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Determination Of Potentially Toxic Elements In Moss Bags Exposed To Urban Atmospheric Deposition: A Case Study Of Çanakkale, Türkiye

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Abstract: This study aims to evaluate seasonal atmospheric PTE accumulation at four urban sampling stations in Çanakkale city centre using the Moss Bag technique. Samples of the *Alleniella complanata* species, used as a bioindicator, were exposed for 45 days at four stations at seasonal intervals. Following exposure, the PTE accumulated in the bags was analysed using an ICP-OES instrument and evaluated using the CF, PLI, and RAF pollution indices. Seasonal differences were identified using Friedman's test, relationships between metals were identified using Spearman's correlation test, and common variance structures and possible source patterns were identified using PCA. The results showed that PTE concentrations after exposure significantly exceeded the initial levels and varied depending on the metal type, seasonal periods, and sampling points. The Friedman test showed that Cr, Zn, Pb, and As metals showed statistically significant differences between seasons, while no significant seasonal change was found for Cu. $RAF > 1$ values indicated that *Alleniella complanata* has effective bioindicator potential. CF values generally indicated 'medium to high contamination ($1 \leq CF < 3$)' levels. $PLI > 1$ values revealed the seasonal cumulative metal load. Spearman correlation identified a significant negative relationship between Cr–Pb and significant positive relationships between Cr–As and Pb–Cu pairs. Two PCA components explained 83.9% of the total variance; PC1 showed a high positive loading with As and Cr, while PC2 showed a high positive loading with Zn and Cu, indicating a common anthropogenic source for these metals.

Keywords: Potentially toxic elements (PTEs), Atmospheric deposition, Moss bag technique, Çanakkale

1.Introduction

Potential toxic elements (PTEs), which naturally occur in inactive mineral forms within the Earth's crust (Rahman and Singh, 2019), become biologically available as a result of anthropogenic activities, significantly altering the natural

30 biogeochemical cycles of ecosystems (Bargagli et al., 2002; Jaishankar et al., 2014). In particular, increased use of metals
31 and metalloids, coupled with urbanisation, industrial processes, agricultural activities, and technological developments,
32 leads to toxic concentrations of PTEs in environmental components (air, water, soil, and biota); creating persistent and
33 difficult-to-reverse effects on ecosystems (Nagajyoti et al., 2010; Shahid et al., 2017). According to ATSDR (2024)
34 toxicological profiles, the most environmentally critical PTE are arsenic (1), lead (2), mercury (3), cadmium (7), zinc (77),
35 chromium (78) and copper (120). The persistence, high toxicity, and bioaccumulation potential of these elements have
36 made them serious environmental and ecological risk factors on a global scale (Järup, 2003; Wu et al., 2014; Engwa et al.,
37 2019; Briffa et al., 2020).

38 The chemical composition of atmospheric deposition is of great importance in terms of the spatial distribution of
39 pollutants, the identification of potential sources, and the assessment of their effects at different geographical scales.
40 However, traditional methods for directly monitoring atmospheric deposition provide limited data due to their high cost
41 and inability to adequately reflect cumulative metal deposition. In this context, biomonitoring is an effective environmental
42 assessment method that allows for low-cost, high-density sampling over large spatial and temporal scales through the use
43 of bioindicator organisms (Wolterbeek, 2002; Szczepaniak and Biziuk, 2003; Capozzi et al., 2016). Bryophytes, in
44 particular, can directly adsorb pollutants deposited from the atmosphere due to their lack of structural components such as
45 roots, vascular tissue, and cuticle, and can accumulate many potentially toxic elements in their bodies through both dry and
46 wet deposition (González and Pokrovsky, 2014; Bargagli et al., 2016; Mahapatra et al., 2019). Various studies have
47 demonstrated that mosses can be used as reliable bioindicators for assessing atmospheric exposure through metal
48 accumulation (Harmens et al., 2008; Aničić et al., 2007; Harmens et al., 2010; Jiang et al., 2018; Lazo et al., 2019;
49 Chaligava et al., 2021; Vergel et al., 2022; Lv et al., 2023; Yavuz et al., 2024; Isinkaralar et al., 2024; Jafarova et al., 2025).

50 In urban and industrial areas where bryophyte cover is insufficient or heterogeneously distributed, the Moss bag
51 technique, a transplant-based active monitoring method, has been successfully applied as an effective biological monitoring
52 technique to assess the bioaccumulation of atmospheric pollutants (Fernández et al., 2004; Aničić et al., 2007; Ares et al.,
53 2012; Capozzi et al., 2016; Vuković et al., 2017; Hu et al., 2018; Shvetsova et al., 2019; Ștefănuț et al., 2019; Sergeeva et
54 al., 2021; Mao et al., 2022; Świsłowski et al., 2022; Urošević et al., 2023; Zinicovscaia et al., 2024; Zinicovscaia et al.,
55 2025).

