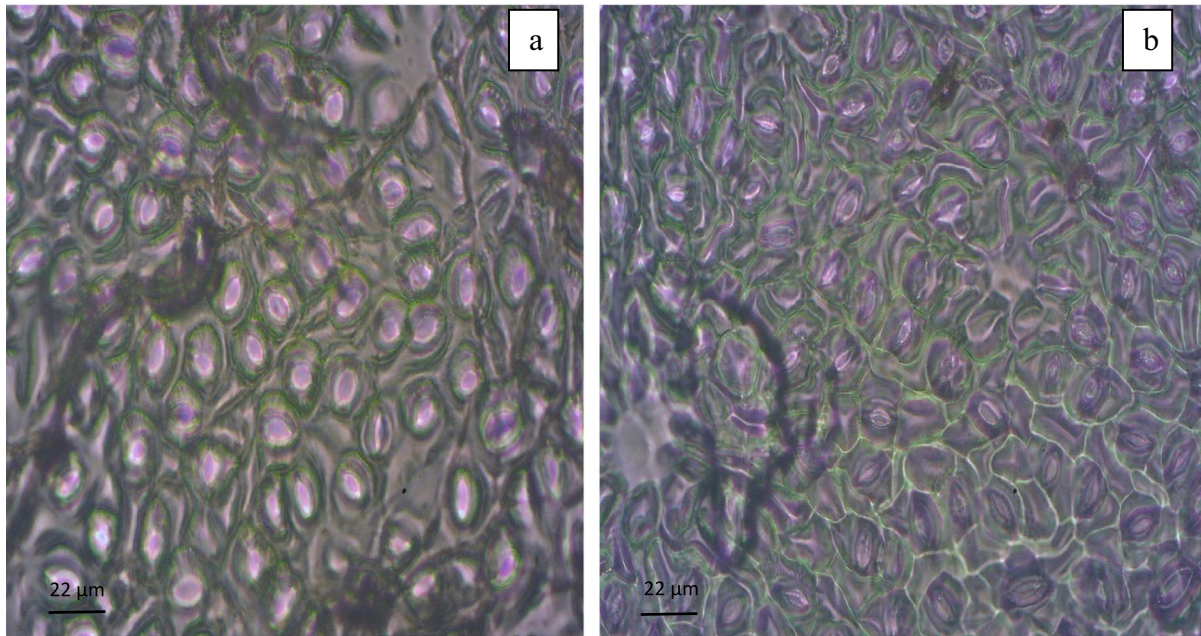


Fig. 4 Microscopic image of stomata of *Psidium guajava* leaves at 40× magnification collected from **a** Chuadanga (control) and **b** Kodomtoli

Table 3 Stomatal pore size of *Psidium guajava* leaves collected from different sites

Sampling location	Stomatal pore size (μm^2)	% decrease in stomatal pore size
Hashadah, Chuadanga	57.0 ± 23.7	-
Modonpur, Narayanganj	34.0 ± 16.4	40
Kodomtoli, Narayanganj	45.6 ± 29.3	20
Doyel Chattar	42.0 ± 15.7	26
Farmgate	47.7 ± 17.7	16
Pallabi, Mirpur	41.1 ± 15.0	28
Gabtoli	47.5 ± 10.0	17

exposed to polluted sites exhibited obvious changes in leaf surface configuration (Alfani et al., 1996).

Stomata are constantly exposed to air pollutants. Therefore, any distinctive or predictable change in stomata caused by pollutants could be used as a diagnostic indicator of exposure to air pollution. According to Eckert and Houston (1982), increased cell permeability induced by pollution may result in the guard cells becoming flaccid and losing water, which closes the stomata. Encrustation or PM deposition on a leaf's surface may also lessen the amount of light that

reaches the leaf, hindering photosynthesis. This could then cause CO_2 to build up in the sub-stomatal cavities, causing the stomata to close. A high dose of SO_2 also promotes stomatal closure (Morgan et al., 2006). The ambient SO_2 concentration was not assessed in the present study. Consequently, the impact of SO_2 on leaf stomata was not taken into account in this study.

HM concentration in PM_{10}

PM and airborne HMs have the potential to reach remote areas despite being mostly emitted from urban or industrial areas due to their long-range transportation. After being deposited, the HMs will actively participate in the biogeochemical cycles within various soil–plant–atmosphere systems. Leaf deposition and foliar absorption, in addition to the well-known root assimilation pathway, contribute to the accumulation of HMs in plants.

