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Research Article

GIS-Based Assessment of Soil Heavy Metal Contamination in Asa Dam Industrial Area Ilorin, Nigeria

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Abstract

Industrial activities are among the major sources of heavy metal accumulation in soils, posing significant threats to environmental quality, ecosystem stability, and public health due to the persistence and bioaccumulative nature of toxic metals. Among these pollutants, lead (Pb) and cadmium (Cd) are widely recognized as critical indicators of industrial contamination because of their potential mobility through soil–water–plant systems and subsequent entry into the food chain. In response to increasing industrialization around the Asa Dam area in Ilorin, Kwara State, Nigeria, this study evaluated the spatial distribution and concentration of Pb and Cd in soils within selected industrial zones. A total of ten soil samples were systematically collected from each industrial site at a depth of 20 cm during the wet season, and sampling locations were georeferenced using a Garmin Global Positioning System (GPS) receiver. The concentrations of Pb and Cd were determined using Atomic Absorption Spectrophotometry (AAS), while spatial distribution patterns were analyzed and mapped using the Inverse Distance Weighting (IDW) interpolation technique within a Geographic Information System (GIS) environment. The results showed that the concentrations of Pb and Cd across all sampled locations remained below the permissible limits recommended by the World Health Organization (WHO). Comparatively higher concentrations were observed around KAM Industries relative to Doyin Investments, although these values were still within acceptable environmental thresholds. The spatial distribution maps further indicated localized variations in heavy metal concentrations without evidence of severe contamination hotspots. Overall, the findings suggest that soils within the Asa Dam industrial corridor are presently not significantly contaminated by Pb and Cd and therefore pose minimal immediate ecological and human health risks. Nevertheless, continuous environmental monitoring is recommended to ensure early detection of potential future contamination associated with ongoing industrial expansion in the area.

Keywords

Industrial Area, Heavy Metal, Environmental, Lead (Pb), Cadmium (Cd), Pollution, Random Sample

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1. Introduction

The rapid growth of industrialization and urbanization has resulted in large quantities of solid, liquid, and gaseous waste being discharged into the environment, thus giving rise to serious environmental pollution problem [1]. The occurrence of contaminants in soil beyond certain level causes deterioration or loss of some geotechnical properties of soil [1]. Heavy metal pollution of aquatic and terrestrial ecosystems is a pervasive environmental and public-health challenge, particularly in rapidly urbanizing and industrializing regions of sub-Saharan Africa. Metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu), manganese (Mn) and iron (Fe) are persistent, can accumulate in sediments and biota, and at elevated concentrations pose well-documented risks to ecological functions and human health through drinking water, food chains and direct contact. The toxicology, persistence and tendency for bioaccumulation of non-essential metals (e.g., Pb, Cd, Hg) make them priority contaminants in environmental monitoring and risk assessment frameworks [2]. A variety of environmental problems have emerged, of which heavy metal pollution is one. Heavy metals such as Lead (Pb) and Cadmium (Cd) are useful indicators of environmental pollution. Heavy metals released into the environment are major forms of pollutants that degrade the quality of today's earth [3]. Reservoirs and riverine systems situated near industrial zones are especially vulnerable because they receiving untreated or partially treated effluents, stormwater runoff, and solid-waste leachates that mobilize heavy metals. Sediments in such systems often act as both sinks and secondary sources: they record historical inputs and can release metals back to the water column under changing redox or pH conditions, with consequences for benthic organisms and fish consumed by local communities. Consequently, integrated assessment of water, sediment and biota concentrations together with contamination indices and ecological/health risk metrics is necessary to characterize contamination status and to inform remediation and management [4]. The Asa Dam / Asa River system in Ilorin (Kwara State, Nigeria) lies within an urban-industrial landscape where small-scale manufacturing, municipal wastes and effluent discharges have been reported to affect water quality. Multiple investigations have documented elevated metal concentrations in Asa River and associated reservoirs: early geochemical surveys and sediment analyses found measurable Mn, Fe, Cr, Zn and Cu in river sediments, while subsequent studies reported heavy-metal burdens in water, sediments and fish tissue, and highlighted potential contamination from industrial effluents and urban runoff. These local findings indicate a recurring pattern of metal enrichment and ecological concern that warrants a focused, contemporary assessment of industrial areas draining to Asa Dam [5, 6]. These findings suggest ongoing anthropogenic contamination and raise concerns regarding ecological integrity and public health, including the safety of fish consumption by local communities. Despite these earlier investigations, there remains a need for updated, systematic, and spatially explicit assessment particularly focused on the industrial areas draining into Asa Dam.

