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Ethical Statements:

i. This study received approval from the Ethics Committee of the University of Jos, Plateau State, Central Nigeria.
ii. All ethical considerations or guidelines by the Ethics Committee of the University of Jos were strictly complied with.
iii. All human-related procedures were performed in accordance with the guidelines and regulations of the University of Jos, Nigeria.

Consent to publish statement: Informed consent to publish this manuscript was obtained from all participants.

Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

ABSTRACT

Organic manure has been used as a nutrient source since the dawn of agriculture. Still, after the widespread use of inorganic fertilizers, bulky organic manures became the second-best option for supplying nutrients. The application of sewage sludge as organic manure in agriculture has raised

concerns about soil contamination, environmental safety, and public health. This study assessed the concentrations of selected heavy metals (cadmium (Cd), chromium (Cr), nickel (Ni), zinc (Zn), copper (Cu), and lead (Pb)) and investigated the presence of pathogens, such as bacteria and parasites, in soils amended with sewage sludge in Jos North and its environs, North Central Nigeria. Soil samples were analyzed for heavy metals (Zn, Cu, Pb, Cr, and Ni) using X-Ray Fluorescence (XRF), and for microbial and parasitological contaminants using standard culture and microscopic techniques. Results showed a significant increase in zinc (Zn) concentration in sludge-amended soils, with a mean difference of 0.0047495% (47.495 ppm) compared to non-sludge soils, while other heavy metals (Cu, Pb, Cr, Ni) did not vary significantly. Although the concentration of these heavy metals remains within the safety limits set by WHO and FAO standards, it is important to monitor their concentrations in relation to soil health and crop safety as they accumulate over time. Bacteriological analysis identified seven bacterial pathogens, with *Escherichia coli* being the most prevalent (40% of samples), while parasitological analysis revealed three species of roundworms. The detection of *E. coli* and other pathogens indicates substantial faecal contamination originating from sewage sludge. These findings highlight potential risks of phytotoxicity, soil quality deterioration, and adverse human and animal health effects, particularly when contaminated soils are used for food production. The study underscores the need for proper sludge treatment, strict monitoring of heavy metal accumulation, and the development of policies to ensure safe agricultural practices as further accumulation over the years may pose a higher risk.

Keywords: Agricultural soils, sewage sludge, heavy metals, pathogens**,** Sewage Sludge and soil.

1. Introduction

The human population is increasing rapidly, and people are migrating from villages to urban areas in search of a livelihood. In third-world countries, around 2.1 billion people will reside in cities by 2030 (Rajput et al., 2022). In addition to climate change and food security concerns, the fact that the population is growing at an alarming rate compels us to adopt an intensive agricultural system to meet our food needs (Rajput et al., 2022). Soil is a nonrenewable resource, and its formation takes thousands of years (Breure et al., 2018). It may be considered that the native inherent capacity of this versatile and worthy natural resource may be exhausted to fulfil the daily food demands of a rapidly increasing population (Brooks and Loevinsohn, 2011). In the coming

era, new technological interventions or cropping systems have to adapt to meet increasing food demands, of which intensive cultivation is one of them. This intensive cultivation will accelerate the nutrient depletion rate from the soil, leading to depletion of native fertility status, which may bring about deficiency or lack of soil organic carbon (Rajput et al., 2022). In today's era, sewage sludge may be a source of fertilizers that could improve soil fertility and productivity due to an array of nutrients and organic matter contents (Usman et al., 2012). Organic manures have been used as a nutrient source since the dawn of agriculture, but after the widespread usage of inorganic fertilizers, bulky organic manures became the second-best option for nutrients. Sludge is a byproduct of wastewater treatment that has been increasingly used as a fertilizer in agriculture due to its nutrient content (Ding et al., 2021). Its reuse in agriculture and/or landscaping is the major management and disposal option throughout the world (Balkrishna et al., 2025). Sewage sludge is a rich source of nutrients, inorganic and organic compounds that make recycling and reuse worthwhile.

A study conducted by Miko & Ibrahim (2024) stated that the primary causes of soil pollution in Kano state, which lead to heavy metal contamination in crops grown from such soils, are using contaminated water for irrigation and household and industrial sludge as fertilizers. Another study conducted by Mahadi & Mohammed (2020) stated that tannery sludge amendment affects soil properties such as pH, organic matter, electrical conductivity, and heavy metal concentration. It also revealed a higher concentration of chromium above the recommended limits in the amendment. Hence, due to the dietary importance of the vegetables to humans, the inflow of sludge into agricultural lands needs to be avoided.

