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Research Article

Characterization and Risk Evaluation of Heavy Metals in Niakhene Soils Using X-ray Fluorescence

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Abstract

Heavy metal contamination in soils poses serious threats to environmental and human health due to metal persistence and toxicity. In Senegal, particularly in the Niakhene region, soil pollution may result from agricultural practices, atmospheric deposition, and past land use. This study aims to determine the concentrations of heavy metals: Nickel (Ni), Arsenic (As), Zinc (Zn), Cesium (Cs), Palladium (Pd), and Tin (Sn) in agricultural soils and to assess their potential environmental and health risks. A total of 47 soil samples were collected at two depths (0–20 cm and 20–40 cm) and analyzed using energy-dispersive X-ray fluorescence (ED-XRF) spectroscopy, a non-destructive and accurate technique. The analysis revealed varying concentrations of heavy metals, with Zn ranging from 0.00 to 29.49 mg/kg, Ni from 20.02 to 47.30 mg/kg, and Arsenic (As) from 0.00 to 5.67 mg/kg. The study found that Cd, Cu, Pb, and Hg were not detectable in the samples. Comparative analysis with EU threshold limit values (TLVs) indicated that concentrations of most metals were within safe limits, although some samples approached the maximum contaminant levels (MCLs) for Nickel and Arsenic. The findings highlight the need for ongoing monitoring and potential remediation to manage soil contamination and protect environmental and human health. These findings highlight the importance of continuous soil monitoring in the region and support the implementation of appropriate soil management and pollution mitigation strategies to safeguard both environmental quality and public health.

Keywords

Heavy Metal Pollution, X-ray Fluorescence, Soil Contamination, Environmental Health Risks, Threshold Limit Values

1. Introduction

Global environmental challenges stem from the notable increase in heavy metal pollution of soil, particularly from Nickel (Ni), Arsenic (As), Zinc (Zn), Chromium (Cr), Lead (Pb), Cadium (Cd), and Mercury (Hg). These metals, which are a result of numerous industrial, mining, agricultural, and urban activities, seep into the environment and linger in soils, endangering both human health and the integrity of terrestrial ecosystems [1, 2]. This study used a non-destructive X-ray fluorescence (XRF) analytical approach to determine the amounts of these metals in soils. This approach, which is well-known for its accuracy and capacity to detect heavy metal concentrations without modifying samples, thoroughly assessed the existence and distribution of these components in the investigated soils [3]. The notable increase in heavy metal contamination of soil, particularly that of nickel (Ni) and arsenic (As), raises concerns about environmental and public

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health risks, as these metals can accumulate in plants and enter the food chain. The accumulation and pollution of urban soil heavy metals, which are significantly influenced by the urban soil environment, is a characteristic that leads to the rapid development of urbanization and the expansion of industrial sectors in and around urban areas. Car emissions, trash disposal, urban waste, and the extensive use of agro-chemicals are the main pathways through which heavy metals are introduced into the urban environment [4-7]. This research offers a thorough understanding of the extent of heavy metal contamination in soil globally. Put differently, prolonged exposure to toxic metals found in soil has primarily resulted in an immediate threat to environmental pollution and health risks for humans, as heavy metals are absorbed by the body through three different routes: ingestion, inhalation, and skin contact [8-14].

The impacts of urban soil buildup of heavy metals on human health are generally the main focus of research. Therefore, urban soil heavy metal pollution its incidence, distribution, and significant impact on dangers to human health has received a great deal of attention in a variety of places. The heavy metals Pb, Zn, and Cu, for example, are usually derived from vehicle emissions, while Hg and Cu are primarily derived from industrial effluents and urban wastes [15]. Conducted an extensive study on soil heavy metals pollution and its spatial distribution pattern in a typical county of Guangdong Province, China. Most recently, Pan et al. examined the dangers to human health posed by soil heavy metal pollution in typical Chinese urban cities [12].