Industrial growth, changing waste-management practices, and expanded urban footprints over time mean that metal loading patterns and contamination risks may have evolved. A contemporary study is therefore warranted to assess current contamination status across multiple environmental compartments (water, sediment, biota/soil), to map spatial distribution, and to evaluate potential ecological and human-health risks relative to national and international guideline values. Industrial activities around Asa Dam in Ilorin, Nigeria, have the potential to introduce heavy metals into soils, water, and biota, posing risks to ecosystem health and human populations. Among these contaminants, lead (Pb) and cadmium (Cd) are recognized as priority metals due to their persistence, toxicity, and ability to bioaccumulate along food chains, ultimately affecting microorganisms, plants, animals, and humans [7, 8]. Heavy metals enter the environment through industrial emissions, leaching from soils, and runoff into surface and groundwater, highlighting the urgent need for systematic environmental assessment in rapidly urbanizing and industrializing catchments.

The present study aims to provide a rigorous, multidisciplinary evaluation of heavy-metal contamination in soils within the industrial zones of Asa Dam. The specific objectives are to: Quantify concentrations of priority heavy metals (Pb, Cd) in soils from selected industrial sites. Map the spatial distribution of these metals using geospatial techniques, including Inverse Distance Weighting (IDW) interpolation, to identify potential contamination hotspots. Compare observed concentrations with national and international regulatory standards (e.g., WHO, FAO, and sediment/soil quality guidelines) to assess compliance. To achieve these aims, the study employs robust analytical techniques, including acid digestion followed by Atomic Absorption Spectrophotometry (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS), ensuring precise quantification of total metal concentrations. Where necessary, sequential extraction protocols will assess metal mobility and bioavailability. Complementary statistical analyses, including ANOVA and multivariate techniques, will evaluate spatial and temporal variability, while GIS-based mapping visualizes contamination gradients across the industrial catchment zones. By integrating chemical concentration data, geospatial analysis, contamination indices, and risk characterization, this study provides a scientific basis for evidence-based management, targeted remediation, and informed community advisories regarding soil use, water safety, and ecosystem protection. The findings are expected to contribute to sustainable environmental management, public health protection, and regulatory decision-making in Ilorin and comparable urban-industrial settings in Nigeria and beyond [7-11]. The study is particularly timely given the rapid industrial expansion and residential growth around Asa Dam, emphasizing the need to understand the extent of heavy-metal accumulation and its potential ecological and human-health implications. Leveraging lessons from previous GIS-based environmental geochemistry studies, such as investigations of Pb distribution in Peruvian mining towns [9], this research applies spatial analytical approaches to characterize contamination patterns and provide actionable insights for stakeholders.

2. The Study Area

Ilorin is located on latitude 8°3'N and 8°5'N and longitude 4°35'E and 4°550'E with an approximation of 100sq. km land mass [12]. The city comprises of Ilorin West, East and South with a population of 777,667 [13]. The major tribe is Yoruba with Hausa, Fulani and Nupe as minority [12]. Asa Dam Area in Ilorin is located in Ilorin West Local Government, dominated by residential houses, offices, industries and a dual major road pass link to Garage Offa, New Yidi Road and Kwara State House of Assembly as shown in Figure 1. The major activities in the area are trading, modern business, Industrial and administrative activities. Selected industries are Doyin Investments, formally called Global Soap and Detergent Industries Limited and Kam Industries (Nigeria) Limited located along Asa Dam Road Ilorin, Kwara State. Doyin Investment manufactures soap and detergent while Kam Industries (Nigeria) Limited manufactures nail shanks of various sizes, umbrella and copper nails, British Reinforcement Concrete (BRC) mesh wire, binding wire, bale tiles drawn wire, straightening wires, Aluminium Roofing Sheet Galvanized Roofing Sheet etc.