56 In this study, the seasonal atmospheric accumulation of PTE was assessed using the moss bag technique at four
57 urban stations located in the city centre of Çanakkale. Furthermore, the moss species *Alleniella complanata* (Hedw.) was
58 used for the first time in biomonitoring studies, contributing to the existing bioindicator literature and demonstrating the
59 potential of this species as a bioindicator for urban PTE emissions. The originality of the research lies in the simultaneous

60 assessment of seasonal changes, pollution indices, inter-element relationships, and potential emission sources using the
61 moss bag technique, which has limited application in Turkey.

62 **2.Materials and Methods**

63 **2.1.Study Area**

64 This study was conducted in the city centre of Çanakkale, located on the southern shore of the Dardanelles Strait
65 in northwestern Turkey (25°40'-27°30' N - 39°27'-40°45' E). Çanakkale province has a total area of 9,933 km² and a
66 population of approximately 568,966 as of 2024 (TÜİK, 2025). Çanakkale has a Csa-type Mediterranean climate according
67 to the Köppen–Geiger classification; summers are hot and dry, while winters are mild and rainy. The average annual
68 temperature is 15.2 °C, the average annual rainfall is 623.2 mm, and the average number of rainy days per year is 83.9.
69 The average annual sunshine duration is measured at 7.2 hours (Ministry of Environment, Urbanisation and Climate
70 Change, 2025). The average wind speed in Çanakkale is 3.9 m/s, and the prevailing wind direction is north–northeast (N–
71 NE). The Dardanelles Strait and its surroundings are characterised geomorphologically by alluvial valley floors, deltas,
72 and bays opening onto the sea along the coast. While the eastern coast features ridges and hills with elevations of 100–400
73 m, the western coast has a hilly topography cut by deep valleys (Doğaner, 1994). The geological structure of the region is
74 complex, consisting of a mixture of metamorphic, igneous and sedimentary rocks.

75 Algae biomonitoring was conducted at four sampling points with different urban land use characteristics (Table 1
76 & Figure 1b).

77 **Table 1.** Geographical coordinates and environmental characteristics of monitoring sites

78 The locations identified in Table 1 were designated as the study sites. Samples were systematically collected from
79 the areas shown in Figure 1, and all required materials were obtained from these same locations. Following the completion
80 of pre-analytical preparation procedures, the study advanced to the experimental and analytical stages.

81 **Figure 1.** (a) Location of the study area within Çanakkale Province, (b) Background area (Ayazma Pınarı Nature Park),
82 (c) Sampling sites.

83 **2.2. Sampling Design**

84 Ayazma Pınarı Nature Park (Bayramiç, Çanakkale) (39°44'43"N, 26°50'35"E), located at the foot of Kazdağı,
85 approximately 60 kilometres from the city centre and at an altitude of approximately 490 metres above sea level, where
86 PTE accumulation is assumed to be low Samples of the moss species *Alleniella complanata* (Hedw.) were collected (Figure

2). *A. complanata* (Hedw.) is a species belonging to the subphylum Bryophyta, class Bryopsida, order Hypnales, and family Neckeraceae.

In this study, the process of preparing moss bags was carried out according to the method described by Ares et al. (2012). In order to obtain samples with homogeneous initial characteristics (Giordano et al., 2009), the green apical parts of the mosses were separated from the brown tissue; soil particles, plant debris and epiphytes were removed. The samples were washed three times with deionised water to completely remove surface debris. They were then air-dried under dim light to remove any excess moisture remaining on them. Distinguishing between anthropogenic inputs and the natural background is important for the accurate assessment of contamination at a site (Villares et al., 2002); in this study, unexposed moss material was used to represent the background level.

The bag dimensions were determined to provide an approximate ratio of 30 mg cm⁻² of algae dry weight/surface area, as proposed by Ares et al. (2012). The algae were placed in nylon nets measuring 10×10 cm with a pore size of 1 mm² to form spherical bags approximately 3–4 cm in diameter. The prepared moss bags were fixed to lighting poles approximately 2 m above the ground. Four Moss bag materials (Ares et al., 2012) were placed at each sampling point for a 45-day exposure period. At the end of the exposure period, the materials were collected and replaced with new samples. In order to evaluate seasonal variability, sampling was conducted between October 2023 and August 2024 to cover four different seasons. The sampling periods covered October–November (autumn), January–February (winter), April–May (spring) and July–August (summer), respectively.