Lead (Pb)

The Pb concentration varied from 11.57 ng/m^3 (Hashadah, Chuadanga) to 718.58 ng/m^3 (Kodomtoli, Dhaka) (Fig. 5). The higher value of Pb may

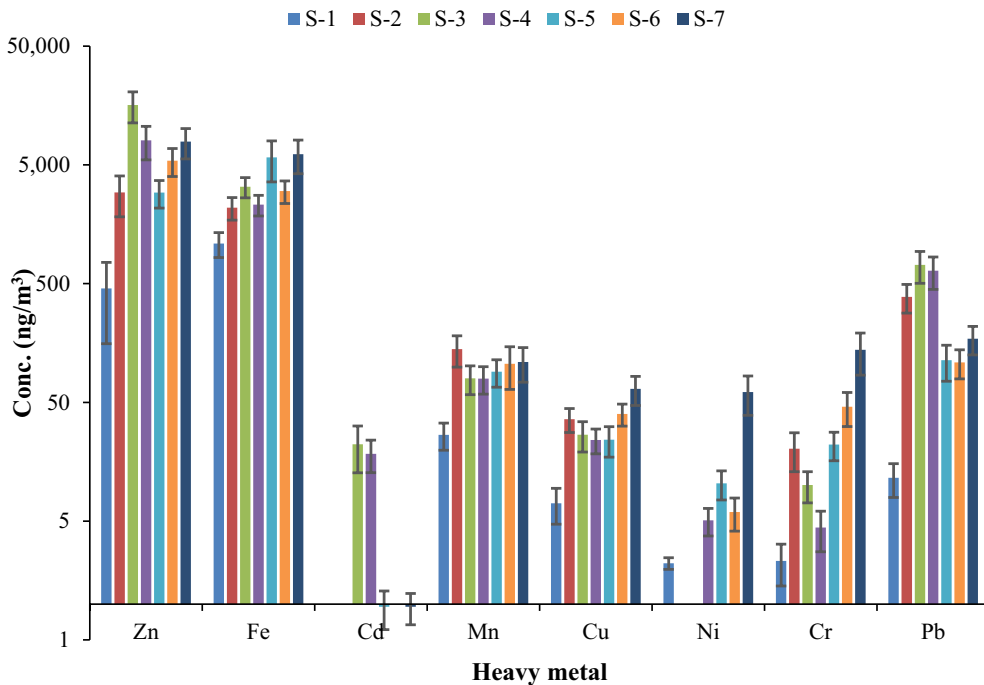


Fig. 5 Concentration of heavy metals in PM₁₀ in the ambient air. S-1= Hashadah, Chuadanga; S-2=Modonpur, Narayanganj; S-3= Kodomtoli, Narayanganj; S-4= Doyel Chattar, Dhaka; S-5= Pallabi, Mirpur, Dhaka; S-6= Farmgate, Dhaka; S-7= Gabtoli, Dhaka

be due to industrial activities along with heavy traffic in Kodomtoli area, while the lower value may be attributed to the relatively lower level of traffic and lack of industrial activities. According to Salam et al. (2003), the level of Pb in Bangladesh’s rural areas is below the detection threshold. Our study showed a different scenario. In rural regions, autorickshaws powered by lead-acid batteries may contribute to significant Pb emission. According to the source composition profile of PM_{2.5} by Begum et al. (2013), the main sources of lead were motor vehicles, soil dust, and fugitive Pb. Anthropogenic sources, primarily from traffic emissions, were responsible for the atmospheric concentration of lead (Basha et al., 2010). Dhaka held the distinction of being the most polluted city globally, as indicated by a recorded lead (Pb) concentration of 463 ng/m³ in PM_{2.5} (Khal-iquzzaman et al., 1997). Steel industries in Kodomtoli area may contribute to significant lead emission in the ambient atmosphere. Lead is used in steel to improve its machinability. It gives rise to a significant release of lead in the atmosphere as 59.98% of input lead ends up in the PM, 0.03% in the stack emissions, and almost no Pb in the slag (Chattopadhyay et al.,

2014). Higher concentration of lead in Doyel Chattar area may be due to the nearby lead acid battery industries in Paltan, Gulistan, and Motijheel area (Rahman et al., 2021). A significant portion of lead can also be emitted from the combustion of coal in brick kiln industry (Bhat et al., 2014; Haque et al., 2022; Majumder et al., 2021; Rai et al., 2016). Thus, the brick kiln industry can be accounted for the higher lead concentration in Modonpur. Lead concentration in heavy traffic areas such as Farmgate and Gabtoli is lower than that of Kodomtoli and Modonpour. The progressive decrease in atmospheric Pb concentration in Dhaka is most likely to have been caused by Bangladesh’s prohibition on leaded gasoline (Shahruckh et al., 2023).