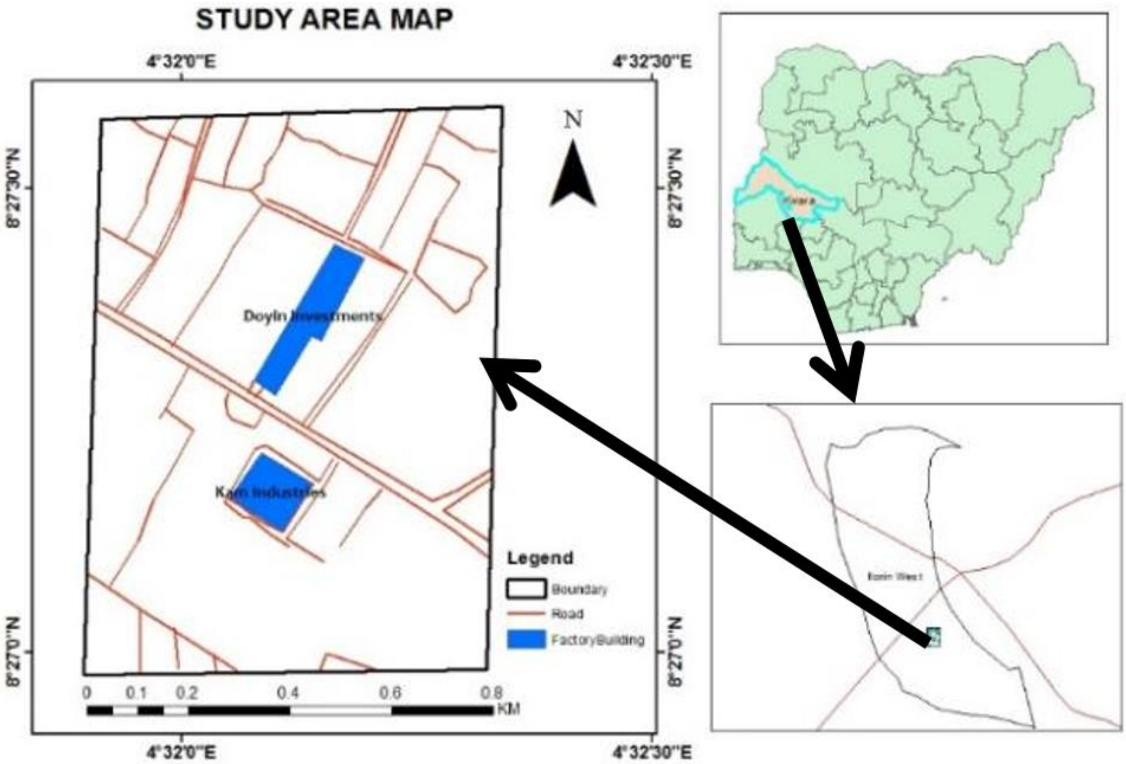

Figure 1. Map of the Study Areas.

3. Materials and Methods

Field Data (soil sample data of selected industrial area), Laboratory Data (Atomic Absorption Spectrophotometry (AAS) equipment (Buck scientific ACCUSYS 211) analysis to measure the Lead (Pb) and Cadmium (Cd) concentration in soil extraction, GPS coordinate data of the sample points, Arc GIS 10.3, Arc Info, Google Earth Plus 5.1, Microsoft Office Excel 2010, Microsoft Office Word 2010, GPS mapper (Garmin), Soil Auger, Mesh Sieve (0.59mm), Conical Flask, Electrical, Hot Plate, Whitman Paper, Funnel and Beaker, Colour printer and Laptop. Ten (10) soil samples were collected at random from ten different points on 6TH August 2016, from each location (industrial area) using a soil auger. The soil samples were collected from the rooting zone depth (20cm) during wet season. The ten soil samples from each location were placed in properly labeled polythene bags. Locations of sampling points were fixed using a Garmin Global Positioning System (GPS) receiver unit shown in the Figure 2.

