ISSN 2449-8955

European Journal of Biological Research

Research Article

DOI: http://dx.doi.org/10.5281/zenodo.18011518

Species-specific accumulation and bioconcentration patterns of phosphorus and heavy metals in urban tree leaves across contrasting pollution gradients in Dhaka, Bangladesh

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Received: 11 August 2025; **Revised submission:** 28 September 2025; **Accepted:** 30 September 2025

https://jbrodka.com/index.php/ejbr

ABSTRACT: Urban trees play a vital role in mitigating environmental pollution, yet their responses to heavy metal stress across contrasting urban gradients remain poorly understood. This study investigates the accumulation patterns of phosphorus (P) and six heavy metals (Zn, Cu, Co, Pb, Ni, Cr) in leaves and associated soils of nine dominant tree species across control and polluted sites in Dhaka, Bangladesh. Two-way ANOVA revealed significant ($p < 0.05$) site effects for P, Ni, and Cr, and pronounced species-specific significant ($p < 0.001$) differences in Zn uptake. Leaf P concentrations generally declined under pollution, while species such as *Syzygium cumini* and *Terminalia catappa* showed elevated heavy metal content, indicating varied tolerance mechanisms. Bioconcentration factors (BCFs) highlighted differential metal accumulation capacities, with increased Pb and Ni uptake in select species under polluted conditions. Pearson correlation and PCA analyses revealed complex interactions among elements, with strong antagonistic relationships between Pb and Co/Cr, and a positive association between Pb, Ni, and Cu. PCA further distinguished control and polluted sites based on metal profiles, underscoring pollution-driven shifts in elemental composition. These findings suggest that species-specific uptake behaviors are crucial for urban ecosystem management. The study identifies resilient tree species with phytoremediation potential, offering valuable guidance for sustainable urban greening and pollution mitigation in rapidly urbanizing cities.

Keywords: Urban trees; Heavy metals; Phosphorus; Bioconcentration factor; Phytoremediation; Environmental pollution.

1. INTRODUCTION

Urbanization is one of the most transformative and ecologically disruptive processes of the 21st century, reshaping landscapes and accelerating environmental degradation, particularly in fast-growing cities of the Global South. As urban centers expand, especially in developing countries, anthropogenic emissions from vehicular traffic, industrial activities, and construction contribute significantly to elevated levels of environmental pollutants, particularly heavy metals, in both air and soil matrices [1-4]. These pollutants not only degrade environmental quality but also pose substantial risks to human health and urban biodiversity. In this context, urban green spaces, particularly roadside and park or garden trees, serve as critical ecological buffers, mitigating pollution through phytostabilization, phytoextraction, and dust interception mechanisms [5-10].

Among the various forms of pollution, heavy metal contamination is particularly concerning due to its persistence, toxicity at low concentrations, and potential for biomagnification in urban food chains [11-13]. Elements such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), cobalt (Co), copper (Cu), and zinc (Zn) are commonly elevated in urban environments. Once deposited onto soil or leaf surfaces, these metals can be absorbed by plants, affecting their physiological integrity, growth, and reproductive success [14-17]. Phosphorus (P), though not a heavy metal, plays a vital role in plant metabolism, particularly in energy transfer, photosynthesis, and membrane synthesis. However, its uptake can be inhibited by soil pollution and heavy metal stress, potentially altering nutrient cycling in polluted urban environments [18-21].

Urban trees exhibit varied responses to pollution, governed by species-specific physiological traits, root morphology, and metal tolerance mechanisms. Some species possess enhanced capacities to accumulate or exclude specific elements, making them ideal candidates for phytoremediation or urban greening under stress conditions [7-8,22-23]. However, there remains a significant knowledge gap regarding tropical urban tree species, especially in rapidly urbanizing South Asian cities such as Dhaka. As one of the most densely populated megacities in the world, Dhaka faces critical air and soil pollution challenges [3-4,24-26]. The city's lack of effective emission control strategies exacerbates the deposition of heavy metals in the urban environment, warranting urgent assessment of urban tree responses to such stressors.

Therefore, this study aims to investigate the distribution and accumulation of phosphorus and selected heavy metals (Zn, Cu, Co, Pb, Ni, Cr) in leaf and soil samples of nine dominant urban tree species across control and polluted sites in Dhaka. It also aims to assess the influence of site and species on leaf elemental concentrations, evaluate metal accumulation capacity through bioconcentration factors, explore inter-elemental relationships, and identify tree species with strong potential for urban phytoremediation.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted in Dhaka, the capital of Bangladesh, one of the world's most densely populated and rapidly urbanizing megacities. Two distinct urban environments were selected: (i) polluted sites, including Gulistan and Sayedabad zones characterized by high vehicular emissions and population density; and (ii) control sites, including the National Botanical Garden and residential areas in Mirpur, with comparatively lower pollution levels and greener surroundings[4]. These contrasting environments provided a basis for assessing the impact of urban pollution on element accumulation in tree species.

2.2. Plant species selection

Nine dominant and widely distributed urban tree species were selected based on their prevalence, ecological significance, and representation in both polluted and control sites[4]. The species include jackfruit tree (*Artocarpus heterophyllus),* banyan tree *(Ficus benghalensis)*, sacred fig tree (*Ficus religiosa)*, arjun tree *(Terminalia arjuna)*, indian almond *(Terminalia catappa)*, mahogany (*Swietenia mahagoni)*, black plum tree (*Syzygium cumini)*, spanish cherry (*Mimusops elengi)*, and false ashoka *(Polyalthia longifolia)*. These species differ in morphology, physiology, and tolerance to urban stress, offering a comparative framework for elemental analysis.