Municipal/Sewage sludge contains a large diversity of pathogenic organisms and toxic chemicals, which may endanger human and animal health and impair the growth of plants (Dumontet et al., 2001). The primary concerns related to sewage sludge are: pathogenic organisms, nitrates, heavy metals, and toxic organic chemicals. Due to the ubiquitous presence of a large variety of pathogenic organisms, e.g., bacteria and viruses, sludge should be considered a biologically hazardous material (Dumontet et al., 2001). Nitrate accumulation in groundwater following excessive applications of sewage sludge, inorganic-N fertilizers, and animal manures is a common phenomenon in intensively cultivated areas (De Haan, 1987). Toxic heavy metals, in particular, Cd, Hg, Pb, Zn, Mo, and Ni are commonly present in sludge (Chen et al., 2022). These

heavy metals accumulate in the environment and hence present a serious long-term pollution problem. Similarly, a large variety of toxic organic chemicals, such as cadmium (Cd), lead (Pb), and Polycyclic Aromatic Hydrocarbons (PAHs) present in sludge are xenobiotic and resist microbial degradation. The presence of excessive levels of any of these toxic components may restrict the levels of application of sewage sludge on agricultural land. This study, therefore, aims to assess the environmental and public health implications of using untreated sewage sludge as manure in agricultural farms in Jos, Central Nigeria, by evaluating soil contamination with heavy metals and pathogens, and analyzing their effects on soil quality and potential risks to food safety and human health. This research addresses a critical gap in the lack of localized data on the environmental impacts of sludge use in agriculture in Jos, Central Nigeria. Most prior studies have been conducted in different agroecological zones globally, making their findings less applicable to this region. Therefore, this study provides region-specific evidence to form regulatory frameworks, promote responsible sludge use, and ensure agricultural sustainability and public safety.

1.1 Study Location

The study area covers Jos North and its surroundings, located in central Nigeria (Fig. 1). It spans from latitudes 9° 52'00" and 10° 01'00" N and longitude 8° °48'00" and 9° °00'00" E. A wide range of land management practices, including the application of fertilizers, contour-ploughing, stone bunds, mulching, and agroforestry, have been adopted by farmers on the Jos Plateau to control soil degradation. Sludge, being a source of fertilizers, is gaining popularity among farmers in Jos and has been applied to agricultural farms. The location of some of these farms included Lamingo, Farin-gada, Mista-ali, Hwollaza, and Hwolshe. The major crops planted on the farms were vegetables (tomatoes, green pepper, lettuce, spinach etc), maize, and guinea corn.