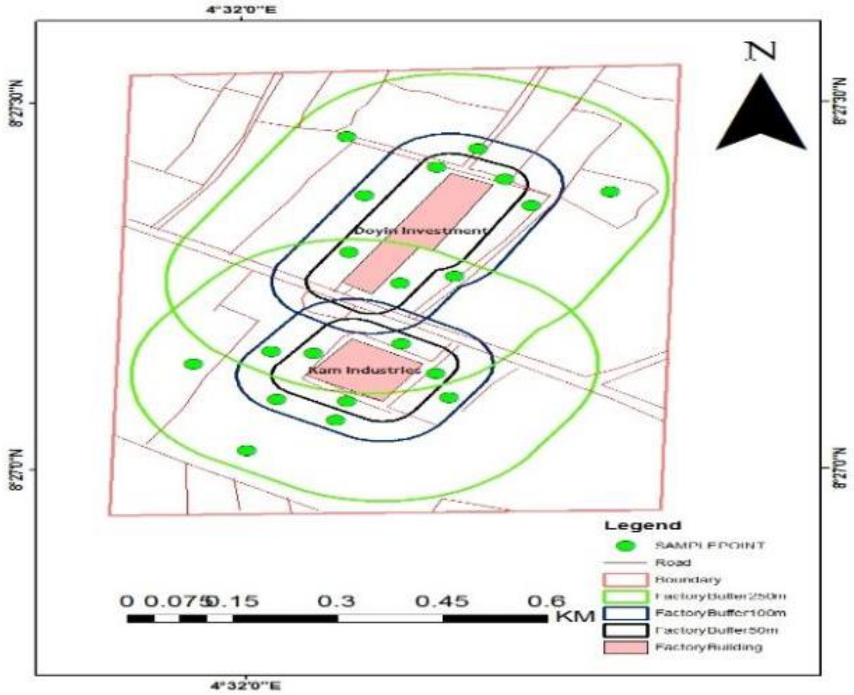

Figure 2. *Soil Sampling Locations.*

3.1. Determination of the Heavy Metal Concentrations in Samples

The soil sample digests were analyzed for Lead (Pb) and Cadmium (Cd) in two replicates, using the Atomic Absorption Spectrophotometry (AAS) equipment (model: Buck scientific ACCUSYS 211 Atomic Absorption Spectrophotometer UCR1370816) of the University of Ilorin Centre for Research Laboratories. Flame type for all analysis was air-acetylene (acetylene and natural oxygen) and suitable working blanks were prepared from solutions used to digest the samples. Necessary dilution was also made using distilled water to maintain concentrations of the metals at suitable concentration range and then results from the equipment were recorded for total metal concentration in the soil samples [14]. Lead (Pb) and Cadmium (Cd) (μg/g) of soil sample were analyzed. Metals Concentrations were extrapolated from the standard Calibration curve. The values obtained from the analysis were converted into actual concentrations of metals in the samples using the following equation:

$$\text{Concentration}(\mu g/g) = CR \times (EV)/(SW) \quad (1)$$

Where CR is the calibration reading, EV is Extract volume, and SW is sample weight.

Extract volume (EV) represents the final volume of digest used for the AAS analysis. Sample weight represents the weight of sample used (3g of soil samples). In this study, extraction volume was 100ml for soil analysis.

3.2. Determination of Spatial Distribution of Lead (Pb) and Cadmium (Cd) in the Study Area

For the creation of the thematic map, 5.1 Google Image was digitized, projected and corrected with the use of PC ARC/INFO. Then the ArcGis 10.3, modules Arc Tools and ArcMap were used for the creation of necessary shape files and query, while the extensions Geostatistical Analyst and Spatial Analyst were used for the geostatistical analysis of the data and the creation of maps [15].

The spatial pattern and distribution of Lead (Pb) and Cadmium (Cd) concentration of unsampled locations in the study area show by employed spatial interpolation. The interpolation is based on the principle of spatial auto correction. There are many spatial interpolation algorithms for spatial data sets, such as Inverse Distance Weighting (IDW) and kriging. There are two categories of interpolation techniques: deterministic and geostatistical. Deterministic interpolation technique creates surfaces based on the measured points or mathematical formulas, for example, inverse distance weighting which is based on the extent of the similarities of the cells while geostatistics interpolation such as kriging is based on statistics and is used for more advanced prediction surface modeling that also includes some measure of the accuracy of the prediction [16] Inverse Distance Weighting (IDW) is example of Deterministic, for depicting the spatial distribution of Lead (Pb) and Cadmium (Cd) concentration in the study area, the IDW interpolation method was employed because it creates surfaces based on the measured point or sample points.

4. Results

4.1. Concentration of Lead (Pb) and Cadmium (Cd) in Soil Samples Collected Around Doyin Investments

Laboratory analysis of soil samples collected around the Doyin Investments area revealed low to non-detectable concentrations of Cadmium (Cd). As shown in Table 1, Cd concentrations ranged from below detection limit (0 mg/kg) to a maximum of 0.67 mg/kg, indicating minimal cadmium enrichment in the soils. This narrow concentration range suggests the absence of significant Cd-emitting activities in the vicinity and aligns with levels typically reported for uncontaminated or slightly impacted soils in industrial–adjacent environments [16, 17]. The observed Cd values are well below internationally accepted soil quality thresholds, such as the WHO/FAO permissible limit of 3 mg/kg and the EU guideline value of 1–3 mg/kg, further confirming that the area is not currently experiencing cadmium contamination at levels of ecological or human-health concern. The comparatively low Cd concentrations around Doyin Investments may reflect effective environmental controls, distance from primary industrial emission points, or a naturally low geochemical background. Continued monitoring, however, remains essential due to the high mobility and bioaccumulation potential of Cd in agricultural and urban soils.

Table 1. Concentration of Lead (Pb) and Cadmium (Cd) in Soil Samples Collected around Doyin Investments.

