



Trace Metal (Fe, Se, Cd, Cr, Pb, Ba) Contamination in Soils and *Prunus amygdalus* Leaves near Delta Steel Company, Ovwian–Aladja, Nigeria: Correlation-Based Source Apportionment and Environmental Implications

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ABSTRACT

The concentrations of six trace metals (Fe, Se, Cd, Cr, Pb, and Ba) were measured in surface soils (0–15 cm) and leaves of the almond plant (*Prunus amygdalus*) collected from three locations within the Delta Steel Company (DSC) complex at Ovwian–Aladja, Delta State, Nigeria, the Steel Melting Shop (SM), the Lime Plant (L/P), and the Rolling Mill (RM). Sampling was conducted monthly over eight months, across wet and dry seasons. Metal concentrations in soil ranged from 411.38–7097.59 mg/kg for Fe, 1.21–14.55 mg/kg for Se, 1.01–6.25 mg/kg for Cd, 0.27–2.98 mg/kg for Cr, 0.78–4.88 mg/kg for Pb, and 121.61–606.07 mg/kg for Ba. The corresponding ranges in vegetation were 181.02–1543.70 mg/kg (Fe), 0.31–4.58 mg/kg (Se), 0.12–2.12 mg/kg (Cd), 0.04–0.88 mg/kg (Cr), 0.08–2.65 mg/kg (Pb), and 83.80–247.25 mg/kg (Ba). Soils at all locations contained metal concentrations exceeding typical background values, with several metals exceeding regulatory thresholds for agricultural soils. Pearson product-moment correlation showed a significant positive relationship ($p < 0.05$) between soil and vegetation concentrations for Pb ($r = 0.856$). The correlation for Cd ($r = 0.680$) was positive but did not reach statistical significance (critical value $r_{0.05} = 0.707$ for $n = 8$). These findings indicate a common anthropogenic source of Pb from DSC operations and measurable soil-to-plant transfer. Long-term accumulation of trace metals may pose risks to the surrounding ecosystem and local agriculture through uptake into edible crops.

Keywords: Trace metals, Soil, Vegetation, *Prunus amygdalus*, Bioaccumulation, Source apportionment

INTRODUCTION

Soil and vegetation near industrial installations are recognised as important sinks and bioindicators of anthropogenic trace metal contamination (Laoye et al., 2025; Guerrieri et al., 2024). Steel manufacturing, in particular, releases a range of trace elements, notably iron, chromium, lead, cadmium, and barium, to the surrounding environment via stack emissions, fugitive dust, process effluents, and solid residues (Rawat et al., 2023; Akporido et al., 2014). Once deposited, these metals can persist in soil for decades owing to their non-biodegradable nature, and a bioavailable fraction can be taken up by plants and enter the food chain (Mitra et al., 2022; Wieczorek et al., 2023; Abbas et al., 2023).

Plant uptake of heavy metals depends on soil pH, organic matter content, metal speciation, plant species, and environmental conditions (Natasha et al., 2022; Wieczorek et al., 2023). Leafy plants generally translocate more metals to their leaves than to fruits or seeds; therefore, leaves are widely used as bioindicators of atmospheric and soil metal contamination around industrial sites (Natasha et al., 2022; Okereafor et al., 2020).

The Delta Steel Company (DSC) at Ovwian–Aladja is an integrated steel plant that manufactures billets and reinforcement rods from iron ore through direct reduction, electric arc furnace (EAF) melting, continuous casting, and hot rolling. Large quantities of dust, fumes, slag, and aqueous effluents are generated during these operations, resulting in the documented contamination of surrounding soils, sediments, and biota (Akporido et al., 2014; Akporido & Ipeaiyeda, 2014). A multi-year study by Agbaire et al. (2014) reported soil Fe and Pb concentrations of 3110 ± 1500 mg/kg and 126 ± 40 mg/kg, respectively, in the vicinity of DSC, and a companion study detected appreciable Fe, Mn, Pb, Cu, Cd,

and Zn in the leaves of *Prunus dulcis* and *Elaeis guineensis* at the same site (Agbaire et al., 2014). However, these earlier studies did not cover the six elements investigated here (Fe, Se, Cd, Cr, Pb, and Ba) simultaneously, nor did they partition the plant complex by individual production zones.