2.3. Sampling procedure

Leaf and soil samples were collected during the dry season (February 2024) to minimize variability due to rainfall. From each site, mature and healthy leaves were collected from three individual trees per species. Simultaneously, topsoil was collected from the base of each sampled tree. All samples were collected in triplicate and stored in clean polyethylene bags for laboratory analysis. Then, the leaf samples were rinsed with distilled water to eliminate dirt and debris. The samples were allowed to air dry; subsequently, they were dried in an oven at 60°C for 24 hours. The dried samples were ground, sieved, and preserved appropriately for further analyses.

2.4. Sample digestion

Soil and plant samples were digested following the acid digestion procedure described by [27], using a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 2:1 ratio. For soil digestion, 1.0 g of air-dried, homogenized soil was placed in a 50 mL beaker, and 10 mL of concentrated HNO_3 was added. The mixture was left to stand overnight for pre-digestion. The following day, the sample was heated on a hot plate until the volume was reduced to approximately 5 mL. After cooling, 5 mL of concentrated $HClO_4$ was added, and the sample was further digested until a clear or whitish residue was observed, indicating complete digestion. The digest was then cooled, filtered through Whatman filter paper, and diluted to 100 mL with deionized water in a volumetric flask.

Similarly, for plant digestion, 0.1 g of finely ground leaf powder was placed in a 50 mL beaker, and 10 mL of concentrated HNO_3 was added. After overnight pre-digestion, the sample was heated on a hot plate until the volume was reduced to about 2 mL. Subsequently, 5 mL of concentrated $HClO_4$ was added, and heating continued until a clear solution was obtained. The digest was then cooled, filtered, and diluted to 50 mL with deionized water in a volumetric flask. All digested samples were stored in pre-cleaned polyethylene bottles for subsequent analysis of phosphorus and selected heavy metals (Zn, Cu, Co, Pb, Ni, Cr).

2.5. Elemental analysis

Concentrations of lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and zinc (Zn) in soil and leaf samples were determined using PerkinElmer PinAAcle 500 Flame Atomic Absorption Spectrophotometer [25,28]. Total phosphorus was determined by a HACH DR 5000 spectrophotometer at 430 nm wavelength after developing a yellow colour from the digest with vanadomolybdate [27]. The instrument was calibrated with certified standard solutions. Analytical blanks and replicate samples were run to ensure data quality.

2.6. Bioconcentration Factor (BCF) calculation

The bioconcentration factor (BCF) was calculated to assess the accumulation potential of each species for individual elements. BCF was computed as the ratio of metal concentration in leaf tissue to that in the corresponding soil [29-31].

$$\text{BCF} = \frac{C\ \text{leaf}}{C\ \text{soil}}$$

where *C* leaf is the concentration of a given element in the plant leaf (mg/kg), and *C* soil is the concentration in soil (mg/kg).

2.7. Data analysis

Data were analyzed using JMP software. A two-way ANOVA was used to evaluate the effects of species, site (control vs. polluted), and their interaction on elemental concentrations and BCFs. Significant differences were tested at $p < 0.05$ using Tukey's HSD post hoc test. Pearson correlation analysis was performed to examine inter-elemental relationships in leaf tissues. To visualize multivariate trends and clustering patterns among species and elements, Principal Component Analysis (PCA) was conducted based on standardized leaf elemental data from the studied sites.

3. RESULTS

3.1. Leaf P and heavy metals

Two-way ANOVA statistics revealed several significant findings regarding the parameters where site had a significant effect on the concentrations of Phosphorus (P), Nickel (Ni), and Chromium (Cr), indicating notable differences in these elements between the studied control and polluted sites (Table 1). Furthermore, Zinc showed a highly significant variation across different species, highlighting substantial interspecific differences in their zinc accumulation. No significant interactions between species and site were observed for any of the other parameters, suggesting that the effect of species on these parameters does not vary significantly across different sites, and vice versa (Table 1).

Table 1. Overall Two-way ANOVA statistics (F-ratios) of the effects of site, species, and their interaction on the leaf properties in Dhaka city.

Source of variation	Species (df=8)	Site (df=1)	Species × Site (df=8)
P	1.69	4.27*	1.26
Zn	7.79***	0.37	0.48
Cu	0.71	1.23	0.85
Co	0.20	0.19	0.74
Pb	0.62	0.28	0.36
Ni	0.83	3.89*	0.94
Cr	0.38	4.5*	0.21

Phosphorus concentrations varied across species and locations, with the highest in *P. longifolia* from non-polluted sites (2.52 ± 1.37 mg/kg) and the lowest in *F. religiosa* from polluted sites (0.25 ± 0.06 mg/kg). However, a general decreasing trend was observed under polluted conditions, particularly in *A. heterophyllus*, *F. benghalensis*, *P. longifolia*, and *T. arjuna*. Conversely, species such as *M. elengi*, *S. cumini*, and *T. catappa* exhibited slightly higher P content accumulation at the polluted site (Table 2). The zinc (Zn) concentration in leaves of the selected plant species showed noticeable variations between the control and polluted sites (Table 2). Among all species, *T. catappa* exhibited the highest Zn content at both sites, with concentrations of 0.16 ± 0.03 mg/kg at the control site and 0.15 ± 0.02 mg/kg at the polluted site. Similarly, *T. arjuna* also showed relatively high Zn levels, recording 0.12 ± 0.05 mg/kg and 0.14 ± 0.03 mg/kg at control and polluted sites, respectively. In contrast, *M. elengi* and *S. cumini* accumulated the lowest Zn concentrations across both environments. Notably, *F. religiosa* demonstrated a substantial increase in Zn accumulation under polluted conditions (0.09 ± 0.03 mg/kg) compared to the control (0.05 ± 0.00 mg/kg), suggesting possible Zn bioaccumulation in response to environmental contamination (Table 2).