2.3. Chemical Analysis

The digestion process of the moss samples was carried out using the Milestone Start-D microwave digestion system; the temperature was raised to 110 °C within 15 minutes and maintained at this temperature for 15 minutes. Subsequently, the concentrations of Pb, Cd, Zn, Hg, As, Cu, and Cr in the dissolved samples were analysed using an inductively coupled plasma optical emission spectrometer (ICP-OES, Perkin Elmer Optima 8000). The limits of detection (LOD) for ICP-OES were Cd 5 ppb, Pb 10 ppb, Cr 5 ppb, Cu 5 ppb, Hg 1 ppb, As 5 ppb, and Zn 5 ppb, respectively. The measurement wavelengths for each element are 228.8 nm (Cd), 220.3 nm (Pb), 205.5 nm (Cr), 324.7 nm (Cu), 253.6 nm (Hg), 188.9 nm (As), and 213.8 nm (Zn). Hg and Cd were excluded from the assessment scope as their concentrations were below the detection limits. Calibration was performed using multi-element standard solutions, and the determination coefficients (R²) for the calibration curves ranged from 0.993 to 0.999, confirming the high accuracy and repeatability of the measurements.

2.4.Data Processing

Various environmental indices were used in the moss samples to assess the level of contamination and environmental risk. The Relative Accumulation Factor (RAF) was calculated to evaluate the element accumulation level of the *A. Complanata* species. RAF is obtained by dividing the difference between the moss content of each element after exposure ($C_{exposure}$) and the element content before exposure ($C_{initial}$) by the initial level:

$$RAF = \frac{(C_{exposure} - C_{initial})}{C_{initial}}$$

According to RAF values, $0.5 < RAF < 1$ indicates slight element accumulation and $RAF > 1$ indicates significant element accumulation (Vuković et al., 2015).

Contamination (CF) was used to determine the level of contamination caused by PTE in the samples. CF is found as the ratio of element concentrations in the exposure (C_{plant}) and background ($C_{background}$) samples.

$$CF = \frac{C_{plant}}{C_{background}}$$

Contamination levels (Hakanson, 1980) are classified as low contamination ($CF < 1$), moderate contamination ($1 \leq CF < 3$), high contamination ($3 \leq CF < 6$) and very high contamination ($CF > 6$).

The Pollution Load Index (PLI) is calculated based on the geometric mean of the CFs to determine the total pollution load of PTE at each sampling point (Tomlinson et al., 1980):

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \dots \times CF_n}$$

PLI values are classified according to the degree of pollution as unpolluted ($PLI \leq 1$), unpolluted to moderately polluted ($1 < PLI \leq 2$), moderately polluted ($2 < PLI \leq 3$), moderately to heavily polluted ($3 < PLI \leq 4$), heavily polluted ($4 < PLI \leq 5$), and extremely polluted ($PLI > 5$) (Zhang et al., 2012).

2.5.Statistical Analysis

In the study, descriptive statistics were calculated for PTE concentrations. The Kolmogorov–Smirnov and Shapiro–Wilk tests were applied to assess the normality of the data, and $p > 0.05$ was considered a criterion satisfying the assumption of normal distribution. Correlation analysis was performed to determine the relationships between metals. Since the data did not meet the assumption of normal distribution and the sample size was limited in each season ($n = 4$), Spearman's rank correlation coefficient was preferred ($p < 0.05$) due to the low reliability of parametric tests.

The distribution between seasons was evaluated using the non-parametric Friedman test due to the small sample size and violation of the normality assumption. The Friedman test is a ranking-based method used to compare three or more related groups with repeated measurements. The statistical significance level was set at $p < 0.05$. To evaluate seasonal

143 accumulation patterns, the mean rank values for each metal across seasons were reported. For the Friedman test, net
144 accumulation values calculated by subtracting background values from post-exposure measured concentrations were used.

145 Principal Component Analysis (PCA) was applied to analyse the multivariate structure in the dataset and identify
146 potential sources of PTE. Prior to PCA, the data were standardised using z-score normalisation. The suitability of the
147 dataset for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) sample adequacy test (>0.50) and Bartlett's sphericity
148 test ($p<0.05$). The selection of components was based on factors above eigenvalue 1 (Kaiser, 1960), and components
149 explaining more than 70% of the total variance were considered (Jolliffe and Cadima, 2016). In the preliminary analyses,
150 the Sample Adequacy Measure (MSA) value for the Pb variable in the Anti-image Correlation matrix was found to be
151 0.318, which is below the threshold of >0.50 . Variables with MSA values below 0.50 are not suitable for factor analysis
152 and reduce the reliability of the analysis (Jolliffe and Cadima, 2016). Therefore, the Pb variable was excluded from the
153 PCA process, limiting the analysis to Cr, Zn, Cu, and As metals. All analyses were performed using IBM SPSS Statistics
154 21 software.