This study is novel in its simultaneous multi-metal assessment (including the less-commonly reported Se and Ba) across three distinct production zones (steel melting shop, lime plant, and rolling mill) within the active DSC complex, combined with eight-month seasonal coverage and Pearson correlation analysis for source apportionment and transfer pathway inference.

In the wider Nigerian context, recent studies have documented elevated heavy metal levels in soils and vegetables near industrial and waste-impacted sites (Okereafor et al., 2020; Abubakar et al., 2025; Laoye et al., 2025) and in crops from Niger Delta communities (Anyanwu et al., 2023). These findings are interpreted against the backdrop of Nigerian environmental governance, particularly standards and guidelines issued by the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Federal Ministry of Environment (FMEnv) for industrial emissions, effluent discharge, and soil protection. While Nigeria-specific numeric limits for many trace metals in industrial vicinities are still evolving, exceedances are commonly benchmarked against international compilations, such as Kabata-Pendias (2011) and WHO/FAO agricultural soil guidelines. Building on this, the present study aimed to (i) quantify the concentrations of Fe, Se, Cd, Cr, Pb, and Ba in soils and leaves of *P. amygdalus* within three strategic production zones of DSC; (ii) examine seasonal variations in these concentrations; and (iii) evaluate

the relationship between metal levels in soil and in vegetation using correlation analysis.

MATERIALS AND METHODS

Study Area

The Delta Steel Company is located along the DSC Expressway in Ovwian–Aladja, Udu Local Government Area of Delta State, Nigeria, on the Udu arm of the Warri River (Akporido et al., 2014). The approximate geographic coordinates (WGS 84) of the three sampling stations within the DSC complex were: Steel Melting Shop (SM) at 5.513° N, 5.723° E; Lime Plant (L/P) at 5.508° N, 5.719° E; and Rolling Mill (RM) at 5.505° N, 5.731° E. These stations were selected to reflect contrasting production activities: SM (electric arc furnace and billet casting), L/P (limestone flux processing), and RM (hot-rolling of billets into reinforcement rods). In the Niger Delta, the wet (rainy) season typically spans April to October and the dry season November to March, based on regional rainfall patterns (NIMET records); the eight-month sampling campaign was designed to capture both seasonal regimes.

Sample Collection

At each sampling station, surface soil samples (0–15 cm depth) were collected monthly over an eight-month period using a 1.5 m stainless steel corer. Although stainless steel can potentially introduce Fe and Cr contamination, the corer was thoroughly acid-washed with 10% (v/v) HNO₃ and rinsed with deionised water between successive sampling events; identically processed field blanks showed all target metal concentrations below the instrument detection limit (0.001 mg/L). Leaves of *Prunus amygdalus* (almond) growing within 30 m of each production unit were collected concurrently. Composite samples, each consisting of five to ten randomly obtained sub-samples collected within a 10 m radius of the production unit, were prepared to account for micro-scale spatial heterogeneity and stored in clean black polyethylene bags with tight plastic clips until laboratory analysis (Okerefor et al., 2020).

Sample Treatment and Digestion

Soil samples were air-dried for 24 h, sieved through a 2 mm aluminium sieve, and stored at 4 °C prior to digestion. A 1-g sub-sample was digested with 20 mL concentrated HNO₃, 10 mL concentrated H₂SO₄, and 5 mL HClO₄ (4:2:1) on a hot plate until dense white fumes were observed. After cooling, 20 mL deionised water was added, and the mixture was gently boiled to dissolve the residue. The digest was filtered through Whatman No. 42 filter paper and made up to 100 mL with deionised water (APHA, 2017; Abbas et al., 2023).