The concentration of Cu in the leaves of the examined plant species showed limited variation between control and polluted sites, with most values remaining in a narrow range of 0.01–0.04 mg/kg (Table 2). *M. elengi* and *T. catappa* exhibited the highest Cu content at the polluted site, with values of 0.04 ± 0.033 mg/kg and 0.03 ± 0.009 mg/kg, respectively. Notably, *F. religiosa* and *T. arjuna* also displayed a slight increase in Cu concentration under polluted conditions (0.02 ± 0.005 mg/kg and 0.02 ± 0.002 mg/kg, respectively), compared to the control site. However, most species, including *A. heterophyllus*, *F. benghalensis*, *P. longifolia*, *S. cumini*, and *S. mahagoni*, exhibited minimal or no change in Cu concentration between sites, suggesting low Cu accumulation capacity or effective regulation. As shown in Table 2, the mean Co content varied only slightly between the sites. For most species, the Co accumulation remained within a narrow range (0.01–0.02 mg/kg), with overlapping standard errors, indicating low variability. Among the analyzed species, *F. benghalensis*, *F. religiosa*, *P. longifolia*, and *S. mahagoni* showed a higher Co concentration at the polluted site compared to the control site. On the other hand, species such as *A. heterophyllus*, *S. cumini*, and *T. catappa* exhibited slightly lower Co accumulation at the polluted site.

Table 2. Leaf phosphorus and heavy metal concentrations (mg/kg) in different tree species from control and polluted sites in Dhaka city.

Species	Site	P (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Co (mg/kg)	Pb (mg/kg)	Ni (mg/kg)	Cr (mg/kg)
Artocarpus heterophyllus	Control	1.16±0.66	0.11±0.03	0.01±0.005	0.02±0.003	0.3±0.28	0.08±0.02	0.09±0.03
	Polluted	0.59±0.24	0.09±0.01	0.01±0.002	0.01±0.005	0.44±0.19	0.02±0.01	0.08±0.03
Ficus benghalensis	Control	0.66±0.16	0.06±0.01	0.01±0.001	0.01±0.005	0.56±0.23	0.05±0.02	0.1±0.04
	Polluted	0.62±0.15	0.06±0.02	0.01±0.002	0.02±0.004	0.33±0.3	0.04±0.02	0.08±0.01
Ficus religiosa	Control	1.31±0.32	0.05±0	0.01±0.002	0.01±0.003	0.33±0.23	0.05±0.03	0.12±0.05
	Polluted	0.25±0.06	0.09±0.03	0.02±0.005	0.02±0.005	0.51±0.21	0.04±0.01	0.08±0.02
Mimusops elengi	Control	0.31±0.14	0.03±0.02	0.01±0.001	0.02±0.004	0.39±0.3	0.09±0.03	0.09±0.03
	Polluted	0.46±0.16	0.04±0.03	0.04±0.033	0.02±0.007	0.49±0.14	0.07±0.02	0.04±0.02
Polialthia longifolia	Control	2.52±1.37	0.05±0.01	0.02±0.002	0.01±0.005	0.46±0.2	0.05±0.03	0.09±0.01
	Polluted	0.64±0.32	0.07±0.01	0.01±0.001	0.02±0.005	0.25±0.19	0.05±0.02	0.09±0.03
Sizium cumini	Control	0.42±0.29	0.03±0.01	0.01±0.001	0.02±0.004	0.34±0.2	0.06±0.01	0.1±0.03
	Polluted	0.47±0.07	0.04±0.01	0.01±0.005	0.01±0.004	0.62±0.23	0.01±0	0.06±0.02
Swietenia mahagoni	Control	0.49±0.10	0.05±0.02	0.01±0	0.01±0.005	0.49±0.22	0.05±0.02	0.1±0.03
	Polluted	0.49±0.13	0.04±0.01	0.01±0.002	0.02±0.006	0.37±0.23	0.03±0.03	0.09±0.03
Terminalia arjuna	Control	0.81±0.48	0.12±0.05	0.01±0.002	0.02±0.003	0.34±0.13	0.06±0.02	0.09±0.03
	Polluted	0.32±0.15	0.14±0.03	0.02±0.002	0.02±0.006	0.47±0.17	0.02±0.01	0.06±0.02
Terminalia catappa	Control	1.16±0.33	0.16±0.03	0.02±0.003	0.02±0.006	0.32±0.22	0.04±0.01	0.08±0.02
	Polluted	1.24±0.34	0.15±0.02	0.03±0.009	0.01±0.005	0.53±0.19	0.07±0.02	0.06±0.01