Copper (Cu)

The Cu concentrations varied from 7.07 ng/m³ (Hashadah, Chuadanga) to 64.92 ng/m³ (Gabtoli, Dhaka) (Fig. 5). Emission of Cu in rural areas is low. In this study, the highest concentration of Cu was obtained from the area with high traffic volume. Over 90% of the copper (Cu) emissions from vehicles can

be attributed to the combined effects of brake wear and exhaust emissions (Johansson et al., 2009). Burning coal in brick kiln can significantly contribute to Cu emission. The primary sources of Cu emissions were the iron industries, smelting, and friction from automobile brakes. According to the findings of Chen et al. (2015), the primary contributors to Cu and Ni emissions are the combustion of coal and oil.

Cadmium (Cd)

The Cd concentration in the rural area was below the detection limit. The highest Cd concentration was recorded in Kodomtoli (22.2 ng/m³) and Doyel Chattar, Dhaka (18.41 ng/m³). The increased Cd concentration may be a result of higher traffic emissions and Cd release from various industrial mechanical operations as documented by Salam et al. (2003) and Salam et al. (2008). Zhao and Zhao (2012) also reported that Cd originated from traffic emissions.

Manganese (Mn)

The Mn concentrations varied from 26.62 ng/m³ (Hashadah, Chuadanga) to 140.5 ng/m³ (Modonpur, Narayanganj). Mn is used in gasoline as it increases the octane number. Thus, traffic emission causes a significant release of Mn in the atmosphere. Begum et al. (2013) reported aged sea salt and fugitive Mn as the main source of Mn. According to Chen et al. (2015), the iron and steel sector, smelting, and friction from car brakes were the main sources of Mn emissions.

Iron (Fe)

The Fe concentration was found to vary from 1086 ng/gm³ (Chuadanga) to 6152 ng/m³ (Gabtoli). This was probably due to the ongoing construction activities of the metro rail, heavy traffic, and industrial activities of the Tejgaon industrial area nearby. The recent Dhaka mass rapid transit development project of the Bangladesh government is responsible for the continual erosion of roads and soils in that area (Moniruzzaman et al., 2022). The lower value of Fe (1086 ng/m³) at Chuadanga was probably due to the lack of industrial activities and less traffic in the area. In comparison to the values reported by Salam

et al. (2003), Salam et al. (2008), and Mondol et al. (2014), Fe showed relatively higher concentrations at all seven sites. Begum et al. (2013) reported road dust, brick kilns, motor vehicles, soil dust, and fugitive Fe as the principal source of iron.

Nickel (Ni)

The highest Ni concentration (61.1 ng/m³) was found in Gabtoli, Dhaka, which was probably due to traffic emissions. In the rural area, Ni concentration was below the detection limit. The primary contributors to the abundance of Ni were motor vehicles, as well as the combustion of coal and oil.

Zinc (Zn)

Zn concentrations varied from 455 ng/m³ (Hashadah, Chuadanga) to 15,956 ng/m³ (Kodomtoli). The highest concentration of Zn was found at Kodomtoli which could be attributed to heavy traffic and the industrial release of Zn from the nearby industrial area. The observed minimum value at the rural site may be attributed to less traffic and industrial activities. The mean value of Zn in PM₁₀ in our study was much higher than the value obtained in previous measurements. The current metro rail project may have a significant contribution to this higher level of Zn. Begum et al. (2013) found traffic emission, brick kilns, aged sea salt, and fugitive Zn as the chief source of Zn. Zn in the atmosphere was determined to be a result of vehicle emissions by Basha et al. (2010), who also suggested using Zn as a marker for gasoline engine emissions.

Chromium (Cr)

The highest Cr concentration (138.44 ng/m³) was found in Gabtoli, Dhaka, while in Hashadah, Chuadanga, the concentration was 2.31 ng/m³. The highest concentration was found in heavy-traffic sites. Cr is used in steel which finds its way into vehicles. Car cylinders are also usually covered with a layer of chromium. Cr is also emitted from coal combustion and incinerators, textile, and steel industries as reported by Chen et al. (2015). Cr concentration was higher in Pallabi which was probably owing to the prevalence of textile industries near the sampling location.