Then, the author can include the relevant findings that urban soils generally contain higher levels of heavy metals compared to farming and peri-urban soils. Furthermore, humans can come into contact with urban soils, with the primary exposure pathways to these heavy metals being ingestion, oral intake, and inhalation. Additionally, a study evaluating soil heavy metal contamination highlighted its significant impact on children's health by applying health risk assessment on both national and regional scales [4, 14, 8, 16]. The principal goals of this reseach are (1) to ascertain the amounts of heavy metal pollution using X-ray fluorescence spectrometry and (2) to evaluate the health concerns associated with heavy metals in Niakhene's urban soils. The heavy metals' (threshold limit values) TLVs or Maximum Contaminant Level (MCL) utilized in this work were taken from EU standards. These norms are accepted values as a heavy metal threshold for European soils from the published literature [17, 18].

2. Experimental Details

2.1. Study Area

The study site is in the department of Tivaouane's Thies region, specifically in Niakhene. The study site is located 184 kilometers away from Dakar. The agricultural site's sandy, light soil is particularly porous to air and water, making it easy to deal with. Natural drainage is made possible by its porous structure. But because it lacks organic matter and is highly filtering, this kind of soil is quickly washed away by rain or irrigation and holds very little water or nutrients. As seen in Figure 1, the 11-hectare agricultural plot is defined by five UTM coordinates.

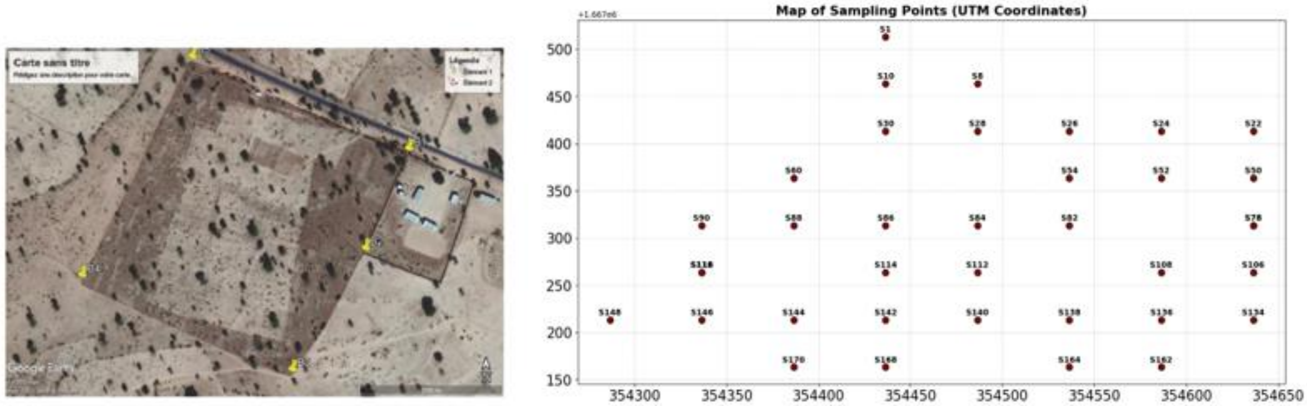

Figure 1. *The schematic map of Niakhene reporting the soils sampling locations.*

2.2. Sampling Method of Soil

The research site's soil has previously been tilled to a depth of 15 cm, causing humus disruption at the surface. For this reason, we took 02 profiles, measuring 0–20 and 20–40 cm, at each sampling point, with a 50 m separation in between. For the place that is cultivated. Seven transepts yielded a total of 36 sample points. At every cultivated site sampling point, the depth of the core was separated into two subsamples: 0–20 cm and 20–40 cm. From the farmed location, we extracted 36 subsamples. The detailed sampling plan with the various points sampled is depicted in the accompanying figure 1.

X-ray Fluorescence Principle

The X-ray fluorescence analysis method works by ionizing atoms by dislodging electrons close to the nucleus by intensely exposing a sample to X-ray radiation. Consequently, the atom adjusts its electron cloud to stabilize [19, 20]. Specifically, an X-ray fluorescence photon is released when an electron is ejected and is replaced by an electron from an outer layer. This radiative transition occurs as a result of the filling of the vacancy. This released photon is a unique indicator of the emitting atom since its energy is equal to the difference in energy between the beginning and final states of the recombined electron. An X-ray emission line spectrum is produced by measuring the fluorescence intensity at each energy level, depending on the makeup of the sample [21]. Depending on the excitation energy, this method enables the total content of elements in the sample with an atomic number over a predetermined threshold to be determined [22]. It's vital to remember that this phenomena mostly impacts elements with higher atomic numbers because heavy metals are less relevant to low atomic number atoms' decreased fluorescence yield [23].