155 3.Results and Discussion

156 3.1. Element accumulation in exposed moss samples

157 Seasonal background values are presented in Table 2, while descriptive statistics for PTE concentrations in
158 exposed seaweed bags are presented in Table 3. The results show that the PTE concentrations detected in the exposed *A.*
159 *complanata* moss bags for the majority of the elements studied have increased significantly compared to the initial element
160 concentrations. This indicates that atmospheric metals accumulate in the moss during the active biomonitoring process. In
161 contrast, for Pb, As, and Cr elements, concentrations close to or below background levels were detected in some seasons
162 and in a limited number of samples. The negative net accumulation values observed for As, particularly in the summer
163 season, are consistent with the findings of Zechmeister et al. (2003) and Rivera et al. (2011), who reported that As can be
164 weakly retained in the moss tissue of some moss species and can be released during the exposure period.

165 The metal contents determined in the background samples were relatively high compared to the background levels
166 reported for different moss species (Anicic et al., 2009a; Iodice et al., 2016; Shvetsova et al., 2019; Zinicovscaia et al.,
167 2024; Zinicovscaia et al., 2025). This may be related to the sampling area's proximity to volcanic–sedimentary geological
168 units rich in metallic mineralisation. Indeed, it has been reported that metal uptake by bryophytes is not limited to
169 atmospheric deposition but may also be sensitive to substrate-derived inputs under certain conditions (Szczepaniak and
170 Biziuk, 2003).

171 **Table 2.** Metal concentrations in seasonal background samples(mg/kg)

172 Overall, background samples (Table 2) showed relatively low and seasonally varying metal concentrations,
173 reflecting natural baseline conditions. In contrast, exposed moss samples (Table 3) exhibited markedly higher and more
174 variable metal levels across seasons, indicating a clear atmospheric input and demonstrating the species' capacity to capture
175 spatial-temporal fluctuations in PTE deposition.

176 **Table 3.** Metal concentrations in seasonal exposed moss samples(mg/kg)

177 The seasonal variation of metal accumulations was assessed using the Friedman test. The results showed
178 statistically significant differences between seasons for Cr, Zn, Pb and As metals (Cr: $p = 0.026$; Zn: $p = 0.044$; Pb: $p =$
179 0.013 ; As: $p = 0.044$), while the seasonal variation for Cu was not statistically significant ($p = 0.058$). Considering the
180 average rankings (Figure 2), it is observed that Cr and As accumulation is higher in autumn and winter seasons and lower
181 in spring and summer periods. The seasonal pattern for Zn was determined as autumn > winter $\approx$ spring > summer, while
182 Pb accumulation was found to be spring > autumn $\approx$ summer > winter. Although relatively higher average rankings were
183 obtained for Cu in spring and autumn, this trend is not statistically supported. The findings indicate that the metals examined
184 in the study exhibit distinct seasonal behaviour and that atmospheric metal accumulation is sensitive to seasonal conditions.
185 In contrast, the lack of significant seasonal variation in Cu suggests that this element may be associated with more stable
186 or continuous sources.

187 **Figure 2.** Mean rank values of metals according to Friedman test by season

188 It is often difficult to attribute trace elements to a specific source, and too much emphasis is placed on
189 anthropogenic sources. This is because many elements in the air have multiple sources, including industrial processes,
190 exhaust fumes, agriculture, erosion of asphalt or concrete roads, etc. (Ştefănuţ et al., 2019), and may also be of natural
191 origin (Di Palma et al., 2017). Urban environments, in particular, are under intense pressure from both stationary sources,
192 such as industrial facilities and residential heating, and mobile sources, such as motor vehicle traffic (Aničić et al., 2009b;
193 Sawidis et al., 2011). Findings reporting Zn, Cr, and Cu as dominant elements in moss bags collected at airports (Vuković
194 et al., 2017) and revealing that urban road dust is significantly contaminated, particularly with Cu, Cr, Zn, and Pb (Duong
195 and Lee, 2011; Adamiec et al., 2016) support that the metal accumulation levels in this study may be related to urban
196 activities, traffic, and industrial emissions.

197 Çanakkale province, with its dense urban life, mining, agriculture, and industrial activities, offers a rich variety of
198 sources for atmospheric metal accumulation. As emphasised by Acar (2006), the urban atmosphere is heavily impacted by
199 petroleum and coal-derived pollutants associated with fossil fuel use. Furthermore, the presence of metal pollution in the
200 Dardanelles Strait (Ilgar et al., 2024), the contribution of small-scale industrial areas to heavy metal pollution (Sungur et
201 al., 2019), and the exposure of rivers such as Sarıçay to various pollutant inputs from agricultural activities and industrial

202 facilities (Akbulut et al., 2010; Kaya et al., 2014; Akarsu et al., 2022; Varol and Tokath, 2024) and similar pollutant
203 accumulations have been detected in the sediments of four dams and two reservoirs (Canlı et al., 2023). Metal
204 accumulations have been observed in the ports of Kepez (Yılmaz and Sadıkoğlu, 2011) and Kilitbahir (Oran and Erginal,
205 2023). and the thermal power plant around Karabiga and other industrial facilities leaving traces of toxic metals in the
206 environmental media (Gümüş et al., 2025).