Almond leaves were air-dried for three days, crushed in a mortar, and homogenised in an electric blender. A 1-g sub-sample was digested with 20 mL concentrated HNO₃ and 5 mL HClO₄ on a hot plate; the mixture was transferred to a fume chamber and left overnight. After cooling, the digest was filtered and diluted to 100 mL with deionised water (APHA, 2017).

Metal Determination

Concentrations of Fe, Se, Cd, Cr, Pb, and Ba in the digests were measured using a GBC Sens AA 3000 atomic absorption spectrophotometre (Model A6358) with a detection limit of 0.001 mg/L. Flame atomic absorption spectrometry (FAAS) was used for Fe, Ba, Cr, and Pb, while graphite-furnace atomic absorption spectrometry (GFAAS) was employed for the trace elements Cd and Se to provide lower detection limits appropriate to their environmental concentrations. The instrument was calibrated using a five-point standard curve prepared from certified stock solutions, with operating conditions optimised for each element. Although a matrix-matched certified reference material (e.g., NIST SRM 2711 soil or 1573a tomato leaves) was not analysed owing to temporary unavailability, quality control was strengthened by regular analysis of reagent blanks (all below detection limits) and standards after every ten samples (Khan et al., 2023). All digests were analysed in triplicate. Relative standard deviations (RSD) for replicate analyses were typically < 8%. Method accuracy was further verified through spike-recovery experiments on representative soil and leaf matrices, yielding recoveries of 87–114% across the six target metals.

Statistical Analysis

Mean, standard deviation, and range of each metal were calculated for each sampling location and season. Pearson product-moment correlation coefficients (*r*) were computed to evaluate the relationship between metal concentrations in soil and in vegetation at *p* = 0.05 significance level (*n* = 8, *df* = 6; *r*_{0.05} = 0.707). In addition, one-way analysis of variance (ANOVA) with Tukey's HSD post-hoc test was employed to test for significant differences in metal concentrations among the three sampling locations. Seasonal differences (wet vs. dry season) were evaluated using independent Student's *t*-tests (or Mann–Whitney *U* tests where normality assumptions were not met) on the monthly data subsets (approximately 4 months per season). Assumptions of normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. Similar correlation-based and comparative approaches have been used to identify shared pollution sources in comparable studies (Khan et al., 2023; Abbas et al., 2023).

RESULTS AND DISCUSSION

Trace Metals in Soil

Table 1: Mean Concentrations (± SD) and Ranges of Trace Metals in Surface Soils (0–15 cm) at Three Production Zones of the Delta Steel Company, Ovwian–Aladja, Nigeria

Metal	RM	L/P	SM	Range (all)
Fe	3332.24 ± 1665.85	824.61 ± 255.72	2468.83 ± 900.45	411.38–7097.59
Se	8.66 ± 2.99	2.86 ± 1.52	8.18 ± 2.74	1.21–14.55
Cd	3.30 ± 1.64	1.68 ± 0.82	4.00 ± 1.35	1.01–6.25
Cr	1.35 ± 0.72	1.08 ± 0.59	0.75 ± 0.91	0.27–2.98
Pb	2.42 ± 1.62	1.80 ± 0.57	2.07 ± 0.41	0.78–4.88
Ba	434.10 ± 108.92	257.13 ± 130.80	419.07 ± 102.68	121.61–606.07

Note. All values are expressed in mg/kg dry weight. RM = Rolling Mill; L/P = Lime Plant; SM = Steel Melting Shop. SD = standard deviation.

The mean concentrations of the six trace metals in soils at the three production zones are summarised in Table 1 and illustrated in Figure 1. Iron was the most abundant metal in the soils, reaching 7097.59 mg/kg at the rolling mill during the dry season. These values are of the same order as those reported by Agbaire et al. (2014) (3110 ± 1500 mg/kg Fe) for soils close to the DSC outfall and exceed values reported for Nigerian scrap-metal and dumpsite soils (Okereafor et al., 2020; Abubakar et al., 2025). The elevated iron levels are consistent with the deposition of iron-rich dusts and scale during billet handling, rolling, and EAF operations (Rawat et al., 2023).