The research deployed an X-ray fluorescence (XRF) spectrometer (Niton XLT900s ED-XRF spectrometer) with a resolution of 178 eV at Mn Kα to analyze certain materials. With a maximum power of 2 W, a 50 kV, 40 A excitation tube, and a 12.7 µm Be window thickness, the spectrometer can produce a 7 mm beam diameter. To specifically target particular elements in the samples taken from Senegal's marketplaces, a variety of filters were applied, including Ag for the excitation source, a sandwich of Al, Ti, and Mo, a Cu filter, and no filter at all. The UniQuant 4 program made the quantitative analysis easier.

3. Results and Discussion

3.1. Heavy Metal Concentrations in Soil Samples

Using the XRF spectrometer, the amounts of heavy metals (HM) As, Pd, Cd, Ni, Zn, and sn were determined based on the elemental analysis. Table 1 shows the descriptive statistics of chemical element concentrations in soil samples.

Table 1. *Summary Statistics of Heavy Metal Concentrations in Niakhene Soils.*

Heavy metals	Min (mg/kg)	Max (mg/kg)	Mean (mg/kg)	Std Dev	N	Std Err
As	0.00	5.67	2.60	1.69	37.00	0.20
Zn	0.00	29.49	12.54	5.96	37.00	0.70
Ni	20.02	47.30	32.88	5.57	37.00	0.65
Cs	0.00	47.66	1.29	7.84	37.00	0.92
Pd	25.35	42.37	34.25	4.01	37.00	0.47
Sn	94.60	121.73	109.53	5.45	37.00	0.64
Cd	0.00	0.00	0.00	0.00	37.00	0.00
Cu	0.00	0.00	0.00	0.00	37.00	0.00
Pb	0.00	0.00	0.00	0.00	37.00	0.00
Hg	0.00	0.00	0.00	0.00	37.00	0.00

(Min (Minimum): The lowest recorded concentration, MAX (Maximum): The highest recorded concentration, Mean (Average): The arithmetic mean of the concentrations Std Dev (Standard Deviation): A measure of the dispersion or spread of the concentrations around the mean, N (Number of Samples): The total number of soil samples analyzed for each metal and Std Err (Standard Error): An estimate of the standard deviation of the sample mean).

Arsenic concentrations in the soil samples range from 0.00 to 5.67 mg/kg, with an average of 2.60 mg/kg and a standard deviation of 1.69 mg/kg. Zinc concentrations vary between 0.00 and 29.49 mg/kg, with a mean of 12.54 mg/kg and a standard deviation of 5.96 mg/kg. Nickel concentrations range from 20.02 to 47.30 mg/kg, with an average of 32.88 mg/kg and a standard deviation of 5.57 mg/kg. Cesium levels range from 0.00 to 47.66 mg/kg, with an average of 1.29 mg/kg and a standard deviation of 7.84 mg/kg. Tin concentrations span from 94.60 to 121.73 mg/kg, with an average of 109.53 mg/kg and a standard deviation of 5.45 mg/kg. Cadmium concentrations range from 25.35 to 42.37 mg/kg, with an average of 34.25 mg/kg and a standard deviation of 4.01 mg/kg. The figure 2 illustrates the distribution of heavy metal concentrations in soil samples from Niakhene. Tin (Sn) exhibits the highest mean concentration, followed by Palladium (Pd) and Nickel (Ni), indicating significant levels of these metals in the study area. Arsenic (As) and Zinc (Zn) also show notable mean concentrations, though with greater variability. Cesium (Cs) presents a lower mean concentration but with a wide standard deviation, reflecting inconsistent distribution across samples. The regional variation in heavy metal concentrations throughout the Niakhene site emphasizes how diverse the contamination is. For elements like nickel and arsenic, there were noticeable differences even though the concentrations of the majority of the elements stayed below the maximum contamination values. Arsenic, for instance, varied from 0.00 to 5.67 mg/kg and nickel from 20.02 to 47.30 mg/kg. Due to specific anthropogenic activities, such as farming techniques or previous land usage, these variances imply that certain places may be more impacted than others. A further indication of this heterogeneity is the very high standard deviations for certain elements (such as cesium and zinc). Future research could detect pollution hotspots and advise targeted soil management measures by utilizing geostatistical techniques or spatial mapping.