207 3.2. Relative Accumulation Factor (RAF)

208 Figure 3 presents the seasonal average RAF values. RAF values between 0.5 and 1 indicate a slight enrichment,
209 while $RAF > 1$ indicates a significant element accumulation. Due to the absence of a root system in the material used in
210 the moss bag technique and its direct exposure to atmospheric deposition, metal uptake occurs primarily through passive
211 adsorption and surface binding processes. Therefore, $RAF > 1$ values indicate that *A. complanata* effectively reflects
212 passive atmospheric PTE accumulation. Literature comparisons have limited interpretative power due to the considerable
213 variation in pre-exposure initial concentrations across different studies (Culicov et al., 2005).

214 In this study, RAF values generally showed accumulation of elements compared to the initial concentrations of
215 the algae. Negative RAF values were observed in some cases. Negative RAF values indicate that no accumulation occurred
216 in the exposed algae samples relative to the background level and that surface loss or removal occurred for the relevant
217 elements. Seasonal average RAF rankings were $Zn > As > Cr > Pb > Cu$ in autumn, $Cr > As > Cu > Zn > Pb$ in winter, Pb
218 $> Cu > Zn > As > Cr$ in spring, and $Pb > Cr > Zn > Cu > As$ in summer. This pattern indicates that PTE accumulation has
219 a distinct seasonal character and is sensitive to atmospheric transport–deposition processes. In particular, the attainment of
220 markedly high RAF values for Zn, Pb, As, Cu, and Cr during certain periods indicates that *A. complanata* possesses
221 effective bioindicator potential for these elements and that atmospheric particle dynamics and seasonal deposition processes
222 jointly shape accumulation.

223 **Figure 3.** Average RAF values for autumn, winter, spring and summer periods in *A. complanata* samples. The red line
224 indicates the ‘ $RAF = 1$ ’ threshold.

225 3.3.Environmental Pollution Indices

226 The contamination factor was calculated to assess pollution levels in the urban areas studied, and the CF values
227 for each station and season are presented in Table 1 using a colour-coded classification. In general, the exposure areas
228 showed moderate contamination ($1 \leq CF < 3$); however, values representing high ($3 \leq CF < 6$) and very high pollution (CF
229 > 6) levels were also observed at some stations (Table 4).

230 When examining seasonal average CF values, metals were ranked as follows during the autumn period: Zn (24.59)
231 > As (3.62) > Cr (3.17) > Cu (2.01) > Pb (1.55). In the winter period, the ranking was Cr (2.43) > As (2.30) > Cu (1.72) >
232 Zn (1.47) > Pb (0.76). In spring, the relative CF levels of metals were Pb (6.47) > Cu (3.63) > Zn (1.89) > As (1.30) > Cr
233 (1.13); while in summer, the order was Pb (3.52) > Cr (1.55) > Zn (1.42) > Cu (1.26) > As (0.93).

234 CF values showed significant variation at the element, station, and seasonal levels. When the seasonal pattern was
235 examined, it was observed that Cu, Pb, and As accumulation reached high levels in the spring–summer period, while Zn
236 and Cr accumulation reached high levels in the autumn–winter period. When the seasons were compared, the autumn
237 period stood out as the period with the highest CF levels recorded for most metals. In this study, Zn showed abnormally
238 high CF values. Abnormal CF values for Zn are also present in the literature; for example, Sergeeva et al. (2021) reported
239 a CF value of 20.4 for Zn in a heavy industrial area.

240 **Table 4.** Distribution of Seasonal CF Values (with Colour-Coded Classification)

241 The Pollution Load Index is an indicator that comprehensively reflects the cumulative effect of multiple metals in
242 the study area, and $PLI > 1$ values confirm the presence of regional metal pressure (Tomlinson et al., 1980). In this study,
243 a $PLI < 1$ value was obtained only at the Industry (S2) station during the winter period; the PLI remaining above 1 at all
244 other stations and periods revealed the presence of cumulative metal load throughout the year.

245 Based on PLI values, the fact that the site falls within the $1 < PLI \leq 2$ (uncontaminated–moderate) and $2 < PLI \leq$
246 3 (moderate) classes indicates that the study area is generally exposed to a moderate cumulative metal effect. The highest
247 PLI values (2.23–3.83) were observed at all stations during the autumn period. The results showed that the site exhibited
248 seasonal variability in terms of multiple metal load but remained above the reference level throughout the year.

