Nigerian Research Journal of Chemical Sciences **(ISSN: 2682-6054)**
Volume 15, Issue 1, 2026

Multivariate Characterization of Heavy Metal Accumulation Patterns in Medicinal Plants from an E-Waste Contaminated Site in Lagos, Nigeria

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Accepted: *August 20, 2026* **Published Online***: August 27, 2026*

ABSTRACT

Electronic-waste (e-waste) recycling introduces potentially toxic metals into terrestrial ecosystems and may increase their accumulation in medicinal plants. This study characterized Pb, Cd, Cu, Ni, and Cr accumulation in three medicinal plants (*Pentodon pentandrus*, *Cyclosorus dentatus*, and *Rhynchospora corymbosa*) collected from an e-waste-contaminated site at Alaba International Market, Lagos, Nigeria, using *Talinum fruticosum* as a control specie. Metal concentrations were determined by atomic absorption spectrophotometry and evaluated using Pearson correlation, principal component analysis (PCA), and hierarchical cluster analysis (HCA). *P. pentandrus* exhibited the highest Pb (221.15 mg kg^{-1}), Cu (481.00 mg kg^{-1}), and Ni (57.45 mg kg^{-1}) concentrations, while *R. corymbosa* showed the highest Cr (29.74 mg kg^{-1}) concentration; Cd ranged from 0.00–0.33 mg kg^{-1}. PCA explained 84.00% of total variance, with Pb and Ni dominating PC1 and Cr, Cu, and Cd contributing mainly to PC2. Pearson correlation showed a strong positive Pb–Ni association (r = 0.97). HCA supported the species-specific accumulation patterns, with *P. pentandrus* showing the greatest dissimilarity. The findings demonstrate distinct elemental fingerprints among medicinal plants and provide baseline information for environmental biomonitoring and preliminary phytoremediation screening in e-waste-impacted environments.

Keywords: E-waste, medicinal plants, heavy metals, chemometrics, PCA, HCA.

INTRODUCTION

Medicinal plants (MPs) are important sources of therapeutic agents and contribute substantially to traditional and complementary healthcare systems. Their use as herbal medicines and dietary preparations makes the quality and safety of plant materials an important public health consideration. However, MPs can accumulate potentially toxic metals from contaminated soils and other environmental sources, creating a route of human exposure through plant-based preparations. Metal accumulation is influenced by environmental conditions and plant-specific characteristics, while prolonged exposure to metals such as lead, cadmium, nickel, chromium, and copper may have adverse health implications [1-3].

Electronic waste is an important anthropogenic source of environmental metal contamination. Electrical and electronic equipment contain metals that may be released during inappropriate dismantling, recycling, processing, and disposal. Informal practices, including manual dismantling and open burning, can introduce Pb, Cd, Cu, Ni, and other potentially toxic elements into surrounding environmental media, resulting in metal contamination around e-waste processing and disposal sites [4-6].

Plants growing in contaminated environment can take up metals and retain or translocate them within their tissues. Consequently, vegetation has been used as an indicator of environmental contamination and investigated for potential phytoremediation applications. However, metal accumulation varies considerably among plant species because of differences in metal uptake, tolerance, translocation, and interactions among elements [7-9]. Such differences are particularly relevant to MPs because species that accumulate elevated concentrations of potentially toxic metals may serve as useful biomonitoring materials while also representing potential sources of human exposure.

Previous studies of heavy metals in MPs have largely focused on individual metal concentrations and associated health risks [10-11]. Although such assessments establish the extent of contamination, analysing metals individually may provide limited insight into the overall accumulation structure of a multi-element dataset. In particular, concentration-based approaches may not adequately reveal similarities or differences among plant species, the metals contributing most strongly to overall variation, or associations among co-occurring elements. Characterizing these multi-element patterns is therefore important for understanding species-specific accumulation in plants growing under similar contaminated conditions.

Multivariate chemometric techniques provide an effective framework for interpreting such multidimensional datasets. PCA identifies major patterns of variation and the elemental variables contributing to them, while HCA groups samples according to similarities in their elemental composition. Pearson correlation analysis provides complementary information on pairwise relationships among metals. The combined application of these approaches can therefore provide a more integrated characterization of multi-element accumulation than independent evaluation of individual metal concentrations [12-14].