S/N	Sample Code	Lead (Pb) (mg/kg)	Cadmium (Cd) (mg/kg)
1	D1	13.33	0.67
2	D2	6.67	0
3	D3	6.67	0
4	D4	10	0.33
5	D5	3.33	0
6	D6	0	0.67
7	D7	10	0.33
8	D8	3.33	0
9	D9	6.67	0
10	D10	10	0

4.2. Concentration of Lead (Pb) and Cadmium (Cd) in Soil Samples Collected Around KAM Industries

Laboratory analyses of soil samples collected in the vicinity of KAM Industries reveal measurable enrichment of both Lead (Pb) and Cadmium (Cd), reflecting the influence of nearby industrial activities. As presented in Table 2, Pb concentrations ranged from 6.67 mg/kg to 40 mg/kg, indicating moderate spatial variability across the sampling locations. The upper value approaches the lower boundary of internationally recognized guideline thresholds for Pb in soils (e.g., 50–300 mg/kg depending on land-use category; WHO, 2007; USEPA, 2011), suggesting localized anthropogenic contributions, likely associated with metallurgical processes, industrial emissions, and vehicular deposition commonly reported around industrial corridors [18, 19]. Cadmium concentrations in the same area were comparatively lower but still displayed detectable variability, ranging from below detection limit (0 mg/kg) to 1.00 mg/kg. Although these values remain within permissible limits established by the WHO/FAO and EU guidelines (1–3 mg/kg), the presence of Cd particularly at the upper end of the recorded range may signal emerging inputs from industrial operations such as metal fabrication, waste disposal, or fuel combustion, which are well-recognized Cd sources in peri-industrial environments [20, 21]. The combined Pb and Cd profiles around KAM Industries highlight a pattern of localized heavy-metal accumulation relative to other areas in the Asa Dam corridor. While concentrations do not currently exceed critical regulatory thresholds, the patterns detected underscore the importance of proactive monitoring, given the potential for incremental build-up of heavy metals in soils subjected to sustained industrial activity. Such monitoring is vital for managing long-term ecological risks, safeguarding human health, and informing evidence-based environmental regulatory decisions.

Table 2. *Concentration of Lead (Pb) and Cadmium (Cd) in Soil Samples Collected around Kam Industries.*

S/N	Sample Code	Lead (Pb) (mg/kg)	Cadmium (Cd) (mg/kg)
1	K1	6.67	0
2	K2	13.33	0
3	K3	10	0.33
4	K4	13.33	0
5	K5	10	0
6	K6	13.33	0.33
7	K7	40	0
8	K8	13.33	0
9	K9	16.67	0
10	K10	13.33	1

4.3. Spatial Distribution of Concentration of Lead in Soil Samples Collected Around Doyin Investment and Kam Industries

The spatial distribution of lead (Pb) in soils across the Asa Dam industrial corridor is presented in Figure 3. The analysis reveals distinct spatial variability, with the highest Pb concentrations concentrated in the vicinity of KAM Industries, while Doyin Investments exhibited relatively low concentrations. This pattern indicates that localized industrial activities significantly influence Pb accumulation in surrounding soils. The spatial mapping was conducted using Inverse Distance Weighting (IDW) interpolation, which enabled the generation of a continuous surface representing Pb concentration gradients across the study area. The IDW map delineates zones of high, moderate, and low Pb accumulation, clearly illustrating that Pb enrichment is primarily localized around KAM Industries, likely due to metal-intensive manufacturing processes such as the production of nail shanks, BRC mesh, binding wires, and roofing materials. In contrast, the low Pb levels observed around Doyin Investments are consistent with its production of soaps and detergents, which generate minimal metal emissions. Importantly, the spatial map shows no evidence of interpolation bias, providing a reliable representation of Pb distribution. These results underscore the value of GIS-based spatial analysis for identifying contamination hotspots, guiding targeted monitoring, and informing environmental management strategies. The observed distribution also provides a basis for risk assessment and proactive mitigation measures, enabling policymakers and environmental regulators to prioritize areas for intervention before Pb concentrations approach critical thresholds [22, 23].

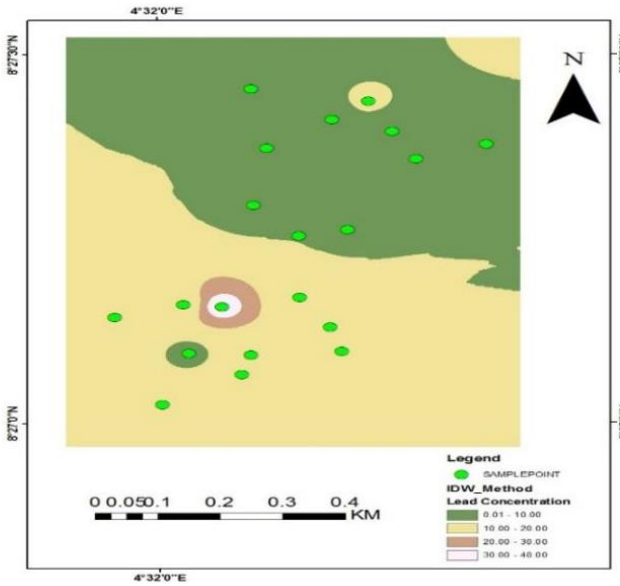

Figure 3. *Spatial Distribution of the Concentration of Lead (Pb) in the Study Area.*