249 **Table 5.** Seasonal PLI values

250 **3.4. Source identification using correlation and Principal Component Analysis (PCA)**

251 The distribution characteristics of seasonal measurement data for Cr, Zn, Cu, Pb and As metals were evaluated
252 using the Shapiro-Wilk test. Since the assumption of normal distribution was not met for some variables and the sample
253 size was small, a non-parametric approach was adopted in the analyses.

254 **Table 6.** Spearman Correlation coefficients (r) between potential toxic elements

255 According to the correlation analysis between metal accumulations, a positive and highly significant relationship
256 was found between Cr and As ($r = 0.724$, $p = 0.002$). A positive and statistically significant relationship was also observed
257 between Pb and Cu ($r = 0.597$, $p = 0.015$). The correlations obtained indicate that the seasonal accumulation of metals may
258 be influenced by similar environmental or anthropogenic factors. In contrast, a negative and statistically significant

relationship was found between Cr and Pb ($r = -0.570$, $p = 0.021$); this suggests that the two elements are controlled by different pollutant sources or are transported into the atmosphere through different transport and deposition dynamics.

The PCA analysis yielded two components with eigenvalues greater than 1. These two components explain 83.9% of the total variance, indicating that the components strongly represent the data set (Jolliffe and Cadima, 2016). The first component (PC1) explains 42.8% of the variance, while the second component (PC2) explains 41.1% (see Figure 4). This indicates that the variation in metals is grouped under the same component, reflecting possible common source effects.

PC1 showed high positive loadings for Cr (0.855) and As (0.929), indicating that this component is associated with a geo-anthropogenic contaminant source related to industrial emissions, coal combustion, and combustion processes. It has been noted that the source of Cr may be related to both geogenic and anthropogenic inputs (Urošević et al., 2023). The factorisation of Cr and As in the same component is consistent with patterns reported similarly in the literature (Aničić et al., 2009a; Zinicovscaia et al., 2021; Vergel et al., 2022; Zinicovscaia et al., 2024) and has been highlighted as indicating combined geogenic–anthropogenic sources. Furthermore, the significant positive relationship detected between Cr and As in the Spearman analysis statistically supports the PC1 component.

PC2 showed high positive loadings for Cu (0.900) and Zn (0.832), and this component was considered a factor associated with typical urban anthropogenic pressures—particularly traffic-related emissions, brake and tyre wear, and small-scale urban industrial activities. Furthermore, the positive and significant correlation observed between Pb and Cu in the study supported the possibility that these metals may be associated with traffic-related emissions in particular. The grouping of Cu and Zn in the same component has been similarly associated with traffic and urban activities in previous studies (Aničić et al., 2009a; Mao et al., 2022; Vergel et al., 2022; Zinicovscaia et al., 2024), and is consistent with the literature defining Zn as a typical anthropogenic element originating from traffic emissions (Ștefănuț et al., 2021; Vuković et al., 2014; Zannoni et al., 2016; Urošević et al., 2023). The main sources of atmospheric Pb are ore and metal processing plants and piston-engine aircraft using leaded aviation fuel, with waste incineration plants and energy production plants contributing to a lesser extent (USEPA, 2025).

Figure 4. Rotated Component Plot of PTE Loads

4. Conclusion

The moss bag technique was used to comprehensively evaluate the seasonal, spatial, and source-based characteristics of atmospheric PTE accumulation. Most of the analysed elements accumulated significantly in *A. complanata* moss bags seasonally exposed in the urban area of Çanakkale. Friedman test results showed that Cr, Zn, Pb and As metals exhibited statistically significant changes between seasons, whereas Cu showed more stable seasonal behaviour.

289 The use of the *Alleniella complanata* species for the first time in biomonitoring studies confirmed that it is an
290 effective bioindicator for reflecting atmospheric PTE accumulation, exceeding the $RAF > 1$ threshold. According to CF
291 values, the study area was generally exposed to ‘moderate ($1 \leq CF < 3$)’ contamination. PLI results showed that $PLI < 1$ was
292 detected only at the Airport station during the winter period; $PLI > 1$ values were recorded in all other station-season
293 combinations. This result indicated the presence of a cumulative metal load throughout the year.

294 PCA and correlation analyses revealed two main sources shaping PTE accumulation. The first component,
295 characterised by a strong relationship between As and Cr, indicated interactions with coal combustion and geogenic inputs.
296 The second component associated Zn and Cu accumulation with urban traffic emissions and small-scale industrial
297 activities. The correlations shown between Cr and As and Cu and As supported the source patterns determined by the PCA
298 results. This study demonstrated that the accumulation of the identified metals in the urban atmosphere of Çanakkale
299 exhibits both temporal and spatial variability; it also contributed to the literature by establishing *A. complanata* as an
300 effective tool for monitoring this variability.