The present study investigated the accumulation patterns of Pb, Cd, Cu, Ni, and Cr in *Pentodon pentandrus*, *Cyclosorus dentatus*, and *Rhynchospora corymbosa* collected from an e-waste-contaminated site at Alaba International Market, Lagos, Nigeria, using *Talinum fruticosum* from a non-contaminated site as the control specie. The specific objectives of this study are to: (i) determine the concentrations and species-specific accumulation patterns of the five investigated metals; (ii) assess the relationships among the metals using Pearson correlation analysis; (iii) identify the principal metal combinations contributing to variation among the plant species using principal component analysis; and (iv) classify the species according to similarities in their metal accumulation profiles using hierarchical cluster analysis. By integrating elemental analysis with complementary chemometric approaches, the study provides a multivariate characterization of heavy-metal accumulation patterns in medicinal plants growing in an e-waste-impacted environment and establishes evidence to support their consideration in environmental biomonitoring and future phytoremediation investigations.

MATERIALS AND METHODS

Study Area and Sampling

The study was conducted at an electronic-waste disposal site within Alaba International Market, Ojo Local Government Area, Lagos State, Nigeria, located at 6°27′14″ N and 3°11′25″ E**.** The site is characterized by informal e-waste handling and disposal activities, including dismantling and other uncontrolled recycling practices that may contribute to heavy-metal contamination of the surrounding environment [15,16].

The study area was divided into five sampling quadrants. Three MP species, *Rhynchospora corymbosa* (L.) Britton, *Pentodon pentandrus* (Schumach. & Thonn.) and *Cyclosorus dentatus* (Forssk.) Ching, were randomly collected from the five quadrants. Five individual plants of each species were collected from each quadrant, giving 25 field specimens per specie**.** The specimens of each specie were combined and thoroughly homogenized to obtain one representative composite sample per species**.** Composite sampling was used to minimize the influence of localized spatial variability and provide an integrated elemental profile for each species within the study site [17].

Talinum fruticosum was selected as the control specie because the three medicinal species sampled at the e-waste site were not available at the control sampling site, a fallow farmland located in Ago Palace Way, Okota, Lagos State, Nigeria, at 6°30′25″ N and 3°17′43″ E. The site was relatively distant from major traffic activity and showed no obvious source of industrial or e-waste pollution at the time of sampling. The control site was divided into four quadrants, from which five *T. fruticosum* specimens were collected per quadrant, giving 20 field specimens**.** The specimens were combined and homogenized to obtain one representative composite control sample**.** All plant samples were placed in appropriately labelled paper bags and transported to the laboratory under conditions that minimized moisture accumulation and fungal growth.

Sample Preparation

The leaves were separated from the stems and washed thoroughly under running tap water to remove adhering soil particles and surface debris, followed by rinsing with distilled water. The cleaned leaves were air-dried and subsequently oven-dried with Thermo Scientific Oven at 60 °C until constant weight**.** The dried samples were pulverized and sieved through a 2 mm sieve to obtain relatively homogeneous material. Approximately 1.0 g of each representative composite sample was weighed into clean porcelain crucibles and dry-ashed in a muffle furnace at 450–500 °C for 4 h**.** After cooling in a desiccator, the ash was dissolved with 10 mL of freshly prepared aqua regia ($HCl:HNO_3$, 3:1, v/v) [19]. The digest was gently heated to reduce the volume, allowed to cool, filtered through Whatman No. 42 filter paper into a 25-mL volumetric flask**,** and made up to volume with deionized water. The resulting digests were transferred into clean, acid-washed polyethylene bottles and stored at 4 °C until instrumental analysis.

Determination of Heavy Metals

The concentrations of Pb, Cd, Cu, Ni, and Cr in the plant digests were determined using flame atomic absorption spectrophotometry (AAS). The target metals were determined using two AAS instruments because the required hollow cathode lamps for all five metals were not available on a single instrument at the time of analysis. Accordingly, Ni and Cr were determined using a Buck

Scientific AAS (Model 210), while Pb, Cd, and Cu were determined using a PerkinElmer Analyst 200. Both AAS instruments were equipped with an air–acetylene flame. The analytical wavelengths used were 232.0 for Ni, 357.9 nm for Cd, 228.80 nm for Cd, 324.75 nm for Cu, and 283.30 nm for Pb. Calibrations were performed using the corresponding metal standards under optimized operating conditions. The same digested composite samples were analysed for all metals to ensure consistency of sample preparation and comparability of the resulting concentrations

Quality Assurance and Control

Quality assurance and quality control procedures were applied throughout sample preparation, and instrumental analysis to minimize contamination and ensure analytical reliability. Analytical grade reagents and deionized water were used throughout, while sample-contact materials were thoroughly cleaned before use. Procedural blanks were included during digestion to monitor potential contamination from reagents and laboratory handling. Recovery were performed using spiked samples and studies gave values ranging from 94–98%, indicating satisfactory analytical accuracy [19].