One-way ANOVA indicated statistically significant differences ($p < 0.05$) among the three locations for soil Fe, Se, Cd, and Ba concentrations (Figure 1). Tukey's post-hoc tests confirmed that the levels at SM and RM were generally higher than those at L/P for these metals, consistent with the greater intensity of high-temperature melting, casting, and rolling operations at SM and RM compared with the lime-flux processing at L/P.

Barium concentrations (121.61–606.07 mg/kg) were notably high at the SM and RM sites, exceeding typical background

values for uncontaminated soils (Kabata-Pendias, 2011). Ba is introduced mainly via burnt lime, which is used to remove impurities during EAF steelmaking. Cd (1.01–6.25 mg/kg) and Pb (0.78–4.88 mg/kg) concentrations exceeded typical soil background values and fell within the ranges reported for Nigerian industrial/roadside soils (Okereafor et al., 2020; Laoye et al., 2025). Cd in steelworks soils has been attributed to the wear of high-precision steel and ferroalloys and the processing of metal scraps (Akporido et al., 2014; Rawat et al., 2023). Selenium (1.21–14.55 mg/kg) exceeded the typical soil range for unpolluted soils (Kabata-Pendias, 2011), reflecting the presence of Se-bearing metal scraps and alloys in the soil.

The chromium levels (0.27–2.98 mg/kg) were somewhat lower than those reported for mechanical waste dumps and smelter-impacted soils elsewhere in Nigeria (Okereafor et al., 2020; Abubakar et al., 2025), but still clearly reflect the steel-making origin of Cr, which is used as a ferroalloy. Cr levels in industrial steel-plant soils are strongly influenced by slag handling and fugitive dust (Rawat et al., 2023).

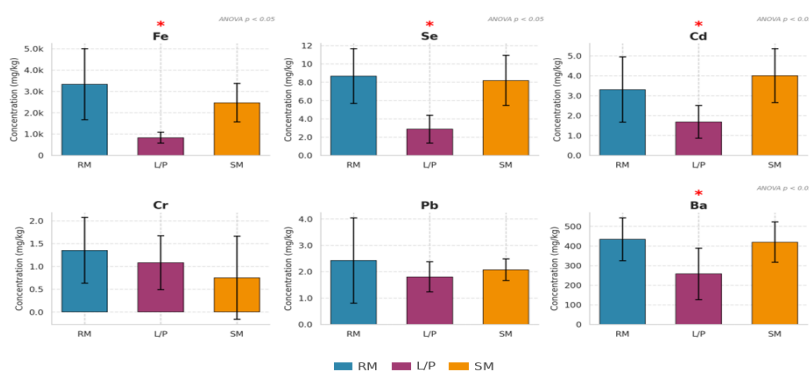


Figure 1: Mean \pm SD Concentrations Of Trace Metals (Fe, Se, Cd, Cr, Pb, Ba) In Surface Soils (0–15 Cm) At The Rolling Mill (RM), Lime Plant (L/P), And Steel Melting Shop (SM) Sites Of The Delta Steel Company, Ovwian–Aladja, Nigeria. Asterisks Indicate Statistically Significant Differences Among Sites ($P < 0.05$). Note the Different Y-Axis Scales for Fe and Ba

Trace Metals in Leaves of *Prunus Amygdalus*

Table 2: Mean Concentrations (\pm SD) and Ranges of Trace Metals in Leaves of *Prunus amygdalus* at Three Production Zones of the Delta Steel Company, Ovwian–Aladja, Nigeria