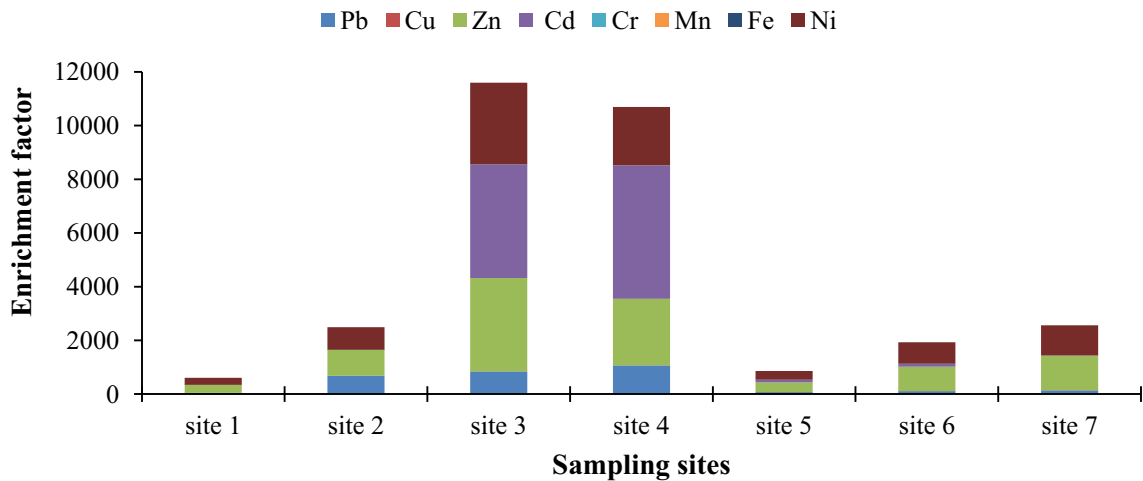


Fig. 6 Enrichment factor of heavy metals in PM₁₀. site 1=Hashadah, Chuadanga; site 2=Modonpur, Narayanganj; site 3=Kodomtoli, Narayanganj; site 4=Doyel Chattar, Dhaka; site 5=Pallabi, Mirpur, Dhaka; site 6=Farmgate, Dhaka; site 7=Gabtoli, Dhaka

Enrichment factor

The highest enrichment of Pb, Cd, Zn, and Ni was observed in site 3 and site 4 which were industrial and traffic congested sites (Fig. 6) implying that these elements were released into the environment via the anthropogenic sources rather than the geogenic ones. Doyel Chattar is a residential area of the University campus that is intersected by two important roads. Despite the restrictions on heavy duty vehicles, the roads in the area frequently experience significant traffic congestion. In addition, the construction activities associated with the Dhaka Mass Rapid Transit Development Project might have contributed to a significant increase in the concentration of Fe and Zn at this site, as noted by Moniruzzaman et al. (2022). It is possible that the increased levels of lead in the Doyel Chattar area are a result of the presence of lead acid battery industries in the nearby Paltan, Gulistan, and Motijheel areas. A study by Khare and Baruah (2010) in north-east India produced comparable results to the current study. The study concluded that high concentrations of Zn and Cd were caused by vehicular exhaust, and high enrichment of Zn was caused by road dust resuspension (Khare & Baruah, 2010). Near highways, car emissions are the main source of non-crustal components that are related to PM (Weckwerth, 2001). As previously stated by Hai-lin et al. (2008) and Wu et al. (2020), the higher Pb concentration could be linked to the residue of pre-emitted lead in soil and industrial operations.

HM concentration in soil

HMs of soil from seven different locations were studied (Fig. 7), which revealed that the metal concentration in soil of urban areas was higher than that of rural areas. Cr, Mn, Ni, and Zn content of all the sampling locations met the standard limit set by Sauerbeck (1985). Cd was detected from the soil of Kodomtoli and Modonpur which were industrial areas. Those two locations failed to meet the standard limit. Higher concentrations of Pb were found in the soil of Kodomtoli, Doyel Chattar, Farmgate, and Pallabi that exceeded the standard concentration. However, linear regression analysis between the metal concentration of air and soil revealed no significant correlation ($p > 0.05$). Significant positive correlation ($p < 0.05$) was found for Pb ($R^2 = 0.605$) and Cu ($R^2 = 0.677$) contents in soil and air of respective locations.

Geoaccumulation index

The geoaccumulation index (I_{geo}) of heavy metals in the soil of Dhaka City was evaluated and is presented in Table 4. According to the classification of Kamani et al. (2018), Cr, Cu, Fe, Mn, and Ni were ranked as uncontaminated ($I_{geo} \leq 0$). The concentration of Zn at sites 3, 4, and 7 was ranked as uncontaminated to moderately contaminated ($0 < I_{geo} \leq 1$), whereas in moderately contaminated ($1 < I_{geo} \leq 2$) at site 6 (1.17). Cd was in the heavily contaminated class ($3 < I_{geo} \leq 4$)

Fig. 7 Concentration of heavy metals (mg/kg) in soils of different locations. S-1 = Hashadah, Chuadanga; S-2 = Modonpur, Narayanganj; S-3 = Kodomtoli, Narayanganj; S-4 = Doyel Chattar, Dhaka; S-5 = Pallabi, Mirpur, Dhaka; S-6 = Farmgate, Dhaka; S-7 = Gabtoli, Dhaka