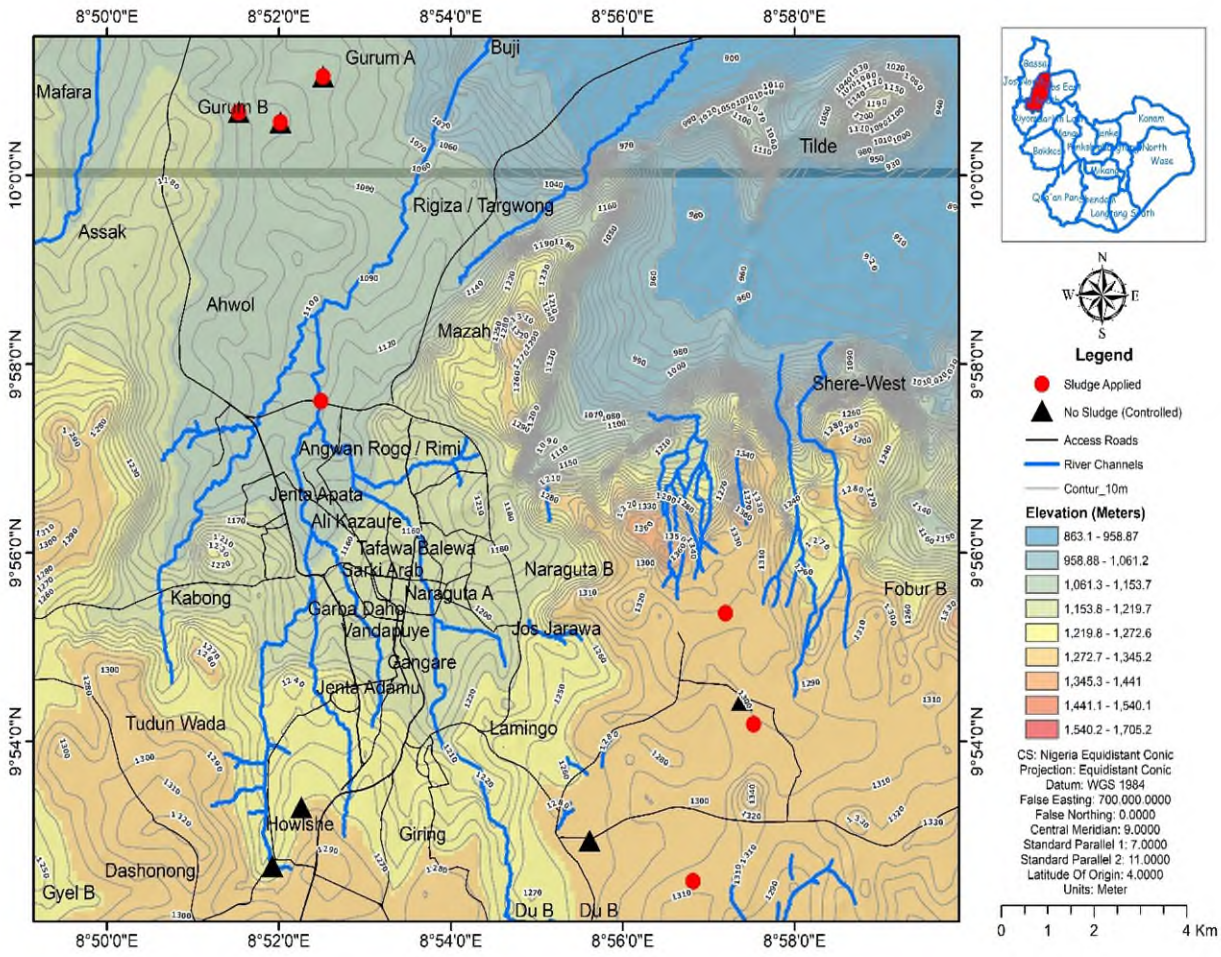

Figure 1: Location Map of Study Area (Modified from Ali et al., 2022)

2. Materials and methods

Farm soil samples were collected from farms that utilize sludge as manure. In view of the heterogeneous nature of the soils, composite samples were collected to get representative samples. Agricultural sites where sludge has been used as manure around Jos were identified, and a total of 20 soil samples were collected from these sites (Table 1). Seven (7) of these soil samples were taken from controlled sites that have not applied sludge, and thirteen (13) of these samples were taken from sludge-amended agricultural soils using the hand auger (Figure 2a and b), all at a depth of 10cm-15cm. The GPS device was used to take the coordinates of the locations. Plastic bags were used to store and transport collected soil samples to the laboratory for analysis.

Descriptive Statistics of Heavy Metal Concentrations in Sludge-Amended Agricultural Soils was done.

S/N	NORTHINGS	EASTINGS	ELEVATION	SAMPLE LOCATION	Sludge Application
1	09 55’ 21.6”	008 57’ 11.9”	1330M	GWASH	Yes
2	09 54’ 10.9”	008 57’ 31.5”	1306M	JUTH	Yes
3	09 54’ 26.2”	008 57’ 23.2”	1310M	JUTH	No(controlled)
4a	09 52’ 31.1”	008 56’ 49.2”	1316M	Haske quarters	Yes
4b	09 52’ 31.1”	008 56’ 49.2”	1316M	Haske quarters	Yes
4c	09 52’ 31.1”	008 56’ 49.2”	1316M	Haske quarters	Yes
4d	09 52’ 31.1”	008 56’ 49.2”	1316M	Haske quarters	Yes
4e	09 52’ 31.1”	008 56’ 49.2”	1316M	Haske quarters	Yes
4f	09 52’ 31.1”	008 56’ 49.2”	1316M	Haske quarters	Yes
5	09 52’ 56.9”	008 55’ 36.9”	1295M	Lamingo dam	No(controlled)
6a	09 57’ 36.4	008 52’ 29.3”	1126M	Farin-gada	Yes
6b	09 57’ 36.4	008 52’ 29.3”	1126M	Farin-gada	Yes
7	10 00’ 33.8”	008 52’ 01.1”	1149	Mista – ali	Yes
8	10 00’ 33.8”	008 52’ 01.1”	1149	Mista – ali	No(controlled)
9	10 00’ 40.2”	008 51’ 31.9”	1158M	Mista – ali	Yes
10	10 00’ 40.2”	008 51’ 31.9”	1158M	Mista – ali	No (controlled)
11	10 01’ 02.9”	008 52’ 30.9”	1124M	Hwol	Yes
12	10 01’ 02.8”	008 52’ 30.9”	1123M	Hwol	No (controlled)
13	09 52’ 40.70”	008 51’ 55.37”	1260M	Domkat Bali	No (controlled)
14	09 53’ 18“	008 52’ 15.60”	1287M	Giyep/Hwolshe	No (controlled)