Metal	RM	L/P	SM	Range (all)
Fe	911.03 ± 78.35	442.95 ± 176.70	622.83 ± 535.99	181.02–1543.70
Se	3.03 ± 1.14	1.41 ± 1.16	2.28 ± 0.80	0.31–4.58
Cd	1.14 ± 0.48	0.71 ± 0.52	1.30 ± 0.70	0.12–2.12
Cr	0.18 ± 0.09	0.32 ± 0.26	0.08 ± 0.03	0.04–0.88
Pb	1.06 ± 1.00	0.62 ± 0.39	0.41 ± 0.21	0.08–2.65
Ba	125.04 ± 38.54	100.31 ± 13.58	175.21 ± 55.40	83.80–247.25

Note. All values are expressed in mg/kg dry weight. RM = Rolling Mill; L/P = Lime Plant; SM = Steel Melting Shop. SD = standard deviation.

Foliar trace metal concentrations at the three sites are summarised in Table 2 and shown in Figure 2. Metal levels in the leaves generally followed the same relative order as in the underlying soil but were approximately 3–6 times lower, consistent with the partial translocation of trace metals from root to shoot reported for tree species growing in industrial soils (Abbas et al., 2023; Nuapia et al., 2018). Iron in vegetation (up to 1543.70 mg/kg at SM) and barium (up to 247.25 mg/kg at SM) were notably elevated (Figure 2). Cadmium concentrations in leaves (0.12–2.12 mg/kg) substantially exceeded WHO/FAO permissible limits for

edible vegetables (0.1 mg/kg) and are consistent with the high Cd loads reported by Abubakar et al. (2025) for spinach grown in industrial-zone farms. Lead in vegetation (0.08–2.65 mg/kg) is attributable to both aerial deposition from steel-making fumes and particulate emissions from site traffic and machinery, and exceeds WHO/FAO leafy vegetable limits (0.3 mg/kg) at the Rolling Mill site (Abubakar et al., 2025; Okereafor et al., 2020).

Selenium, chromium, and barium concentrations in leaves were higher during the wet season than during the dry season, probably because rainfall enhances the wash-off of airborne

deposition onto plant surfaces, where metals can subsequently be taken up via the leaf cuticle (Natasha et al., 2022). However, independent Student's t-tests comparing wet- and dry-season means ($n \approx 4$ months per season) did not detect statistically significant differences for any metal ($p > 0.05$).

The observed trends are biologically plausible, but the modest number of sampling events per season and high month-to-month variability limited statistical power. Larger per-season sample sizes or more frequent sampling would be required to confirm seasonal patterns.

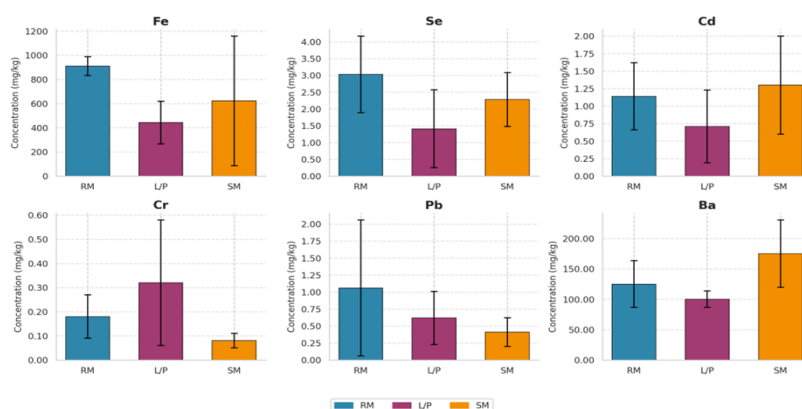


Figure 2: Mean \pm SD Concentrations Of Trace Metals In Leaves Of *Prunus Amygdalus* At The Same Three Production Zones. Metal Concentrations in Leaves Were Generally 3–6 Times Lower Than In the Corresponding Soils

Correlation between Soil and Vegetation

Table 3: Pearson Correlation Coefficients (r) Between Trace Metal Concentrations in Soil and *Prunus amygdalus* Leaves

Metal	r (soil – vegetation)	Significance ($p < 0.05$)
Fe	-0.358	NS
Se	-0.630	NS
Cd	0.680	NS
Cr	0.498	NS
Pb	0.856	Significant
Ba	-0.343	NS

Note. NS = not significant. The critical value for significance at $p < 0.05$ (two-tailed, $df = 6$) is $|r| = 0.707$.