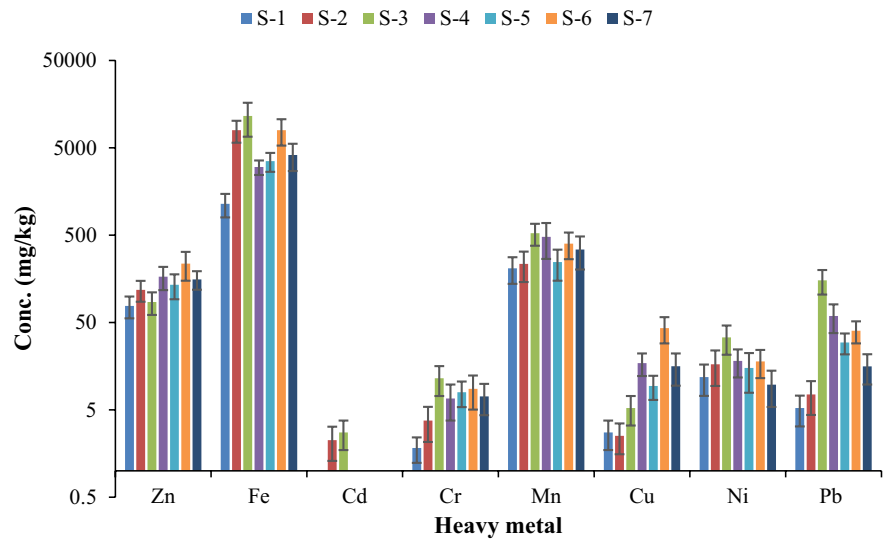


Table 4 Geoaccumulation index (I_{geo}) of soil of the selected sites

Geoaccumulation index (I_{geo})	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Zn	-0.44	0.17	-0.29	0.67	0.36	1.17	0.57
Fe	-6.21	-3.41	-2.87	-4.81	-4.59	-3.41	-4.35
Cd	-2.35	3.88	4.17	-1.94	-2.35	-2.94	-1.94
Cr	-6.39	-5.34	-3.73	-4.50	-4.27	-4.14	-4.43
Mn	-2.77	-2.60	-1.44	-1.58	-2.54	-1.83	-2.06
Cu	-5.03	-5.16	-4.10	-2.39	-3.26	-1.06	-2.51
Ni	-3.41	-2.92	-1.90	-2.80	-3.06	-2.82	-3.70
Pb	-2.00	-1.49	2.86	1.50	0.49	0.94	-0.42

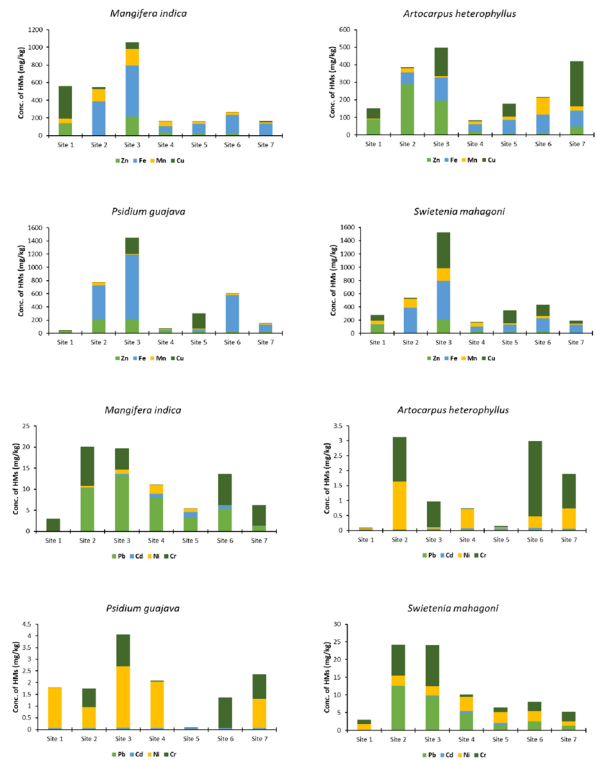
Table 5 Contamination factor (CF) and pollution load index (PLI) of soils from different sites