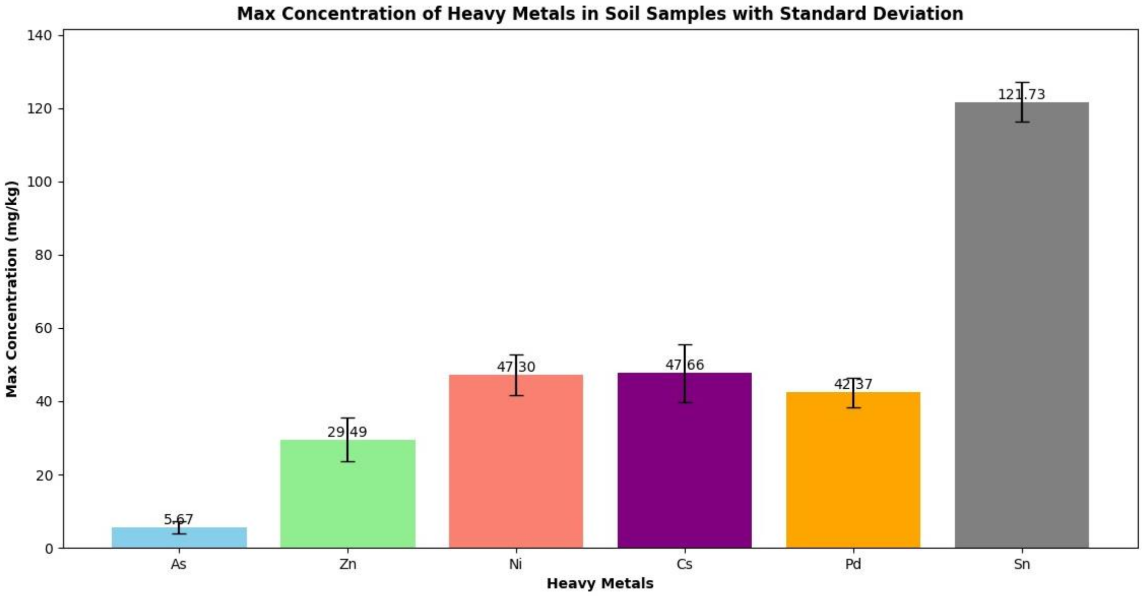

Figure 2. *Maximum Concentrations of Heavy Metals in Soil Samples with Standard Errors.*

The absence of detectable levels for Cadmium (Cd), Copper (Cu), Lead (Pb), and Mercury (Hg) suggests these metals are not currently contributing to soil contamination in the study area.

3.2. Risks Associated with Heavy Metals in Soil

In environmental science and soil health studies, understanding the permissible levels of heavy metals in soil is critical for assessing contamination and its potential impact on both human health and the environment. The table 2, presents the threshold limit values for various heavy metals in soils. These values serve as guidelines to help identify contamination levels that could be harmful and to inform remediation efforts. The metals included in this table are commonly monitored due to their potential toxicity and prevalence in industrial and agricultural settings.