4.4. Spatial Distribution of Concentration of Cd in Soil Samples Collected Around Doyin Investment and Kam Industries

Figure 4 presents the spatial distribution of cadmium (Cd) concentrations in soils across the Asa Dam industrial corridor. Cd was analyzed in conjunction with Pb to provide a comprehensive assessment of heavy-metal contamination in the study area. The spatial analysis reveals that elevated Cd concentrations are localized in a limited area surrounding KAM Industries, whereas lower Cd levels are observed in the soils between KAM Industries and Doyin Investments. This pattern suggests that Cd accumulation is influenced by specific industrial activities rather than being uniformly distributed across the corridor. The distribution map was generated using the Inverse Distance Weighting (IDW) interpolation method, which provides a continuous surface representing the concentration gradients of Cd. The IDW map effectively identifies zones of high, moderate, and low Cd accumulation, demonstrating that Cd enrichment is more localized and less widespread than Pb. The higher Cd concentrations near KAM Industries likely reflect emissions associated with metal processing and manufacturing operations, whereas the lower concentrations around Doyin Investments are consistent with its limited metal-related industrial activities. The spatial distribution map provides critical insights for environmental monitoring, risk assessment, and management. By highlighting areas with elevated Cd concentrations, policymakers and environmental regulators can prioritize targeted interventions and preventive measures to mitigate potential soil contamination. Additionally, these spatial data support community awareness programs and long-term environmental surveillance, ensuring that Cd levels remain within safe thresholds as industrial activities continue to develop in the Asa Dam corridor [22, 23].

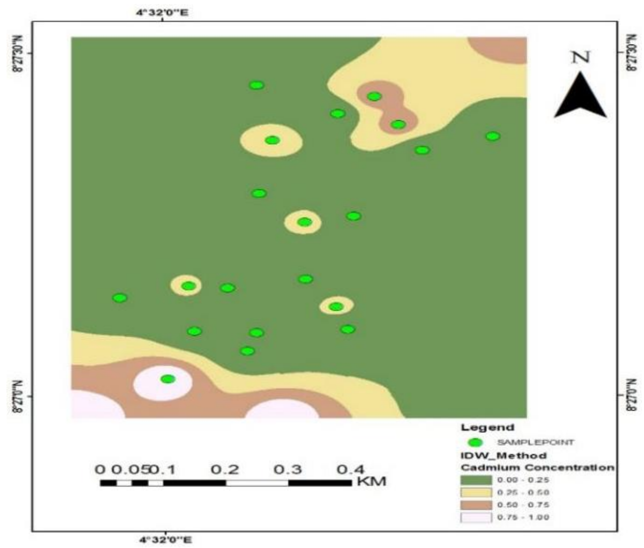

Figure 4. Spatial Distribution of the Concentration of Cadmium (Cd) in the Study Area.

5. Discussion

5.1. Concentration of Lead (Pb)

Lead (Pb) is widely recognized as one of the most hazardous heavy metals due to its persistence, bioaccumulation potential, and toxicity to plants, animals, and soil microorganisms. Its presence in agricultural and industrial environments is commonly linked to emissions from lead mining, combustion of leaded fuels, disposal of sewage sludge, application of contaminated manure, and various industrial manufacturing processes [24]. Pb contamination in soils can impair microbial activity, inhibit enzymatic processes, and disrupt plant physiological functions, even at relatively low concentrations. In the present study, Pb concentrations in all soil samples were below the maximum permissible limit of 70 mg/kg established for agricultural soils [25], indicating that the study area is not currently experiencing Pb pollution at levels that pose ecological or public health risks. The highest Pb concentration recorded was 40 mg/kg in the vicinity of KAM Industries, while the Doyin Investments area exhibited a markedly lower maximum concentration of 13.33 mg/kg. These values fall well within the World Health Organization (WHO) guideline thresholds, confirming that the soils are non-toxic with respect to Pb contamination. The spatial pattern of Pb distribution reflects the nature and intensity of industrial activities within each zone. KAM Industries engages in extensive metal-based manufacturing, including the production of nail shanks, umbrella and copper nails, binding wires, British Reinforcement Concrete (BRC) mesh, drawn wire, straightened wire products, and various roofing sheets, which may contribute to localized Pb emissions. In contrast, Doyin Investments is primarily involved in the production of soap and detergents, activities that generally generate lower levels of metal contaminants. This industrial contrast aligns with the observed Pb concentration gradient, where higher values cluster around KAM Industries while lower values dominate the Doyin Investments area. Overall, the Pb concentrations recorded in this study, with a maximum of 40 mg/kg, remain significantly below the permissible limit of 70 mg/kg [26]. These findings indicate that the soils within the Asa Dam industrial corridor are currently unpolluted by Pb and pose minimal immediate environmental or health concerns. Nonetheless, the elevated levels near KAM Industries highlight the importance of continued monitoring, particularly as industrial activities expand or intensify.