Contamination factor (CF)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Mn	0.22	0.25	0.55	0.50	0.26	0.42	0.36
Cu	0.05	0.04	0.09	0.29	0.16	0.72	0.26
Zn	1.11	1.69	1.23	2.39	1.93	3.37	2.23
Ni	0.14	0.20	0.40	0.22	0.18	0.21	0.12
Cr	0.02	0.04	0.11	0.07	0.08	0.09	0.07
Fe	0.02	0.14	0.21	0.05	0.06	0.14	0.07
Pb	0.38	0.54	10.86	4.23	2.11	2.87	1.12
Cd	0.29	22.00	26.00	0.39	0.29	0.20	0.39
Pollution load index (PLI)	0.13	0.35	0.79	0.38	0.28	0.44	0.29

at site 2 and heavily contaminated to extremely contaminated ($4 < I_{geo} \leq 5$) at site 3. Other sites exhibited low concentration. Pb fell in uncontaminated to

moderately contaminated ($2 < I_{geo} \leq 3$) level at sites 5 and 6, moderately contaminated at site 4, and moderately to heavily contaminated ($2 < I_{geo} \leq 3$) at site 3.

Fig. 8 Concentration (mg/kg) of heavy metals in leaves of four different species grown at different locations. Site 1 = Hashadah, Chuadanga; Site 2 = Modonpur, Narayanganj; Site 3 = Kodomtoli, Narayanganj; Site 4 = Doyel Chattar, Dhaka; Site 5 = Pallabi, Mirpur, Dhaka; Site 6 = Farmgate, Dhaka; Site 7 = Gabtoli, Dhaka



Contamination factor

The contamination factor (CF) of heavy metals in the soil of Dhaka City was evaluated and is presented in Table 5. Based on CF classification, Cr, Cu, Fe, Mn, and Ni were ranked as low contamination ($CF < 1$) for all the sites. Zn (1.17) ranked in the moderate contamination class ($1 < CF < 3$). Cd was in the heavily contamination class ($3 > CF > 6$) at sites 3 and 4. Other sites exhibited low contamination. Sites 4, 5, and 6 were moderately contaminated, and sites 3 and 4 were heavily contaminated with Pb.

Pollution load index

The pollution load index (PLI) for different sites was shown in Table 5. All sites showed low contamination according to the PLI classification (Jorfi et al., 2017). PLI found in this study was significantly lower compared to the other studies done in this part of the world (Nargis et al., 2022; Islam et al., 2015). However, as we tried to relate

biomonitoring with the metal accumulation index, we collected root-zone soil for this study. Root-zone soil differs significantly from road dust in terms of heavy metal concentration.

HMs in leaf blades of plants

The uptake of HMs by plant leaves from the atmosphere has received less attention in studies than root metal transfer, which has been extensively researched (Pourrut et al., 2011). Markert (1992) proposed a “Reference Plant” that described the mean concentration of all the inorganic elements in plants. Markert (1992) reported that plants originating from uncontaminated environments may exhibit leaf metal concentrations of the following values: 1 mg kg^{-1} Pb, 0.05 mg kg^{-1} Cd, 150 mg kg^{-1} Fe, 1.50 mg kg^{-1} Cr, 10 mg kg^{-1} Cu, 200 mg kg^{-1} Mn, 1.50 mg kg^{-1} Ni, and 50 mg kg^{-1} Zn. The plants collected from the control site met the “criteria of reference plant” in terms of inorganic element concentration.

Plants grown in traffic areas accumulated a high amount of Pb (Fig. 8). The soils of those respective locations also contained a high concentration of lead

Table 6 MAI of the tree species grown at different locations with varying pollution loads

Plant species	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
<i>Artocarpus heterophyllus</i>	3.18	2.66	3.11	2.44	2.75	3.06	2.74
<i>Mangifera indica</i>	3.88	2.34	2.5	3.12	3.27	2.57	3.15
<i>Psidium guajava</i>	3.18	2.55	2.6	2.79	2.81	3	3.13
<i>Swietenia mahagoni</i>	2.73	3.67	3.15	2.84	2.8	2.79	3.06

(Fig. 7). But only 3% of the Pb in the root gets transferred to the shoot, according to Zimdahl's (1976) description of the Pb translocation from roots to tops. The uptake and transport of Pb from atmospheric deposition were examined by Dalenberg and Driel (1990). According to their findings, leaves transmit between 33 and 95% of the total Pb concentration in plants to other plant organs. In the present study, Pb content in plant leaves and PM fraction were observed to significantly correlate, suggesting that Pb bound to PM in the atmosphere may aid in plant leaf uptake of Pb. The result of our investigation aligns with the findings of Shahid et al. (2017) and Gajbhiye et al. (2022).