The soil–vegetation correlation coefficients for the six metals are presented in Table 3 and visualised in Figure 3. The Pearson correlation between soil and vegetation concentrations was significant ($p < 0.05$) only for lead ($r = 0.856$). For cadmium, the correlation was positive ($r = 0.680$) but fell just short of the critical value ($r_{0.05} = 0.707$) required for significance at $n = 8$. The significant Pb correlation suggests a common steel-making source and a direct soil-to-plant transfer pathway for this metal — a pattern also reported by Abbas et al. (2023) and Khan et al. (2023) for industrial-drain-impacted plants. The near-significant positive Cd result

is suggestive of a similar pathway but requires confirmation with a larger sample size or analysis of individual replicate pairs rather than monthly aggregates. No significant correlations were found for Fe, Se, Cr, and Ba, indicating that the transfer of these metals from soil to plants is modified by soil properties (pH, organic matter, and cation exchange capacity) and the important role of airborne deposition on leaf surfaces (Wieczorek et al., 2023; Natasha et al., 2022). Indeed, in integrated steel-plant environments, atmospheric deposition often dominates over root uptake for Fe and Ba (Rawat et al., 2023; Nuapia et al., 2018).

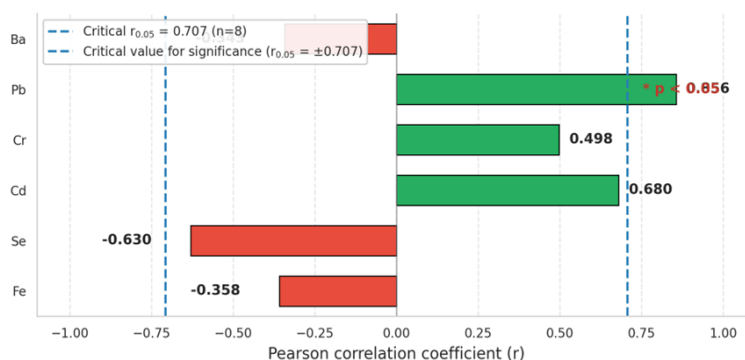


Figure 3: Pearson Correlation Coefficients (r) Between Trace Metal Concentrations In Soil And *Prunus Amygdalus* Leaves. Dashed Vertical Lines Indicate the Critical Value for Significance at $P < 0.05$ ($|r| = 0.707$). Only Pb Showed A Statistically Significant Positive Correlation ($R = 0.856$); Cd ($R = 0.680$) Was Positive But Not Significant

Environmental Implications

The accumulation of Fe, Ba, Se, Cd, and Pb in soils and leaves of *Prunus amygdalus* at levels that, in several cases, exceed regulatory and typical background values indicates that the vicinity of DSC has experienced appreciable long-term trace metal enrichment from industrial operations. While these metals are non-biodegradable and can persist in soils for decades, the actual ecological and potential human health risks depend on metal speciation, bioavailability, the fraction transferred into edible plant parts, local land-use and cultivation practices, and human or animal consumption patterns — none of which were directly quantified in this study.

The significant soil–vegetation correlation for lead is noteworthy given lead's well-characterized neurotoxic and neurodevelopmental effects, especially in children (Balali-Mood et al., 2021; Mitra et al., 2022). However, because *Prunus amygdalus* is not a commonly consumed leafy vegetable or forage crop in the region, direct dietary exposure via this species is unlikely. The primary concern is the potential for analogous uptake into locally grown edible vegetables, forage, or staple crops if cultivation occurs in close proximity to the plant. Cadmium concentrations in leaves also exceeded WHO/FAO limits for vegetables, reinforcing the need for caution regarding any future leafy-green cultivation immediately adjacent to the facility.