The concentration of lead in the leaves of nine plant species was assessed at both a control and a polluted site (Table 2). The results revealed species-specific variations in Pb uptake. At the control site, Pb concentrations ranged from 0.30 ± 0.28 mg/kg (*A. heterophyllus*) to 0.56 ± 0.23 mg/kg (*F. benghalensis*), while at the polluted site, concentrations varied between 0.25 ± 0.19 mg/kg (*P. longifolia*) and 0.62 ± 0.23 mg/kg (*S. cumini*). Notably, an increase in Pb concentration at the polluted site compared to the control was observed in *A. heterophyllus*, *F. religiosa*, *M. elengi*, *S. cumini*, *T. arjuna*, and *T. catappa*. Conversely, *F. benghalensis*, *P. longifolia*, and *S. mahagoni* exhibited reduced Pb accumulation at the polluted site. The concentration of Ni in leaf tissues of nine urban tree species was also analyzed at both control and polluted sites (Table 2). At the control site, Ni concentrations ranged from 0.04 to 0.09 mg/kg, while values at the polluted site ranged from 0.01 to 0.07 mg/kg. The highest mean Ni level at the control site was recorded in *M. elengi* (0.09±0.03 mg/kg), whereas the lowest value was observed in *T. catappa* (0.04±0.01 mg/kg). Notably, *T. catappa* and *M. elengi* also showed relatively higher Ni concentrations at the polluted site (0.07±0.02 mg/kg for both species). The concentration of Cr in the leaf tissues of the studied tree species was also shown in Table 2. Across all species, Cr levels ranged from 0.08 to 0.12 mg/kg at the control site and from 0.04 to 0.09 mg/kg at the polluted site. Interestingly, Cr accumulation did not follow a consistent increasing trend at the polluted site, as might be expected under elevated pollution load. Several species, such as *M. elengi*, *S. cumini*, *T. arjuna*, and *T. catappa* exhibited lower mean Cr content at the polluted site than the control site. Among the studied species, *F. religiosa* had the highest Cr accumulation at the control site (0.12±0.05 mg/kg), while *M. elengi* showed the lowest concentration at the polluted site (0.04±0.02 mg/kg).

3.2. Soil properties

Soil parameters revealed distinct differences between the control and polluted sites (Table 3). P concentration was slightly higher in the polluted site (2.42±0.23 mg/kg) compared to the control site (2.17±0.24 mg/kg). Similarly, Zn levels were notably elevated in the polluted site (0.19±0.04 mg/kg) compared to the control site (0.13±0.02 mg/kg). Copper concentrations also showed an increase at the polluted site (0.05±0.012 mg/kg) versus the control site (0.03±0.005 mg/kg). Cobalt levels were marginally higher in the polluted site (0.02±0 mg/kg) than in the control site (0.018±0.003 mg/kg), and lead concentrations were slightly increased in the polluted site (0.32±0.02 mg/kg) compared to the control site (0.29±0.03 mg/kg). In contrast, nickel content was very similar between the polluted site (0.048±0.009 mg/kg) and the control site (0.046±0.008 mg/kg). Interestingly, chromium content was slightly lower in the polluted site (0.15±0.01mg/kg) compared to the control site (0.16±0.012 mg/kg). Overall, the majority of the analyzed parameters, specifically P, Zn, Cu, Co, and Pb, exhibited higher concentrations in the polluted site relative to the control site, suggesting the presence of pollution.

Table 3. Soil parameters from control and polluted sites in the study areas.

Parameters	Control site	Polluted site
P (mg/kg)	2.17±0.24	2.42±0.23
Zn (mg/kg)	0.13±0.02	0.19±0.04
Cu (mg/kg)	0.03±0.005	0.05±0.012
Co (mg/kg)	0.018±0.003	0.02±0
Pb (mg/kg)	0.29±0.03	0.32±0.02
Ni (mg/kg)	0.046±0.008	0.048±0.009
Cr (mg/kg)	0.16±0.012	0.15±0.01

3.3. Bioconcentration of phosphorus and heavy metals in plant species

The bioconcentration factor (BCF) values of seven elements such as P, Zn, Cu, Co, Pb, Ni, and Cr varied among the nine studied plant species and between the control and polluted sites, reflecting species-specific and metal-specific responses to urban pollution (Table 4). For phosphorus (P), most species showed lower BCFs at the polluted site, suggesting a decline in P uptake efficiency under stress. Notably, *F. religiosa* (0.60 to 0.10) and *T. arjuna* (0.37 to 0.13) showed substantial reductions. Zinc BCFs also declined in several species, such as *A. heterophyllus* (0.85 to 0.24) and *T. catappa* (1.23 to 0.79), though *F. religiosa* demonstrated a slight increase (0.38 to 0.47). For copper, BCFs generally decreased at polluted sites, except *M. elengi*, which showed a marked increase (0.33 to 0.80), indicating enhanced Cu accumulation. Cobalt BCFs mostly declined from a baseline of 1.11 at control sites to 0.5 or 1.0 at polluted sites, though in species where control BCFs were initially lower (0.56), values tended to increase at the polluted site, indicating variable species-specific uptake behavior (Table

4). Lead showed mixed patterns; for example, *F. benghalensis* exhibited a decrease (1.93 to 1.03), while *S. cumini* increased its Pb accumulation capacity (1.17 to 1.94). For nickel, BCFs mostly decreased under polluted conditions, such as in *A. heterophyllus* (1.74 to 0.42), while *T. catappa* showed an opposite trend (0.87 to 1.46). Chromium BCFs remained relatively stable or showed slight reductions across most species (Table 4). These patterns suggest that metal accumulation in urban tree species is not only influenced by pollution levels but also by intrinsic species traits, highlighting their differential capacity to tolerate or accumulate specific metals under environmental stress.

Table 4. Bioconcentration factor of phosphorus and heavy metals in leaf tissues of nine urban tree species from control and polluted sites in Dhaka city.