5.2. Concentration of Cadmium (Cd)

Cadmium (Cd) is a highly toxic heavy metal that poses significant risks to human health, plants, and soil microorganisms even at low concentrations. Common sources of Cd contamination in soils include phosphate fertilizers, non-ferrous smelting operations, Pb and Zn mining activities, sewage sludge application, and fossil fuel combustion [27, 28]. Due to its mobility and persistence in the environment, Cd can accumulate in soils and enter the food chain, potentially causing chronic health issues in humans and ecological disturbances. International guidelines set the permissible concentration of Cd in soils between 1.4 and 3 mg/kg [29, 30]. In this study, Cd concentrations in all soil samples were observed to be low, with the highest recorded concentration of 1.00 mg/kg occurring in soils adjacent to KAM Industries. In comparison, soils near Doyin Investments recorded a maximum Cd concentration of 0.67 mg/kg. These results indicate that, although Cd is detectable throughout the study area, its levels remain well below international thresholds and within the normal range of 1–

10 mg/kg for soil [26]. The slightly elevated Cd levels observed near KAM Industries likely reflect localized industrial contributions, whereas the lower concentrations at Doyin Investments are consistent with the nature of its operations, which primarily involve soap and detergent production and generate minimal Cd emissions. Overall, the data demonstrate that soils across both industrial zones remain uncontaminated with respect to Cd. These findings suggest minimal environmental risk from Cd at present but underscore the importance of ongoing monitoring, particularly in areas of concentrated industrial activity, to ensure that future accumulation does not exceed safe limits as shown in Table 3.

Table 3. *Some standards for heavy metals in soils (in mg/kg).*

S/N	Parameters	Denmark Standards	WHO Standards	NESREA Standards
1	Cadmium	5	10	3 – 6
2	Chromium	Not fixed	Not fixed	Not fixed
3	Lead	40	70	250 – 500
4	Iron	Not fixed	Not fixed	Not fixed
5	Zinc	500	200	300 – 600

5.3. Spatial Distribution of Lead (Pb)

The spatial analysis revealed distinct patterns in the distribution of lead (Pb) concentrations across the two industrial zones surrounding Asa Dam. Pb was detected at all sampling locations, indicating that its presence is widespread across the study area. Despite this broad distribution, concentrations remained within the permissible limits recommended by the World Health Organization (WHO), suggesting that the soils are not currently experiencing Pb contamination at levels hazardous to human or ecological health. The highest Pb concentrations and the most pronounced spatial clusters were consistently observed in the vicinity of KAM Industries, whereas the Doyin Investments area exhibited comparatively lower Pb levels. This spatial gradient suggests that industrial emissions or operational practices near KAM Industries may be contributing to localized Pb enrichment. However, the distribution pattern did not show interpolation bias, and Pb was not exclusively concentrated around any single industrial source [22, 23]. The Inverse Distance Weighting (IDW) interpolation technique effectively visualized the spatial variability of Pb, delineating zones of very high, high, medium, and low concentrations across the study area. The IDW-derived map successfully addressed one of the core research objectives by providing a clear and interpretable representation of Pb distribution in soils. This spatial mapping enhances understanding of pollutant dispersion and serves as a critical tool for identifying potential accumulation zones [31, 32]. Although Pb concentrations are within acceptable limits, the relatively higher values near KAM Industries underscore the need for continuous environmental monitoring, particularly as industrial activities expand. The spatial distribution map holds significant value for policymakers, environmental regulators, and public health officials, as it enables targeted intervention, informed remediation planning, and proactive land management. Additionally, publicly accessible Pb distribution maps can play an important role in community awareness initiatives and help mitigate the risk of lead exposure and associated health effects.

5.4. Spatial Distribution of Cadmium (Cd)

The spatial analysis revealed clear patterns in the distribution of cadmium (Cd) across the industrial zones surrounding Asa Dam. Overall, Cd concentrations remained below the World Health Organization (WHO) permissible limits, indicating that soils within both industrial areas are currently not contaminated with respect to this metal. Despite the generally low levels, Cd was detected throughout the study area, demonstrating a widespread but low-intensity presence. Spatial interpolation using the Inverse Distance Weighting (IDW) technique provided a detailed visualization of Cd variability, distinguishing zones of low, moderate, and relatively elevated concentrations [31, 32]. The IDW-generated map showed that areas proximate to KAM Industries exhibited higher Cd concentrations compared to Doyin Investments, suggesting localized emissions or depositional processes linked to industrial activities. However, a few sampling points within the Doyin Investments area also displayed moderately elevated concentrations, indicating that contributions to soil Cd levels may not be exclusively limited to a single industrial source. The spatial distribution map demonstrated no interpolation bias and effectively captured the gradient of Cd concentrations across the study area. This visualization not only supports the accuracy of the dataset but also addresses the research objective of identifying potential hotspots of Cd accumulation. The ability to spatially differentiate areas of higher Cd loading is particularly valuable for environmental monitoring, targeted remediation, and strategic land-use planning. Although Cd concentrations are currently within acceptable limits, the higher values observed near KAM Industries highlight the need for ongoing surveillance to prevent future escalation. The spatial mapping of Cd serves as an important tool for policymakers, environmental agencies, and the local population by promoting awareness of heavy-metal risks and supporting evidence-based environmental management aimed at preventing uncontrolled increases in soil Cd levels.