Table 2. *Threshold Limit Values for Heavy Metals in Soil.*

Heavy Metals	As	Zn	Ni	Cd	Cs	Cu	Pb	Sn	Hg
Threshold limit value (mg/kg)	20	300	50	3	-	100	300	-	1

In this section, we compared the detected concentrations of heavy metals with the established limit values. A comparative analysis of heavy metal concentrations in soil samples has been conducted to assess environmental and health risks. This analysis aims to determine whether the levels of metals like Arsenic (As), Zinc (Zn), Nickel (Ni), Cesium (Cs), Palladium (Pd), Tin (Sn), Cadmium (Cd), Copper (Cu), Lead (Pb), and Mercury (Hg) fall within safe limits established by regulatory guidelines. The figure 3 showed comparison of arsenic (As) concentrations across different samples relative to the MCL, mean, minimum, and maximum provides valuable insights.

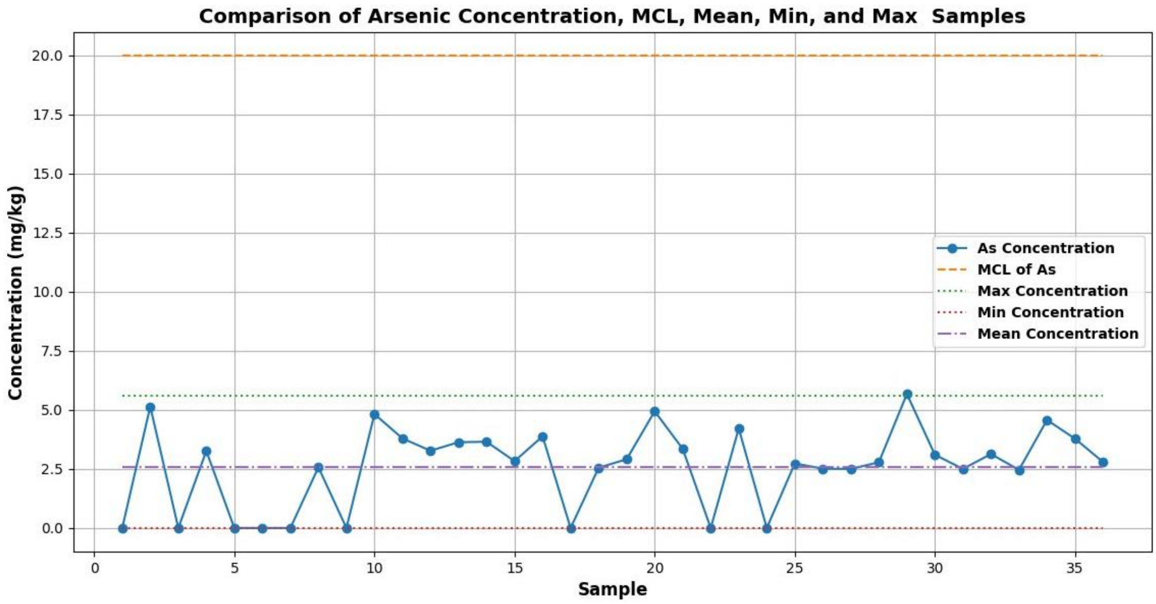

Figure 3. *Comparison of Arsenic Concentrations, MCL, Mean, Minimum, and Maximum Across Samples.*

The arsenic concentrations in all 36 samples are well below the MCL of 20 mg/kg, which is reassuring and indicates that the arsenic levels in the study area are within safe limits for soil contamination. The highest observed concentration of 5.67 mg/kg, although higher than the mean, remains significantly below the MCL, underscoring the safety of the samples with respect to arsenic contamination. The mean arsenic concentration of 2.6 mg/kg serves as a benchmark for the central tendency of the dataset. This value is notably lower than the MCL, reinforcing the conclusion that typical arsenic levels are safe. Several samples have an arsenic concentration of 0 mg/kg, indicating areas with no detectable arsenic presence. This suggests that some parts of the study area are naturally free from arsenic or have been successfully remediated. The figure 4 provides a comparative analysis of Nickel (Ni) concentrations across different samples. It highlights the Ni concentrations relative to the Maximum Contaminant Level (MCL), mean, minimum, and maximum values.