Species	Site	P	Zn	Cu	Co	Pb	Ni	Cr
Artocarpus heterophyllus	Control	0.53	0.85	0.33	1.11	1.03	1.74	0.56
	Polluted	0.24	0.47	0.2	0.5	1.38	0.42	0.53
Ficus benghalensis	Control	0.30	0.46	0.33	0.56	1.93	1.09	0.63
	Polluted	0.26	0.32	0.2	1	1.03	0.83	0.53
Ficus religiosa	Control	0.60	0.38	0.33	0.56	1.14	1.09	0.75
	Polluted	0.10	0.47	0.4	1	1.59	0.83	0.53
Mimusops elengi	Control	0.14	0.23	0.33	1.11	1.34	1.96	0.56
	Polluted	0.19	0.21	0.8	1	1.53	1.46	0.27
Polialthia longifolia	Control	1.16	0.38	0.67	0.56	1.59	1.09	0.56
	Polluted	0.26	0.37	0.2	1	0.78	1.04	0.6
Sizium cumini	Control	0.19	0.23	0.33	1.11	1.17	1.3	0.63
	Polluted	0.19	0.21	0.2	0.5	1.94	0.21	0.4
Swietenia mahagoni	Control	0.23	0.38	0.33	0.56	1.69	1.09	0.63
	Polluted	0.20	0.21	0.2	1	1.16	0.63	0.6
Terminalia arjuna	Control	0.37	0.92	0.33	1.11	1.17	1.3	0.56
	Polluted	0.13	0.74	0.4	1	1.47	0.42	0.4
Terminalia catappa	Control	0.53	1.23	0.67	1.11	1.1	0.87	0.5
	Polluted	0.51	0.79	0.6	0.5	1.66	1.46	0.4

3.4. Pearson correlation

The Pearson correlation analysis (Figure 1) reveals intricate associations between leaf phosphorus (P) and selected heavy metals (Zn, Cu, Co, Pb, Ni, Cr) in samples from the control urban site in Dhaka. Phosphorus exhibited generally weak and statistically non-significant correlations with all measured metals, with the highest negative relationship observed with nickel ($r = -0.25$). Zinc demonstrated a moderate positive correlation with copper and a weaker association with cobalt, indicating potential co-accumulation patterns. Copper, in turn, showed a strong association with Zn, but was negatively correlated with Co ($r = -0.37$) and only weakly related to the other metals. A notable finding was the strong and highly significant inverse correlation between Co and lead, suggesting possible antagonistic uptake mechanisms. Additionally, Co was negatively correlated with Ni. Although Pb showed this strong negative interaction with Co, it exhibited moderate, non-significant positive correlations with both Cu and Ni. Among all pairs, Ni and chromium (Cr) displayed the strongest positive association ($r = 0.58$, $p < 0.001$), which may point to a shared environmental source or similar uptake mechanisms. Other correlations involving Cr were generally weak and non-significant. These results suggest subtle but ecologically relevant interactions among trace metals in plant tissues, even in urban environments considered relatively unpolluted.

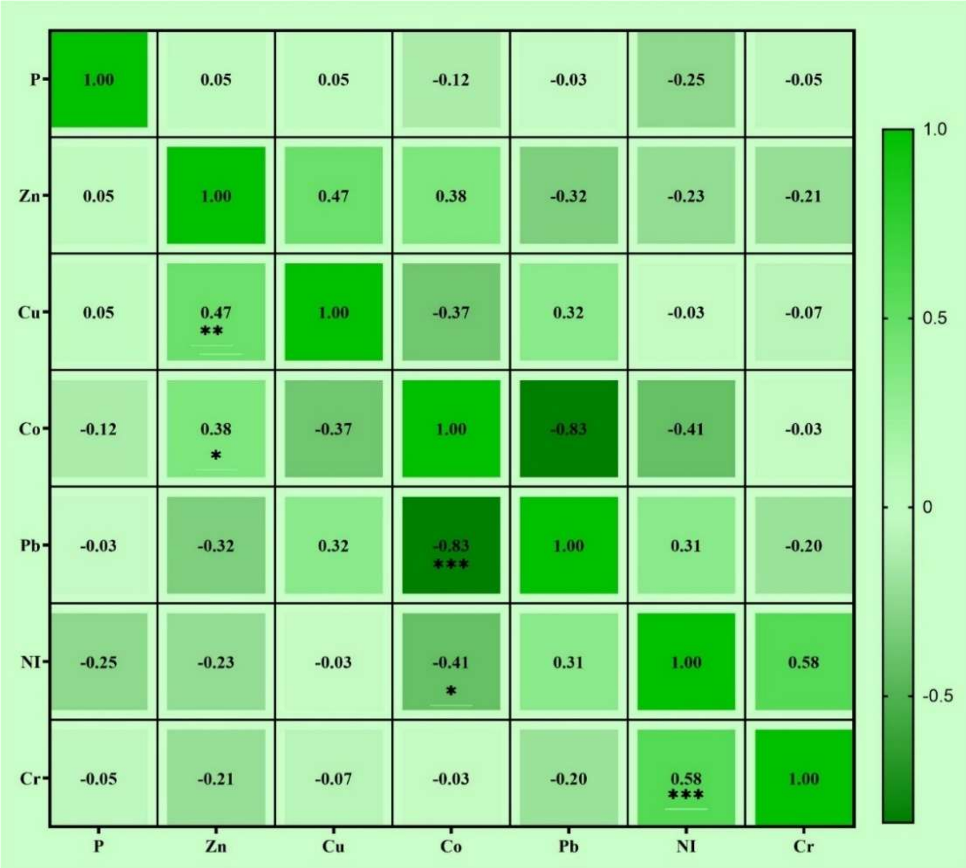

Figure 1. Pearson correlation matrices of leaf phosphorus and heavy metals (Zn, Cu, Co, Pb, Ni, Cr) from the control site in Dhaka city.