Therefore, these findings support precautionary measures rather than definitive statements of current population-level harm. They highlight the desirability of (i) routine monitoring of soil and vegetation within and around the DSC complex, (ii) installation of improved dust-capture and fume-extraction systems at the steel melting shop and rolling mill to reduce atmospheric emissions, and (iii) targeted follow-up research that includes off-site control sites, distance-decay profiling, assessment of locally important edible crops, and, if warranted, human biomonitoring.

Limitations

Several limitations of the present study should be acknowledged. First, contemporaneous control (background) sampling sites outside the industrial influence zone were not included; comparisons relied on published background values (Kabata-Pendias, 2011) and earlier studies conducted at or near DSC (Akporido & Ipeaiyeda, 2014; Agbaire et al., 2014). While this approach demonstrates clear elevation relative to typical uncontaminated soils, it does not fully account for possible local geological or pedogenic variations. Second, the correlation analysis was performed on $n = 8$ monthly aggregates; analysis of individual sample pairs (if multiple plants or soil cores had been treated separately) might have greater power to detect relationships, particularly for Cd. Third, only total (acid-digestible) metal concentrations were determined; bioavailability, chemical speciation, and root-to-shoot translocation mechanisms were not investigated. Fourth, while almond leaves proved useful as bio-indicators, *Prunus amygdalus* is not a primary food crop in Delta State; therefore, direct inferences about current human dietary exposure via this species are limited. These caveats temper risk interpretations and underscore the value of expanded future studies that address these gaps.

CONCLUSION

This study shows that soils and vegetation near the Delta Steel Company contain elevated concentrations of Fe, Ba, Cd, Se, Pb, and Cr relative to background values, with the highest loadings at the Steel Melting Shop and Rolling Mill. One-way ANOVA confirmed significant spatial differences for several

metals, while seasonal trends in vegetation were not statistically significant.

Pearson correlation analysis revealed a strong positive relationship between soil and leaf Pb concentrations ($r = 0.856$, $p < 0.05$), indicating a common industrial source and direct soil-to-plant transfer. Cd showed a positive but non-significant correlation ($r = 0.680$).

These findings support prioritised actions: (i) installation of improved dust and fume extraction systems at the Steel Melting Shop and Rolling Mill; (ii) establishment of routine soil and vegetation monitoring within and around the DSC complex; (iii) discouraging cultivation of leafy vegetables for human or livestock consumption within the immediate plant boundary pending further studies on edible crops; and (iv) expanded research incorporating off-site controls to better quantify enrichment and exposure risks.

Although limited by the absence of contemporaneous off-site controls and modest seasonal replication, this study provides valuable baseline data on trace metal impacts from steel production in the Niger Delta region.