According to Klocek et al. (2003), plants' essential Cd level should not exceed 0.15 mg kg^{-1} to be useful for consumptive purposes. Although Cd is not required for metabolic processes, both the root and leaf systems are capable of successfully absorbing it (Kabata-Pendias, 2000). According to Abollino et al. (2002), Cd concentration in soil, PM emission intensity, and physico-chemical characteristics of the soil all affect plant Cd content. The examined plant species had a Cd level that ranged from 0.25 to 1.35 mg kg^{-1} dry matter. Cd concentration in plants grown in the rural area was below the detection limit. The highest Cd concentration (1.35 mg/kg) was observed in *M. indica* grown in Farmgate; however, Cd concentration in soils of Farmgate was below the detection limit. Thus, it can be predicted that elevated concentration of Cd can be caused by atmospheric deposition of Cd from heavy traffic and industrial activities. In the current study, Cr, Cu, Fe, Ni, and Zn concentration in plant leaves grown in industrial and roadside locations was greater than that of the plants grown in the rural area (Fig. 8).

Plants quickly and easily absorb Ni from the soil until certain Ni concentrations are reached in plant tissues. Kozlov et al. (2000) examined the movement of Cu and Ni-rich particles in birch trees and hypothesized that stomata may be the route by which particles

penetrate plant leaves. On the other hand, Ashton (1972) supported the observation of the present study which states that, in environments with airborne PM bound Ni, plant tops concentrate the most Ni. Roberts (1975) also noted a substantial absorption of foliar-applied Zn and Fe. Thus, Fe, Ni, and Zn accumulation may also be attributed to anthropogenic sources. Although Cr is present in large concentrations in most soils, plants have very little access to it (Kabata-Pendias, 2000). Higher Cr concentration in polluted areas than in rural area (Fig. 8) signifies that plants can absorb Cr from the air.

The Mn pool in soils should directly affect the Mn content of plants because Mn appears to be readily absorbed by plants when it is present in soluble forms (Kabata-Pendias, 2000). Except for *M. indica* grown in Modonpur and Kodomtoli, Mn concentration in plants did not vary that much which indicated that Mn in particulates did not contribute to plant Mn concentration.

As Fig. 8 depicts, *Swietenia mahagoni* and *Mangifera indica* are capable of accumulating substantial amounts of Pb and Cr in their leaves. The result of the current study validates the findings of the earlier research by Intan et al. (2023). Emile and Barde (2020) also revealed that *Mangifera indica* is a hyper-accumulator plant and could be employed as a bio-monitor for pollution studies.

Metal accumulation index

Table 6 depicts the metal accumulation index (MAI) values for the chosen plant species. The local atmospheric chemistry, climatic conditions, height of the tree species, and the genetic features of the plant are some of the variables that affect the index (Hu et al., 2014; Liu et al., 2007). Similar species can have varying MAI values in different locations. In the present study, the MAI value (3.88) was maximum in *Mangifera indica* at site 1 and the lowest MAI (2.5) was observed for *Psidium guajava* at site 3. The

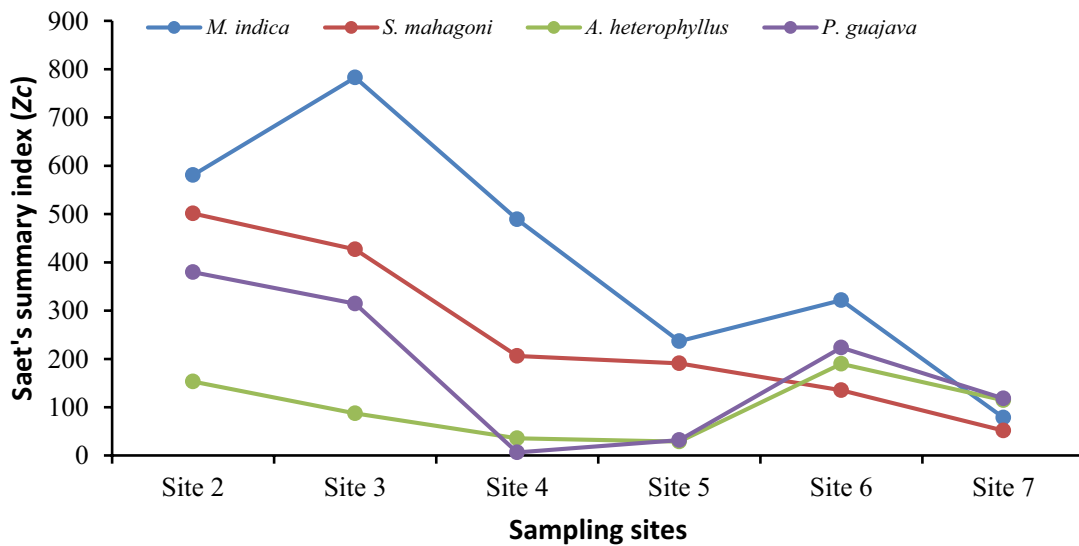


Fig. 9 Saet’s summary index of the tree species grown at different locations with varying pollution loads. Site 2=Modonpur, Narayanganj; Site 3=Kodomtoli, Narayanganj; Site 4=Doyel Chattar, Dhaka; Site 5=Pallabi, Mirpur, Dhaka; Site 6=Farmgate, Dhaka; Site 7=Gabtoli, Dhaka