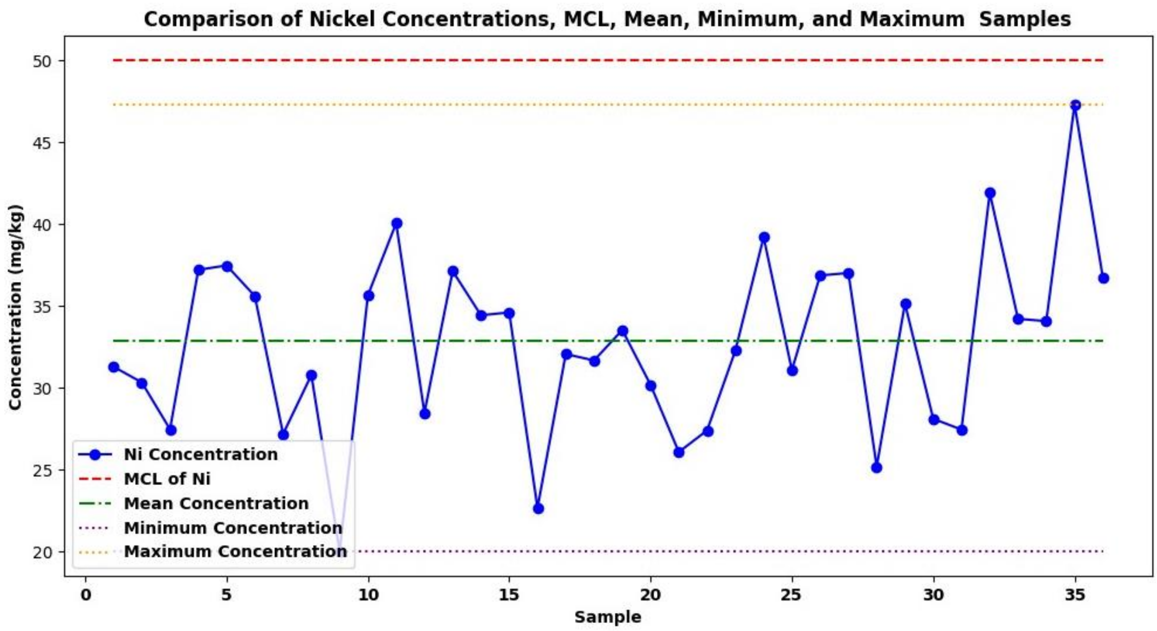

Figure 4. *Comparison of Nickel Concentrations, MCL, Mean, Minimum, and Maximum Across Samples.*

The comparison of nickel (Ni) concentrations across different samples relative to the Maximum Contaminant Level

(MCL), mean, minimum, and maximum provides valuable insights into the nickel contamination levels in the study area. The Ni concentrations in all 36 samples are below the MCL of 50 mg/kg. This indicates that nickel levels in the study area are within the safe limits for soil contamination. The highest observed concentration of 47.3 mg/kg, although approaching the MCL, remains below it, highlighting the relative safety of the samples concerning nickel contamination. The comparative analysis of nickel concentrations against the MCL, mean, minimum, and maximum values reveals that all samples are within safe limits, with the highest concentration approaching the MCL. This indicates a generally safe environment concerning nickel contamination, although the observed variability and proximity of some values to the MCL suggest the need for ongoing monitoring and targeted investigations in areas with relatively higher concentrations. The Figure 5 compares Zinc (Zn) concentrations across various samples to the Maximum Contaminant Level (MCL) of 300 mg/L, providing an overview of zinc contamination in the study area.