Data Processing

The concentrations of Pb, Cd, Cu, Ni, and Cr obtained for the representative composite samples were organized into a heavy metal concentration matrix for multivariate analysis. Because the metals occurred at different concentration levels, the data were standardized using z-score transformation before chemometric analysis. Standardization placed the variables on a common scale and prevented metals with larger numerical concentrations from disproportionately influencing the multivariate analyses [20]. The concentration of the composite sample for each plant species values were used for subsequent multivariate analyses. All statistical and chemometric analyses were performed using Python 3.

Statistical Analysis

An integrated multivariate approach was employed to characterize heavy-metal accumulation patterns among the investigated MPs. All chemometric multivariate analyses and visualization were implemented using appropriate Python-based statistical and plotting packages.

PCA was applied to the normalized dataset to reduce dimensionality and extract dominant patterns of variance among samples. Score plots were used to assess sample clustering, while loading plots were used to identify compounds contributing to variance structure. [12,21].

HCA was used to classify the plant samples according to similarities in their heavy-metal accumulation profiles. Euclidean distance was used as the similarity measure and Ward's linkage method was employed for clustering [21].

Results were visualized using dendrograms to illustrate hierarchical relationships and treatment-based clustering patterns.

Pearson correlation analysis was performed to evaluate the strength and direction of associations among Pb, Cd, Cu, Ni, and Cr in the investigated plant samples [21]. The Pearson correlation coefficient (r) was used to quantify pairwise relationships among the metals. Positive values indicated that two metals tended to vary in the same direction, whereas negative values indicated an inverse relationship. The resulting correlation coefficients were visualized as a correlation heatmap**.**

The PCA, HCA, and Pearson correlation results were interpreted collectively to characterize the heavy metal accumulation fingerprints of *P. pentandrus*, *C. dentatus*, *R. corymbosa*, and *T. fruticosum (*the control). The combined application of these techniques provided an integrated assessment of species-specific heavy-metal accumulation patterns in MPs from the e-waste-impacted environment [12].

RESULTS AND DISCUSSION

Heavy Metal Concentrations and Species-Specific Accumulation Patterns

The concentrations of Pb, Cd, Cu, Ni, and Cr in the investigated MPs are presented in Figure 1**.** Interspecific differences were observed, indicating distinct heavy-metal accumulation profiles among plants growing under the e-waste-impacted conditions. Cu was the most abundant metal in the contaminated-site plants, followed by Pb and Ni, whereas Cd occurred at comparatively low concentrations. The control, *Talinum fruticosum,* showed consistently low concentrations of all investigated metals.

Pentodon pentandrus recorded the highest Pb (221.15 mg kg^{-1}), Cu (481.00 mg kg^{-1}), and Ni (57.45 mg kg^{-1}) concentrations among the contaminated site species. *Rhynchospora corymbosa* exhibited the highest Cr concentration (29.74 mg kg^{-1}) and a high Cu concentration (455.38 mg kg^{-1}). *Cyclosorus dentatus* showed comparatively lower concentrations of Pb (152.75 mg kg^{-1}), Cu (99.28 mg kg^{-1}), and Ni (30.48 mg kg^{-1}). Cd remained the least abundant metal, ranging from 0.00 to 0.33 mg kg^{-1}.

These results indicate distinct elemental fingerprints among the three medicinal species. *P. pentandrus* was characterized by relatively high Pb, Cu, and Ni accumulation, whereas *R. corymbosa* showed a prominent Cu–Cr profile. *C. dentatus* exhibited comparatively lower accumulation of the major metals.

Such interspecific variation is consistent with the recognized influence of plant-specific differences in metal uptake, transport, sequestration, and tolerance [7,9]. However, these mechanisms were not directly investigated in the present study and therefore cannot be inferred from the observed concentrations alone.