highest average MAI (3.05) was observed for *Swietenia mahagoni* (Table 6) and followed the decreasing order of *Mangifera indica* > *Artocarpus heterophyllus* > *Psidium guajava*. All four of the plant species under investigation showed site-specific differences in the current investigation. Hu et al. (2014) and Liu et al. (2007) reported similar findings. Nadgórska-Socha et al. (2017) also demonstrated site-specific differences in MAI values for various plant species. This may be attributed to the different pollution loads in different locations. The findings show that different plant species have varying capacities for removing pollutants and that these capacities depend on several different conditions. Our study suggested that the uptake ability of *Swietenia mahagoni* was the highest among the four species followed by *M. indica*. The selection criteria for urban tree species for biomonitoring are based on the measurement of leaf functional traits and leaf surface microstructure characteristics, as these attributes are easily measurable and highly responsive to environmental changes (Rodríguez-Santamaría et al., 2022). High MAI plant species should also be employed as barriers between susceptible regions, like parks, schools, and residential areas, and contaminated areas like heavy traffic and industrial areas (Hu et al., 2014; Nadgórska-Socha et al., 2017).

Saet’s summary index (Zc)

Saet’s summary index (Zc) was calculated for plant leaves of four different plant species collected from different locations and are presented in Fig. 9.

Though Zc index is applied grossly for assessing and classifying soils in terms of heavy metal concentration, we calculated the Zc of plant leaves from varying pollution load. According to the classification of Vodyanitskii (2010), leaves of *M. indica* collected from all locations fell under the extremely hazardous class in terms of heavy metal concentration. Similar results were found for *S. mahagoni* except for site 6. The higher Zc index of the plant species may indicate a higher metal accumulation capacity of the plant leaves compared to other species. Thus, assessing the heavy metal concentration of the plant leaves, it can be stated that *M. indica* has the highest accumulative capacity followed by *S. mahagoni*, *P. guajava*, and *A. heterophyllus*.

Conclusions

In this study, four urban plant species were evaluated for their biomonitoring capacities as they can reduce environmental pollution through bioaccumulating

contaminants in their tissues. In some sites, the foliar configuration was found to change in the form of a decline in stomatal pore size. Particulate matter was also collected from the selected sites to assess their heavy metal loads. The morphological study of the particles indicated that the particles were nearly spherical to irregular in shape and were not respiratory fractions. The higher values of enrichment factors for Cd, Ni, Pb, and Zn implied that those elements were mostly emitted from anthropogenic sources. The geoaccumulation index (I_{geo}) and contamination factor indicated extreme pollution of some sites with respect to Cd and Pb. However, no significant correlations were found among the metal concentrations of soil, plant, and PM_{10} . A positive correlation between Pb content in plant leaves and PM_{10} indicated that plant leaves could be a suitable biomonitor for heavy metal pollution in urban environments. *S. mahagoni* exhibited the highest MAI value followed by *M. indica*. These two species were also found to exhibit a build-up of Pb and Cr. As a result, both *S. mahagoni* and *M. indica* species could be employed as Pb and Cr bioaccumulators in urban areas. Saet's summary index (Zc) suggested that *M. indica* has the highest bio-accumulative property followed by *S. mahagoni*. Researchers and regulatory agencies may find the species-specific results useful in using trees to monitor environmental health and air quality. The results of our study are likely to provide additional guidance to urban planners in conducting future screening studies for urban greenbelt development.

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Author contributions 1)Zuairia Binte Jashim: Conceptualization, Methodology, Investigation, Data curation, Writing – Original draft preparation.

2)Saif Shahrukh: Writing – Reviewing and Editing.

3)Shahid Akhtar Hossain: Supervision, Project administration, Funding Acquisition, Resources.

4)Jahan-E-Gulshan: Investigation.

5)Md. Mominul Islam: Supervision, Project administration, Funding Acquisition, Resources.

6)Muhammad Nurul Huda: Supervision, Project administration, Funding Acquisition, Resources.

7)Mohammad Enayet Hossain: Supervision, Validation, Formal Analysis, Writing – Reviewing and Editing.

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Data availability All relevant data has been added to the manuscript.

Declarations

Ethical approval No human participants or animals were involved in the study.

Consent to participate Not applicable.

Consent for publication Consent has been taken from all the coauthors by the corresponding author.

Competing interests The authors declare no competing interests.

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