Table 1: Sampling site, elevation, coordinates, and sludge application



Figure 2: (a) Sample collection at Farin-gada (b) Sample collection at Lamingo

2.1. Sample analysis

X-ray Fluorescence (XRF) was used for the heavy metals analysis, while standard culture and microscopic techniques were used for microbial and parasitological contaminants.

2.2. Determination of contamination factor (CF), Index of geo-accumulation (Igeo), and Pollution Load Index (PLI)

Statistical data was analyzed using SPSS and Excel. The soil quality assessment was carried out by evaluating the Contamination Factor, index of geoaccumulation (Table 2), and the Load Pollution Index.

The CF provides insight into the extent of contamination from sewage sludge and the potential environmental impact. Contamination factor is calculated using equation 1

$$CF = \frac{C_{sample}}{C_{bacground}} \qquad \text{Equation….1}$$

Where:

C_{sample} is the concentration of the metal in the sample.

$C_{background}$ is the average crustal abundance of the element

Table 2: Geo-accumulation Index (Kumar et al., 2025).

Contamination Factor	**Terminology**
<1	low contamination
1-3	moderate contamination
3-6	considerable contamination
>6	very high contamination

2.3. Pollution Load Index (PLI)

The Pollution Load Index (PLI) (Table 3) provides an overall assessment of the level of heavy metal pollution across different sites in the study area. The PLI is derived from the contamination factors of multiple metals and gives a cumulative indication of the overall pollution status.

$$PLI=(CF1\times CF2\times\cdots\times CFn)1/n \quad \text{Equation}\ldots. 2$$

Where;

CF is the Contamination Factor of various heavy metals 1,2…n

Table 3: Pollution Load Index Classification (Kumar et al., 2017)

Pollution Load Index (PLI)	**Terminology**
< 1	Unpolluted

1 - < 2	Unpolluted -to- moderately polluted
2 - < 3	Moderately Polluted
3 - < 4	Highly Polluted
4 - < 5	Very Highly Polluted

Table 4. Maximum permissible pollutant concentrations, potentially toxic elements, and limit values for heavy metal concentrations in soil from WHO, FAO, and the 86/278/EEC Directive.

	WHO—World Health Organization	*** FAO—Food and Agriculture Organization**	**# Directive 86/278/EEC**
Heavy Metal Limits	**Maximum Permissible Pollutant Concentrations in the Receiving Soils (mg kg^{-1})**	**Maximum Permissible Concentration of Potentially Toxic Elements in Soil (mg kg^{-1} Dry Solids)**	**Limit Values for Concentrations of Heavy Metals in Soil (mg kg^{-1} of Dry Matter of Soil)**
Arsenic (As)	8	50	-
Cadmium (Cd)	4	3[5]	1 to 3
Chromium (Cr)	-	400 (prov.)	-
Copper (Cu)	-	80	50 to 140
Fluoride (F)	635	500	-
Lead (Pb)	84	300	50 to 300

	WHO—World Health Organization	* FAO—Food and Agriculture Organization	# Directive 86/278/EEC
Heavy Metal Limits	**Maximum Permissible Pollutant Concentrations in the Receiving Soils (mg kg^{-1})**	**Maximum Permissible Concentration of Potentially Toxic Elements in Soil (mg kg^{-1} Dry Solids)**	**Limit Values for Concentrations of Heavy Metals in Soil (mg kg^{-1} of Dry Matter of Soil)**
Mercury (Hg)	7	1	1 to 1.5
Molybdenum (Mo)	0.6	4	-
Nickel (Ni)	107	50	30 to 75
Zinc (Zn)	-	200	150 to 300