REFERENCES

- Abbas, M. T., Wadaan, M. A., Ullah, H., Farooq, M., Fozia, F., Ahmad, I., Khan, M. F., Baabbad, A., & Ullah, Z. (2023). Bioaccumulation and mobility of heavy metals in the soil–plant system and health risk assessment of vegetables irrigated by wastewater. *Sustainability*, 15(21), 15321. <https://doi.org/10.3390/su152115321>
- Abubakar, S., Mohammed, A. Y., Garba, A. A., Bello, A., & Uba, B. (2025). Assessment of heavy metal contamination in soils and vegetable crops from Sharada industrial zone, Kano State, Nigeria. *FUDMA Journal of Sciences*, 9(6), 15–26.
- Agbaire, P. O., Ipeaiyeda, A. R., & Onianwa, P. C. (2014). Concentrations of seven heavy metals in the leaves of oil palm tree (*Elaeis guineensis*) and almond tree (*Prunus dulcis*) in the steel production areas of Delta State, Nigeria. *IOSR Journal of Applied Chemistry*, 7(8), 39–47.
- Akporido, S. O., Agbaire, P. O., & Ipeaiyeda, A. R. (2014). Effect of steel production on the quality of soil around Udu section of Warri River in the vicinity of a steel plant, Nigeria. *Asian Journal of Applied Sciences*, 7(7), 552–567.
- Akporido, S. O., & Ipeaiyeda, A. R. (2014). An assessment of the oil and toxic heavy metal profiles of sediments of the Benin River adjacent to a lubricating oil producing factory, Delta State, Nigeria. *International Research Journal of Public and Environmental Health*, 1(2), 40–53.
- Anyanwu, I. N., Beggel, S., Sikoki, F. D., Okuku, E. O., Unyimadu, J. P., & Geist, J. (2023). Pollution of the Niger Delta with total petroleum hydrocarbons, heavy metals and nutrients in relation to seasonal dynamics. *Scientific Reports*, 13, 14079. <https://doi.org/10.1038/s41598-023-40995-9>
- APHA. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association / American Water Works Association / Water Environment Federation.
- Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*, 12, 643972. <https://doi.org/10.3389/fphar.2021.643972>

- Guerrieri, N., Mazzini, S., & Borgonovo, G. (2024). Food plants and environmental contamination: An update. *Toxics*, 12(5), 365. <https://doi.org/10.3390/toxics12050365>
- Kabata-Pendias, A. (2011). *Trace elements in soils and plants* (4th ed.). CRC Press.
- Khan, S. N., Nafees, M., & Imtiaz, M. (2023). Assessment of industrial effluents for heavy metals concentration and evaluation of grass (*Phalaris minor*) as a pollution indicator. *Heliyon*, 9(9), e20299. <https://doi.org/10.1016/j.heliyon.2023.e20299>
- Laoye, B., Olagbemide, P., Ogunnusi, T., Akpor, O., Kumar, R., Orosun, M. M., & Ullah, Q. (2025). Heavy metal contamination: Sources, health impacts, and sustainable mitigation strategies with insights from Nigerian case studies. *F1000Research*, 14, 134. <https://doi.org/10.12688/f1000research.160148.4>
- Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., Idris, A. M., Khandaker, M. U., Osman, H., Alhumaydhi, F. A., & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University – Science*, 34(3), 101865. <https://doi.org/10.1016/j.jksus.2022.101865>
- Natasha, N., Shahid, M., Bibi, I., Iqbal, J., Khalid, S., Murtaza, B., Bakhat, H. F., Farooq, A. B. U., Amjad, M., Hammad, H. M., Niazi, N. K., & Arshad, M. (2022). Zinc in soil–plant–human system: A data-analysis review. *Science of the Total Environment*, 808, 152024. <https://doi.org/10.1016/j.scitotenv.2021.152024>
- Nuapia, Y., Chimuka, L., & Cukrowska, E. (2018). Assessment of heavy metals in raw food samples from open markets in two African cities. *Chemosphere*, 196, 339–346. <https://doi.org/10.1016/j.chemosphere.2017.12.134>
- Okerefor, U., Makhatha, M., Mekuto, L., Uche-Okerefor, N., Sebola, T., & Mavumengwana, V. (2020). Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *International Journal of Environmental Research and Public Health*, 17(7), 2204. <https://doi.org/10.3390/ijerph17072204>
- Rawat, A., Srivastava, A., Bhatnagar, A., & Gupta, A. K. (2023). Technological advancements for the treatment of steel industry wastewater: Effluent management and sustainable treatment strategies. *Journal of Cleaner Production*, 383, 135382. <https://doi.org/10.1016/j.jclepro.2022.135382>
- Wieczorek, J., Baran, A., & Bubak, A. (2023). Mobility, bioaccumulation in plants, and risk assessment of metals in soils. *Science of the Total Environment*, 882, 163574. <https://doi.org/10.1016/j.scitotenv.2023.163574>