301 **Declarations**

302 **Ethical Approval**

303 This study did not involve human participants or animals, and therefore did not require ethical approval.

304 **Funding**

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307 **Availability of data and materials**

308 The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable
309 request.

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FIGURE FILE

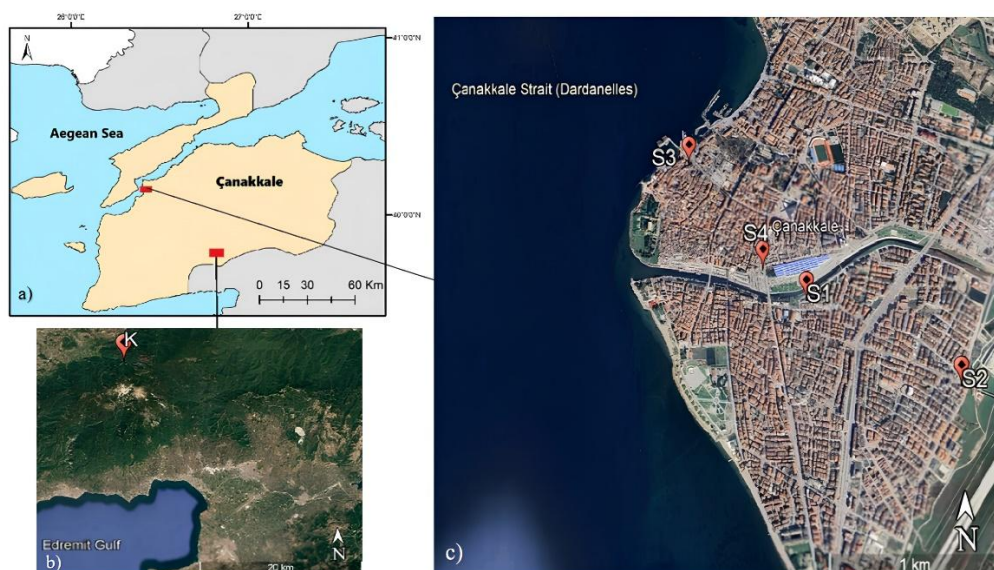


Figure 1. (a) Location of the study area within Çanakkale Province, (b) Background area (Ayazma Pınarı Nature Park), (c) Sampling sites.