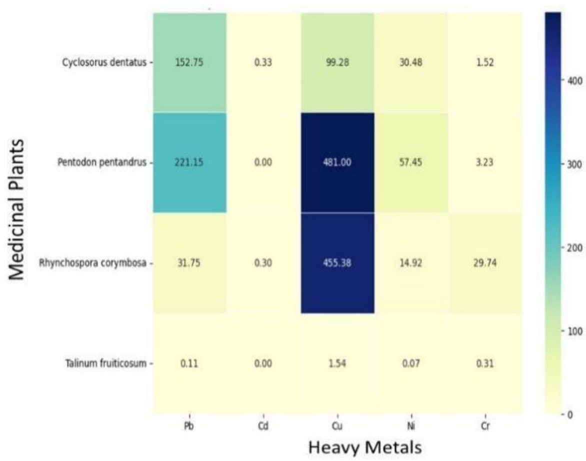

Figure 1: Heatmap showing species-specific heavy metal accumulation patterns in MPs

The markedly lower concentrations in *T. fruticosum* provided a contrasting reference profile. The concentration data provide the basis for comparing species-specific accumulation patterns.

Therefore, the concentration profiles demonstrate that the five metals did not accumulate uniformly among the investigated species.

Correlation Analysis of Heavy Metal Accumulation

The Pearson correlation matrix of Pb, Cd, Cu, Ni, and Cr is presented in Figure 2**.** Pearson correlation analysis was used to examine the relationships among the investigated metals and identify similarities in their accumulation patterns across the studied plant species. The analysis complements the concentration data by providing an integrated view of the extent to which the metals co-varied within the plant tissues. A very strong positive correlation was observed between Pb and Ni (r = 0.97), indicating closely similar accumulation patterns for the two metals across the plant species. Given that corresponding soil-metal concentrations were not determined; this relationship is interpreted as co-accumulation rather than evidence of a common environmental source.

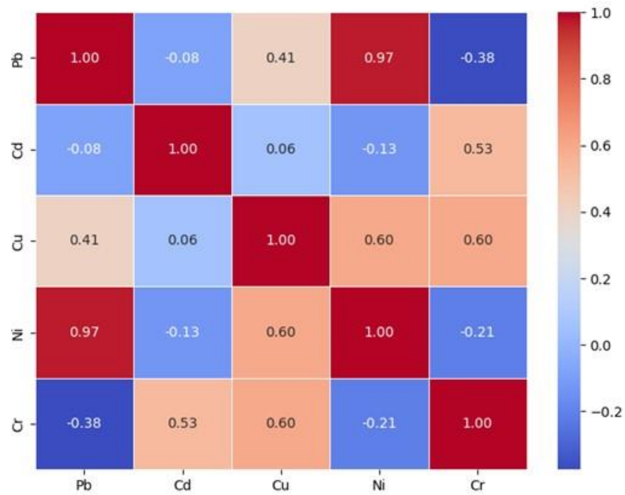

Figure 2: Pearson correlation matrix showing the relationships among Pb, Cd, Cu, Ni, and Cr concentrations in the investigated MPs.

Moderate positive correlations were observed between Cu and Ni (r = 0.60), Cu and Cr (r = 0.60), and Cd and Cr (r = 0.53), indicating partially similar accumulation patterns. These associations may reflect similarities in metal distribution and uptake within the plants; however, the present dataset does not permit direct attribution to specific environmental sources or transfer mechanisms. Weak negative correlations occurred between Pb and Cr (r = −0.38), Cd and Ni (r = −0.13), and Ni and Cr (r = −0.21), indicating dissimilar accumulation patterns for these metal pairs. Such differences may reflect species-dependent variation in metal uptake and accumulation, although the underlying physiological mechanisms were not investigated.

In summary, the correlation analysis identified Pb–Ni as the strongest metal association, with additional moderate associations involving Cu, Cr, and Cd. These relationships provide complementary evidence for interpreting the multivariate elemental structure and form a basis for the subsequent PCA and HCA analyses.

Principal Component Analysis

PCA was used to characterize the major patterns of variation in heavy-metal accumulation among the investigated plant species. PC1 explained 47.52% of the total variance, while PC2 explained 36.48%, giving a cumulative variance of 84.00% as shown in Figure 3**.** The first two components therefore captured most of the variation in the standardized elemental dataset and were retained for interpretation.