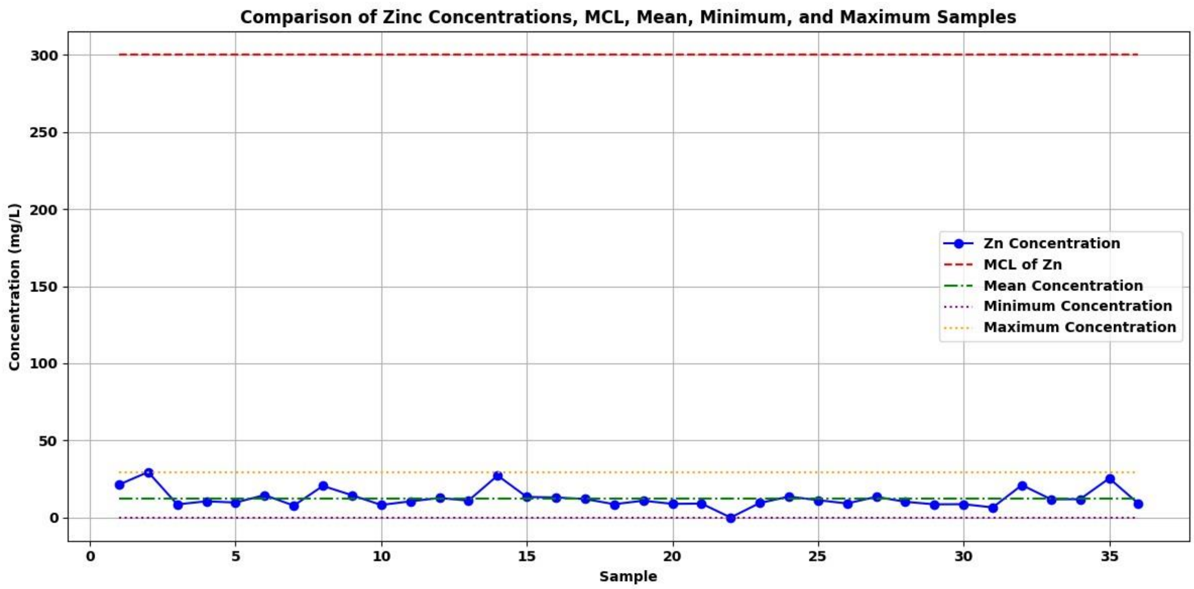

Figure 5. *Comparison of Zinc (Zn) Concentrations, Maximum Contaminant Level (MCL), Mean, Minimum, and Maximum Across Samples.*

The Zn concentrations in all 36 samples are well below the MCL, with the highest value recorded at 29.49 mg/L, indicating no immediate risk of zinc toxicity. The mean concentration is 12.54 mg/kg, suggesting generally low levels of contamination, while the minimum concentration is 0 mg/kg, showing some samples have negligible or no zinc presence. Despite variability in Zn levels, influenced by factors such as soil composition and proximity to zinc sources, all concentrations remain safely within the MCL, indicating a low risk of zinc-related health issues.

Although the total quantities of heavy metals were evaluated in this study, it is crucial to remember that their bioavailability is directly related to the risk they pose to ecosystems and human health. The portion of a metal that is biologically available for plant absorption or human exposure may not always be represented by the total amount of the metal in the soil. A number of soil characteristics, including as pH, organic matter concentration, and redox potential, affect bioavailability. For instance, metals like nickel and arsenic may move more readily in acidic or low-organic soils. To offer a more accurate assessment of the dangers to the environment and human health, future research should include bioavailability studies, such as chemical speciation or sequential extraction.

4. Conclusion

The soil analysis in Niakhene, Senegal, revealed that the concentrations of heavy metals, including Zinc (Zn), Nickel (Ni), and Arsenic (As), are notably elevated, with some values approaching or exceeding established threshold limits. The study identified variations in heavy metal concentrations, with Nickel and Arsenic levels nearing the maximum contaminant levels, indicating potential environmental and health risks. The observed metal levels are attributed to both natural and anthropogenic factors, such as industrial activities and agricultural practices. Although Cadmium (Cd), Copper (Cu), Lead (Pb), and Mercury (Hg) were not detected, the presence of other metals at elevated levels suggests a need for continued monitoring. To address these issues and mitigate potential risks, it is recommended to implement regular soil quality assessments and pollution control measures. This includes monitoring environmental factors that influence metal mobility and ensuring effective management practices to reduce contamination. By taking these steps, we can better protect both public health and soil integrity in Niakhene.

Abbreviations

As	Arsenics
Cu	Copper
Pb	Lead
Hg	Mercury
TLVs	Threshold Limit Values
Cd	Cadmium
Ni	Nickel
Zn	Zinc
MCL	Maximum Contaminant Level
XRF	X-ray Fluorescence

Conflicts of Interest

The authors declare no conflicts of interest.

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