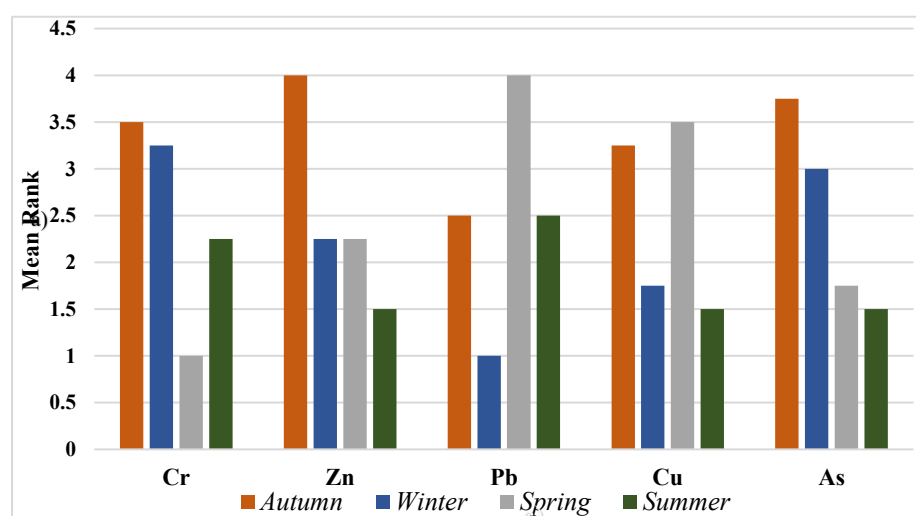


Figure 2. Mean rank values of metals according to Friedman test by season

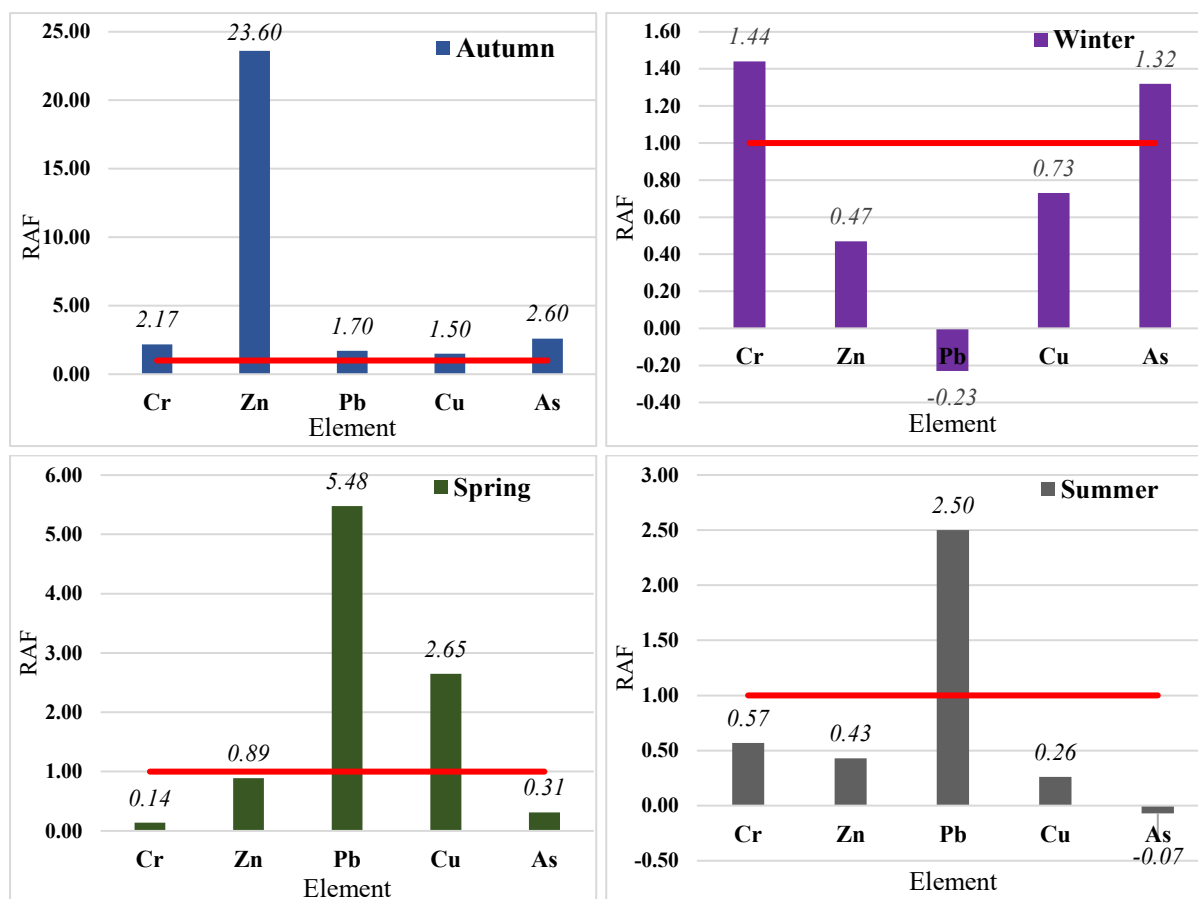


Figure 3. Average RAF values for autumn, winter, spring and summer periods in *A. complanata* samples. The red line indicates the 'RAF = 1' threshold.

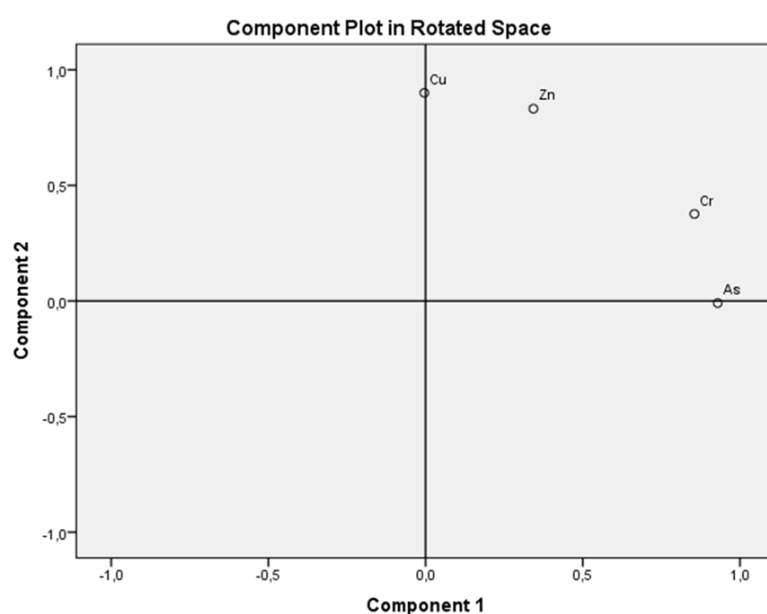


Figure 4. Rotated Component Plot of PTE Loads

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