5.5. Synthesis and Implications

The integrated assessment of lead (Pb) and cadmium (Cd) concentrations, combined with spatial distribution analysis, demonstrates that soils within the Asa Dam industrial corridor are currently within internationally accepted safety thresholds for both heavy metals [18-20]. Slightly elevated concentrations observed near KAM Industries reflect localized industrial activities, particularly metal-based manufacturing processes, while soils around Doyin Investments exhibited consistently lower levels, consistent with its less metal-intensive operations. This spatial heterogeneity underscores the influence of industrial type and intensity on soil heavy metal accumulation, a phenomenon widely reported in similar industrial environments [22, 23]. The coupling of quantitative concentration measurements with GIS-based spatial mapping provides a robust framework for environmental monitoring, enabling the identification of potential hotspots and patterns of contaminant dispersion. Such integrative approaches have been recommended as best practices for assessing and managing heavy metal contamination in rapidly developing industrial areas [31, 32]. By visualizing the spatial extent and intensity of Pb and Cd accumulation, policymakers, environmental regulators, and urban planners can prioritize targeted interventions, optimize remediation strategies, and implement preventative measures before contamination reaches critical thresholds. These findings also have important implications for public health and community awareness. Continuous environmental surveillance, periodic soil testing, and repeated spatial mapping are essential to prevent the future accumulation of heavy metals in soils, water, and crops, particularly as industrial expansion continues. Early detection of potential contamination can reduce the risk of heavy metal exposure to humans and the ecosystem, ensuring sustainable industrial development while maintaining soil quality and environmental safety. Furthermore, this study provides a baseline dataset that can inform long-term monitoring programs, regulatory policies, and educational initiatives aimed at promoting safe industrial practices and environmental stewardship in the Asa Dam region [31, 32].

6. Conclusion

This study assessed the concentrations and spatial distribution of lead (Pb) and cadmium (Cd) in soils across industrial zones surrounding Asa Dam, Ilorin, with the aim of evaluating potential contamination associated with rapid industrial expansion in the area. The results demonstrate that Pb and Cd concentrations in all sampled locations remain below the permissible limits established by the World Health Organization (WHO), indicating that soils within the study area are not currently experiencing heavy-metal pollution at levels considered hazardous to the environment or human health. Spatial analysis revealed that both heavy metals were present across the entire study area, although with varying concentrations. Slightly elevated Pb and Cd levels were observed in proximity to KAM Industries compared with the Doyin Investments area, suggesting localized contributions from industrial activities. Nevertheless, the overall concentrations remained within safe thresholds, and no site exhibited contamination levels indicative of acute or chronic toxicity. The observed spatial patterns highlight the importance of continuous monitoring, as ongoing industrial growth could alter contamination dynamics over time. The findings of this research provide valuable baseline information for environmental scientists, regulatory agencies, and policymakers seeking to prioritize environmental surveillance, design mitigation strategies, or enforce sustainable industrial practices. Long-term monitoring and expanded assessments including additional metals, seasonal comparisons, and risk evaluations are recommended to ensure early detection of emerging pollution risks and to safeguard soil quality and public health in the Asa Dam industrial corridor.

Abbreviations

AAS	Atomic Absorption Spectrophotometry
BRC	British Reinforcement Concrete
Cd	Cadmium
Cr	Chromium
Cu	Copper
Fe	Iron
GPS	Global Positioning System
IDW	Inverse Distance Weighting
Mn	Manganese
Pb	Lead
WHO	World Health Organization
Zn	Zinc

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Author Contributions

Isiaka Lukman Alage: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft

Ebeiyamba Okon Ekpo: Investigation, Methodology, Writing – review & editing

Seyi Festus Olatoyinbo: Investigation, Methodology, Writing – review & editing

Data Availability Statement

Datasets are available upon request, and selected network-related code can be accessed publicly on GitHub at https://github.com

Conflicts of Interest

The authors declare no potential conflicts of interest related to this research.

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