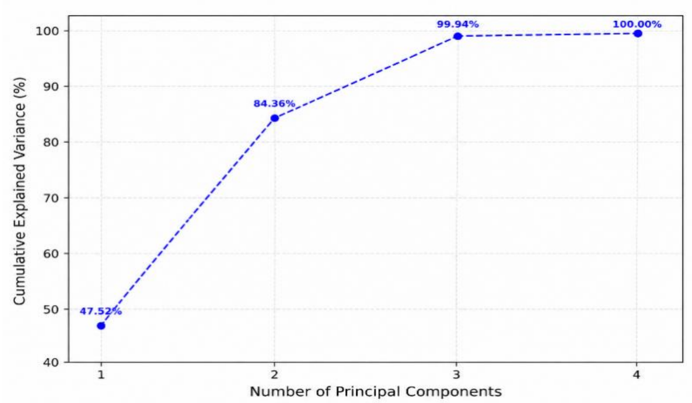

Figure 3: Scree plot showing the variance explained by the principal components.

The PCA biplot (Figure 4) showed clear separation of the investigated plant species according to their elemental accumulation profiles. *Pentodon pentandrus* was positioned strongly on the positive side of PC1, whereas *Rhynchospora corymbosa* was separated primarily along the positive direction of PC2. *Cyclosorus dentatus* occupied an intermediate position, while *Talinum fruticosum*, was located in the negative region of both components.

The species distribution was consistent with their measured elemental concentrations. The positive PC1 position of *P. pentandrus* corresponded to its comparatively high Pb and Ni concentrations, whereas the positive PC2 position of *R. corymbosa* was associated particularly with its higher Cu and Cr concentrations.

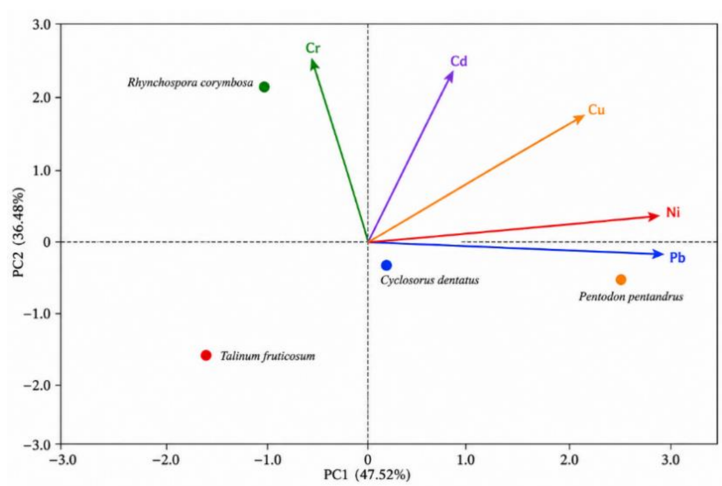

Figure 4: PCA biplot showing the distribution of MPs and the contributions of heavy metals to PC1 and PC2.

C. dentatus occupied an intermediate position, consistent with its comparatively moderate accumulation profile. In contrast, *T. fruticosum* was positioned negatively on both components, corresponding to its substantially lower concentrations of the investigated metals.

From Figure 4, Pb (1.106) and Ni (1.150) showed the strongest positive loadings on PC1, with Cu also contributing positively (0.697). PC2 was characterized principally by Cr (1.100), Cu (0.813), and Cd (0.755), whereas Pb and Ni contributed comparatively little to this component. Thus, PC1 was primarily associated with a Pb–Ni accumulation pattern, while PC2 represented a secondary Cr–Cu–Cd pattern. More so, The PCA results were consistent with the Pearson correlation analysis. In particular, the strong Pb–Ni association ($r = 0.97$) corresponded with their dominant positive loadings on PC1, while the moderate associations involving Cu, Cr, and Cd were reflected in their relatively high positive loadings on PC2. This agreement indicates that the principal patterns identified by PCA were consistent with the observed inter-metal relationships.

Therefore, PCA differentiated the MPs according to their heavy-metal accumulation profiles. PC1 was dominated by Pb and Ni, whereas PC2 was characterized mainly by Cr, Cu, and Cd, providing a concise multivariate representation of the elemental fingerprints while supporting HCA.