The Pearson correlation matrix (Figure 2) revealed distinct patterns of association among leaf phosphorus and heavy metal concentrations in tree species from the polluted urban environments of Dhaka. Notably, significant negative correlations were observed between cobalt and lead ($r = -0.86$, ***$p < 0.001$) and between chromium and lead ($r = -0.60$, ***$p < 0.001$), suggesting antagonistic interactions. Cr also showed a significant positive correlation with Co (0.52*), whereas Cu was moderately negatively correlated with Cr ($r = -0.45$*). The majority of correlations between phosphorus and heavy metals were weak and statistically non-significant, except for a weak positive correlation with Ni. These findings indicate a heterogeneous pattern of elemental interactions in leaf tissues, possibly reflecting species-specific uptake, translocation, and detoxification strategies under polluted conditions.

3.5. Principal Component Analysis (PCA)

PCA was performed to assess the multivariate distribution patterns of leaf phosphorus and heavy metal contents across control and polluted urban sites in Dhaka city. The first two principal components (PC1 and PC2) cumulatively explained 53.61% of the total variance, with PC1 contributing 31.01% and PC2 accounting for 22.60% (Figure 3). The PCA score plot revealed a clear spatial separation between the control and polluted sites along both principal components. Leaf samples from the control group were positioned in the positive quadrant of PC2 and the negative quadrant of PC1, whereas those from polluted sites clustered in the lower right quadrant, exhibiting negative PC2 and positive PC1 scores (Figure 3). The non-overlapping error bars around the group centroids further confirm a statistically meaningful differentiation in elemental composition between the two site types.

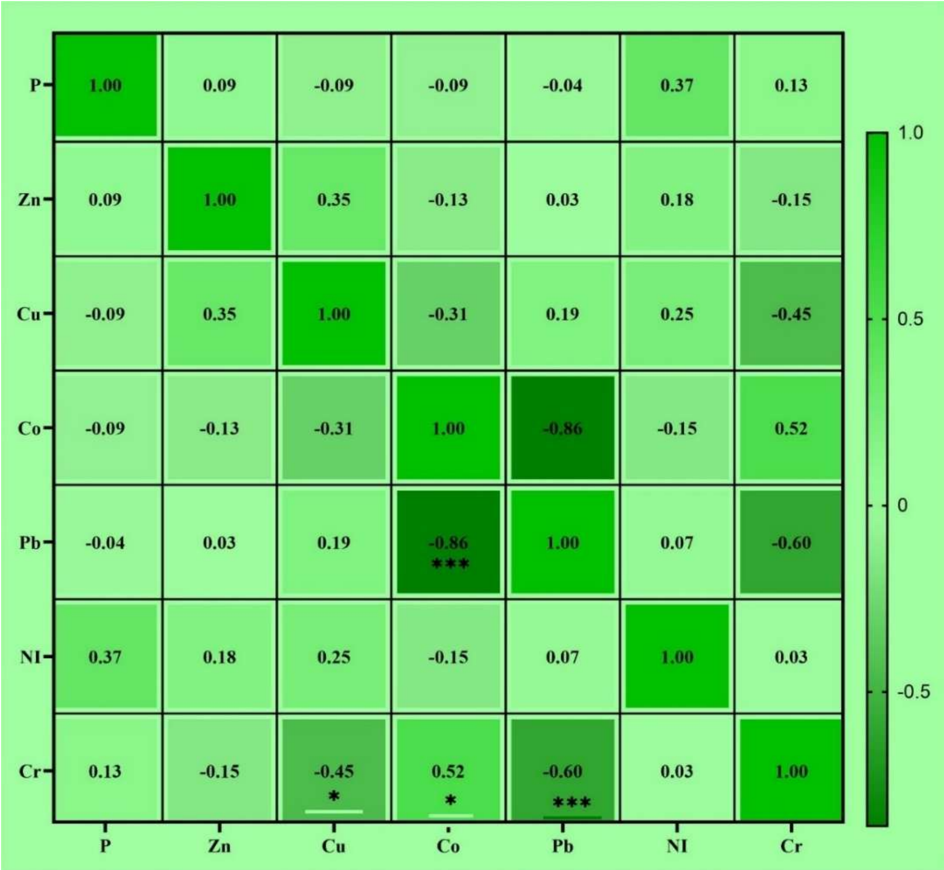

Figure 2. Pearson correlation matrices of leaf phosphorus and heavy metals (Zn, Cu, Co, Pb, Ni, Cr) from the polluted site in the city of Dhaka.