Hierarchical Cluster Analysis

HCA was performed using Ward's linkage method and Euclidean distance to evaluate similarities among the four investigated MPs based on their overall heavy-metal accumulation profiles [21,22]. The dendrogram showed that *Talinum fruticosum* clustered most closely with *Cyclosorus dentatus*, indicating relatively similar overall elemental profiles. *Rhynchospora corymbosa* joined this cluster at a greater linkage distance, reflecting its more distinct profile, particularly its comparatively higher Cu and Cr concentrations. In contrast, *Pentodon pentandrus* exhibited the greatest dissimilarity, joining the other species at the highest linkage distance. This separation is consistent with its comparatively high Pb, Cu, and Ni concentrations and its positive positioning along PC1.

Generally, HCA supports the presence of distinct heavy-metal accumulation profiles among the investigated plant species and is broadly consistent with the concentration patterns and PCA results. However, because the analysis was based on one composite sample representing each species, the clusters should be interpreted as descriptive relationships among the sampled species rather than statistically validated population-level groupings.

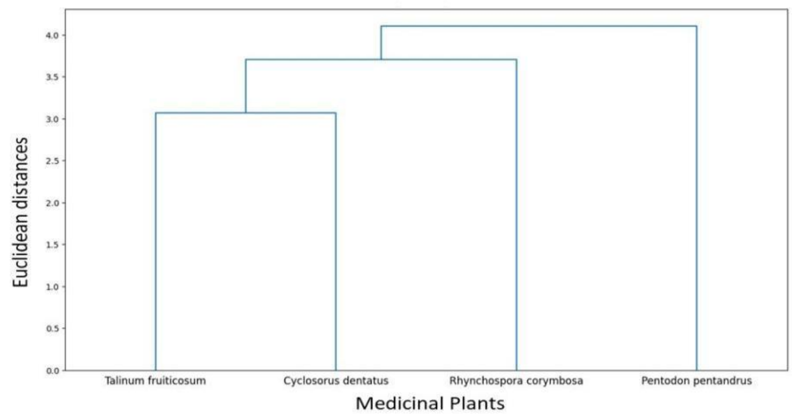

Figure 6: Hierarchical cluster dendrogram showing similarities among MP species

The integrated concentration and chemometric analyses demonstrate distinct species-specific accumulation patterns for Pb, Cd, Cu, Ni, and Cr among the investigated plants. The comparatively low concentrations in *Talinum fruticosum* from the reference site, relative to the plants collected from the e-waste-impacted site, indicate a clear difference in elemental accumulation between the two locations. However, because soil concentrations and source-apportionment data were not determined, specific environmental sources of individual metals cannot be established.

The strong Pb–Ni correlation ($r = 0.97$) and moderate associations involving Cu, Cr, and Cd indicate distinct patterns of metal co-accumulation. These relationships should be interpreted as associations within plant tissues rather than evidence of common contamination sources, given the absence of corresponding soil and environmental measurements.

The contrasting accumulation profiles also suggest potential value for environmental biomonitoring. *Pentodon pentandrus*, with relatively high Pb and Ni concentrations, and *Rhynchospora corymbosa*, with comparatively greater Cu and Cr accumulation, may provide complementary information on metal contamination. Similar species-dependent accumulation patterns have been reported in contaminated environments [9,23].

The findings provide a useful baseline for environmental biomonitoring of MPs in e-waste-impacted environments and demonstrate the value of integrating elemental analysis with multivariate chemometric techniques.

Therefore, *P. pentandrus* and *R. corymbosa* may be considered as potential candidates for further investigation, rather than confirmed phytoremediators.

Human Health Implications

The species-specific accumulation patterns observed in this study have implications for the safe use of MPs collected from e-waste-impacted environments. *Pentodon pentandrus* exhibited comparatively high Pb and Ni concentrations, whereas *Rhynchospora corymbosa* showed relatively greater accumulation of Cu, Cr, and Cd. In contrast, *Talinum fruticosum* from the control site contained substantially lower concentrations of the investigated metals. These differences indicate that MP species may contribute differently to potential human exposure when collected from contaminated environments.

The presence of potentially toxic metals, particularly Pb, Cd, and Cr, warrants attention because prolonged exposure to these elements has been associated with neurological, renal, developmental, skeletal, and carcinogenic effects [24-26]. However, actual health risk depends on metal concentrations, quantity and frequency of consumption, duration of exposure, and individual characteristics.

The present study was designed to characterize species-specific metal accumulation using chemometric techniques. The findings indicate potential exposure concerns rather than established health risks**.**

Therefore, the results support routine monitoring of MPs harvested from e-waste contaminated environments before their use in herbal preparations. The chemometric framework provides a useful basis for identifying species with contrasting accumulation characteristics and can support future risk assessments incorporating consumption and exposure data [10, 27].

Implications for Phytoremediation

The species-specific accumulation patterns provide preliminary information for phytoremediation screening. *Pentodon pentandrus* showed comparatively high accumulation of Pb and Ni, while *Rhynchospora corymbosa* exhibited relatively greater accumulation of Cu, Cr, and Cd. These profiles suggest that both species warrant further investigation as potential candidates for metal uptake in contaminated environments. However, phytoremediation effectiveness depends on metal tolerance, biomass production, translocation, and overall removal efficiency, not accumulation alone [28, 29]. *Cyclosorus dentatus*, with comparatively moderate metal concentrations, may be more relevant for biomonitoring than metal extraction, whereas *Talinum fruticosum* served primarily as the reference species because of its low metal accumulation.

Therefore, the observed profiles are preliminary evidence for candidate-species selection, rather than confirmation of phytoremediation capability.

Generally, the findings provide a basis for further studies incorporating soil–plant relationships, metal transfer, tolerance, and remediation performance in e-waste contaminated environments [20,23].

CONCLUSION

This study demonstrated the usefulness of an integrated chemometric approach combining Pearson correlation analysis, PCA and HCA for characterizing heavy-metal accumulation patterns in MPs from an e-waste-contaminated site in Lagos, Nigeria.

Distinct species-specific accumulation profiles were observed. *Pentodon pentandrus* was characterized by comparatively high Pb and Ni concentrations, while *Rhynchospora corymbosa* showed greater accumulation of Cu and Cr. *Cyclosorus dentatus* exhibited a comparatively intermediate accumulation profile, whereas *Talinum fruticosum*, used as the reference species, showed markedly lower concentrations of the investigated metals. The strong Pb–Ni correlation and the complementary patterns revealed by PCA and HCA demonstrate that the investigated metals contributed differently to the elemental fingerprints of the plant species. The agreement among the concentration profiles, correlation structure, PCA, and HCA provides an integrated characterization of species-specific heavy-metal accumulation that could not be adequately captured by concentration data alone.

Therefore, the findings establish distinct multivariate heavy-metal fingerprints among MPs growing in the e-waste-impacted environment and provide information for environmental biomonitoring and the selection of plant species for further investigation.

Limitations of the Study

The analyses were based on composite plant samples representing each species, which provided representative elemental profiles but limited assessment of within species variability and population level statistical inference. In addition, corresponding soil-metal concentrations and plant–soil transfer measurements were not incorporated; consequently, specific contamination sources, metal-transfer processes, and indices such as bioconcentration and translocation factors could not be established.

The investigation was also limited to leaf tissues, five metals (Pb, Cd, Cu, Ni, and Cr), and a single sampling period. Root-to-shoot metal distribution, seasonal variation, metal speciation, biomass production, metal tolerance, and removal efficiency were not assessed. Accordingly, the observed accumulation patterns may be observed as species-specific elemental profiles.

Recommendations for Future Studies

Future investigations should incorporate independent replicated sampling, multiple seasons, and larger numbers of plant species and specimens to characterize spatial and temporal variability in metal accumulation. Coupling plant analyses with soil-metal concentrations and plant–soil transfer measurements would enable assessment of metal mobility, bioconcentration, and translocation.

Also, future studies should incorporate replicated sampling, seasonal variation, soil–plant relationships, and metal transfer and tolerance measurements [23]. Additionally, it should examine root, stem, and leaf tissues, together with metal speciation, biomass production, metal tolerance, and removal efficiency, to determine whether species such as *Pentodon pentandrus* and *Rhynchospora corymbosa* possess genuine phytoremediation potential.

Therefore, these species are potential candidates for further investigation rather than confirmed phytoremediators. Integrating these measurements with multivariate chemometric approaches would strengthen environmental biomonitoring and provide a more robust basis for evaluating medicinal plants growing in e-waste contaminated environments.

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