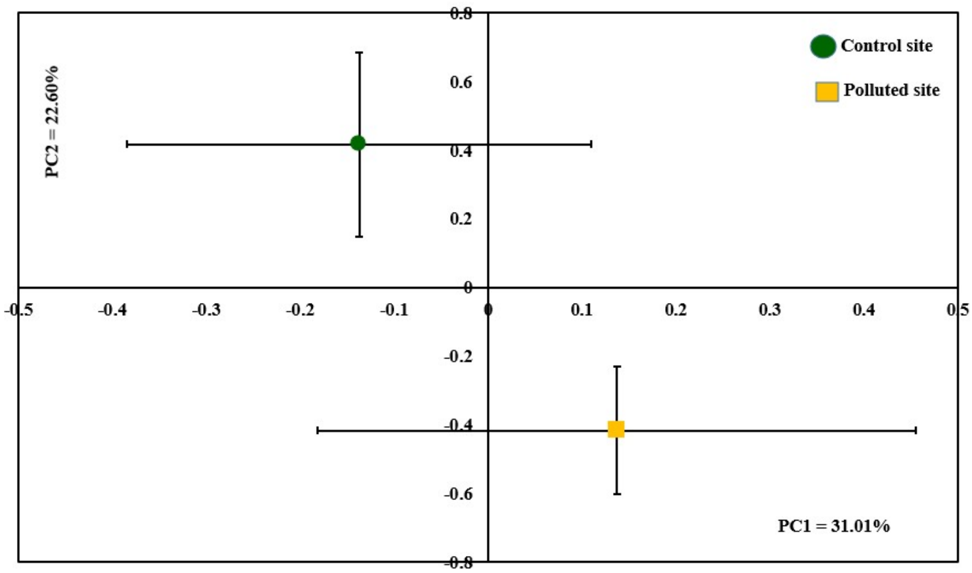

Figure 3. Principal Component Analysis (PCA) showing clear spatial separation and compositional differences between the two environments.

The PCA biplot (Figure 4) showed the interrelationships among the P and six elements (Zn, Cu, Co, Pb, Ni, and Cr) across urban tree species.PC1, which explained the largest proportion of variance (31.01%), was positively associated with Pb, Ni, and Cu, indicating that these metals share a common pattern of accumulation among certain species. In contrast, Zn and Co were negatively associated with PC1, suggesting an inverse relationship with the aforementioned metals. PC2 was mainly influenced by Cr and Ni in the positive direction and Zn in the negative direction. P was positioned near the origin, implying a relatively weak influence on the overall variation and limited correlation with the heavy metals analyzed. Notably, Pb and Ni vectors were closely aligned, suggesting a strong positive correlation between their accumulation patterns. These results suggest that urban tree species differ in their ability to accumulate specific heavy metals and that certain metals, particularly Pb, Ni, and Cu, may share similar uptake mechanisms or environmental drivers, while others like Co and Zn may be regulated differently.

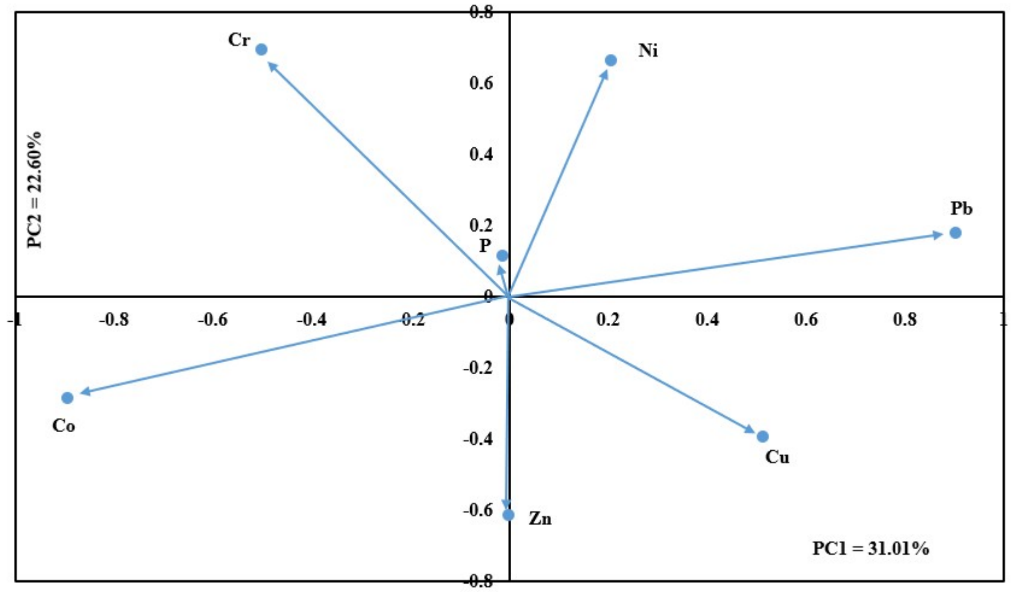

Figure 4. Principal component analysis (PCA) showed the relationships among phosphorus and heavy metals (Pb, Ni, Cu, Zn, Cr, Co) in leaf samples collected from both control and polluted sites in Dhaka city.

4. DISCUSSION

The present study provides compelling evidence of species-specific and site-dependent variations in leaf phosphorus and heavy metal concentrations among dominant urban tree species in Dhaka. Differences observed in element accumulation patterns between control and polluted sites emphasize the complex interplay of environmental exposure and plant physiological responses under urban pollution stress.

4.1. Impact of urban pollution on leaf elemental composition

Phosphorus concentrations showed a general declining trend at polluted sites for most species, notably in *F. religiosa*, *P. longifolia*, *A. heterophyllus* and *T. arjuna*, indicating potential interference in phosphorus uptake under pollution stress. Reduced P bioavailability in polluted environments may be linked to heavy metal-induced disruptions in root metabolism and membrane permeability [14,19,32-33]. However, a few species such as *M. elengi* and *S. cumini* showed slightly elevated P content at the polluted site, possibly due to efficient nutrient acquisition mechanisms or root-microbe interactions that mitigate metal stress [32]. The accumulation of zinc displayed pronounced interspecific variation, with *T. catappa* and *T. arjuna* exhibiting consistently higher Zn concentrations. Elevated Zn in *F. religiosa* under polluted conditions suggests adaptive bioaccumulation, consistent with previous studies reporting Zn-induced stress tolerance through increased antioxidant defense [7,34-73]. Copper, cobalt, and nickel concentrations remained relatively stable across sites for most species, except for a few species-specific deviations. The limited variation in Cu could be attributed to its tight homeostatic regulation in plants due to its dual role as a micronutrient and a toxicant at high levels [37-39]. Notably, *M. elengi* showed increased Cu accumulation at the polluted site, further reflected in its enhanced Cu bioconcentration factor (BCF), suggesting active uptake under stress conditions. Lead accumulation patterns varied across species, with *S. cumini*, *T. arjuna*, and *T. catappa* showing increased Pb content at the polluted site. This aligns with previous reports where urban trees demonstrated enhanced Pb uptake in roadside or industrial zones [40-42]. Conversely, some species such as *F. benghalensis* and *S. mahagoni* showed reduced Pb under pollution, indicating either lower root uptake or effective exclusion mechanisms. Chromium contents were generally lower at the polluted site, contrary to typical trends under anthropogenic inputs. Species such as *M. elengi* and *S. cumini* demonstrated reduced Cr content under pollution, possibly due to Cr-induced oxidative stress impairing transport systems [43-45]. These results reflect complex metal-specific and species-specific physiological responses to urban environmental stress.

4.2. Bioconcentration patterns and phytoremediation potential

The bioconcentration factor data further underscore the differential metal accumulation capacities of the studied species. A marked reduction in P and Zn BCFs under pollution was evident in most species, highlighting possible competitive inhibition by other metals or altered soil chemistry. Interestingly, *F. religiosa* and *T. arjuna* showed steep declines in P BCFs, suggesting their sensitivity to environmental phosphorus limitation under stress. Conversely, species like *S. cumini* exhibited increased Pb BCFs under polluted conditions (1.17 to 1.94), suggesting potential for phytostabilization. Similarly, *T. catappa* demonstrated a substantial increase in Ni BCF (0.87 to 1.46), indicating its capacity to accumulate Ni even under elevated metal loads, making it a candidate for Ni phytoremediation [7,22,46-47]. Enhanced Cu accumulation in *M. elengi* also reinforces its tolerance and possible application in Cu-contaminated areas. These patterns affirm that bioconcentration is not solely governed by soil metal content but is a complex function of species traits, physiological plasticity, and rhizosphere interactions [47]. The variability in Co and Ni BCFs particularly reflects the influence of metal speciation, root exudates, and microbial activity [18,49-50].

4.3. Correlation and multivariate insights into elemental interactions

Pearson correlation analysis revealed subtle but ecologically significant interactions among P and heavy metals. In control site samples, the weak associations between P and other metals suggest minimal interference in elemental uptake under low-stress conditions. The strong positive correlation between Ni and Cr may reflect shared sources or co-transport pathways [51-53]. At the polluted site, a significantly negative relationship between Pb and both Co and Cr implies antagonistic uptake or competition at root-level transporters [10,53]. PCA provided additional evidence of divergence between control and polluted environments. The distinct clustering of samples and loadings of Pb, Ni, and Cu on PC1 suggest these metals are key contributors to pollution-induced elemental shifts. The alignment of Pb and Ni vectors in the biplot further underscores their correlated uptake patterns under stress [6,54-55]. The weak influence of P on the principal components suggests that its accumulation is less affected by coexisting metal concentrations and more by plant nutrient status and soil phosphorus chemistry.

4.4. Implications for urban ecology and tree selection

Moreover, the contrasting uptake behavior across tree species highlights the need for strategic species selection for urban greening and phytoremediation. *S. cumini*, *T. catappa*, and *M. elengi* emerged as promising candidates for Pb, Ni, and Cu accumulation, respectively, suggesting their utility in pollution-buffering green infrastructures. On the other hand, sensitive species such as *F. religiosa* and *T. arjuna*, which exhibit reduced nutrient and metal uptake under pollution, may require supportive soil amendments for urban planting. These findings align with recent urban ecology frameworks emphasizing functional trait-based species selection to optimize ecosystem services under environmental stress [56-58]. Incorporating heavy metal uptake traits into urban tree management can enhance both environmental remediation and human health outcomes in polluted megacities like Dhaka.

5. CONCLUSION

This study highlights distinct species-specific and site-dependent variations in phosphorus and heavy metal accumulation among urban trees in Dhaka. Decline in leaf P, Ni, and Cr under pollution stress reflects disruptions in nutrient uptake, while bioconcentration patterns reveal that metal accumulation is influenced by both species traits and environmental conditions. *S. cumini*, *T. catappa*, and *M. elengi* showed strong phytoremediation potential, whereas *F. religiosa* and *T. arjuna* appeared more sensitive to pollution. These findings offer practical guidance for selecting resilient species to enhance urban green infrastructure and mitigate environmental pollution.

Author Contributions: MAK: Concept, Sampling and data collection, writing original draft, review and editing, Resources, Methodology. SA: Sampling and data collection, Methodology, Formal analysis, Software. MAR: Formal analysis, Writing – review & editing, Writing – original draft. MZH: Methodology, Formal analysis, Writing original draft. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest: The authors declare no potential conflict of interest.

Source of Funding: This work has not received any financial support.

Ethical Approval: Not required for this study.

Acknowledgements: The authors are grateful to the Centre for Advanced Studies and Research in Biological Sciences, University of Dhaka, for providing partial funding to conduct this research work in 2023-2024.

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