3. Results and Discussion

3.1. Descriptive Statistics of Heavy Metal Concentrations in Sludge-Amended Agricultural Soils. The laboratory results for heavy metals (Zinc [Zn], Copper [Cu], Lead [Pb], Chromium [Cr], Nickel [Ni], and Cadmium [Cd]) across different agricultural locations reveal varying concentrations, with notable differences between locations (Fig. 3) that may be linked to factors such as the use of sludge or other inputs. The concentrations of the heavy metals are presented below

Zinc (Zn):

The concentrations of zinc across the sites range from 22 ppm in CN/07/M-A (Mista-Ali) to 207 ppm in CN/04C/HQ (Haske Quarters). The elevated concentration of 207 ppm at CN/04C/HQ (Fig. 3) is significantly higher than locations such as Gwash. Lamingo, Hwoll, suggesting a possible source of Zn contamination, likely from sludge application or external environmental

inputs (Feng et al., 2023). Other locations, such as CN/01/Gwash (90 ppm) and CN/04B/HQ (60 ppm), have moderate Zn levels. The widespread presence of zinc in these soils is expected, as Zn is commonly found in fertilizers and industrial waste. Although it remains within the safety limits set by WHO (1989), FAO (2000), and EEC (2020) standards, as shown in Table 4, it is important to monitor its concentrations in relation to soil health and crop safety (Van et al., 2024). Low zinc levels in soils affects plant growth and yield, and lower zinc contents in edible portions of crops leading to malnutrition. On the other hand, high concentrations of zinc can inhibit root development, reduce biomass, and severe toxicity can cause plant death. It also inhibits the growth of microorganisms and reduces the activity of crucial soil enzymes like dehydrogenase.

Copper (Cu):

Copper concentrations are relatively low across most sites, with values ranging from 6 ppm in CN/01/Gwash to 49 ppm in CN/06A/F-D (Fig. 3). The highest concentration at CN/06A/F-D (49 ppm) may indicate exposure to sludge or other fertilizers that contribute to elevated Cu levels (Balkrishna et al., 2025). Copper is essential for plant growth in small amounts, but excess levels, such as those observed in CN/06A/F-D, may pose risks to soil and plant health over time (Nandi et al., 2024). Locations like CN/01/Gwash with **only 6 ppm of Cu** suggest minimal contamination and low external input, possibly indicating that sludge use is limited or absent in this area (Hechmi et al., 2024).

Lead (Pb):

Lead concentrations vary significantly, ranging from 14 ppm in CN/02/Juth to 165 ppm in CN/06A/F-D (Fig.3 & 4). The high Pb concentration at CN/06A/F-D (165 ppm) could pose environmental and health concerns, as lead is a toxic element even in small amounts (Ali et al., 2024). The source of this elevated lead level could be linked to industrial contamination or the application of sludge (Li et al., 2024). In contrast, lower levels at locations like CN/02/Juth (14 ppm) suggest less exposure to lead, indicating varying environmental conditions or different agricultural practices (Singh et al., 2024). A low concentration of lead (Pb) has no detrimental effects on soil and considered safe for agriculture and gardening.

Chromium (Cr):

Chromium concentrations also display notable variation, ranging from 87 ppm in CN/06B to 173 ppm in CN/04A/HQ. The higher Cr concentrations at CN/04A/HQ (173 ppm) and CN/04B/HQ (139 ppm) (Fig. 3) suggest that these locations are subject to significant Cr input, potentially from the use of industrial by-products or treated sludge. High levels of chromium in soil can affect soil chemistry and crop safety (Huang et al., 2024). However, certain locations, such as CN/06B (87 ppm), have relatively lower Cr concentrations, which may be indicative of less external input (Tang et al., 2024). Low chromium is generally not considered a significant agricultural problem; however, from the nutritional and soil health perspectives, low chromium can result in low chromium content in forages, and may affect the nutritional quality of food grown on that soil.

Nickel (Ni):

Nickel concentrations across the locations vary moderately, with values ranging from 24 ppm in CN/07/M-A to 46 ppm in CN/01/Gwash (Figure 3). The concentrations suggest that nickel is present in all the sampled soils, with CN/01/Gwash (46 ppm) showing the highest concentration. This could be due to nickel-bearing sludge or environmental factors contributing to the higher presence of the element (Butar Butar et al., 2025). Lower concentrations at CN/07/M-A (24 ppm) and CN/12/D-B (24 ppm) indicate less exposure to nickel, potentially signifying differences in sludge application or environmental inputs. The presence of nickel is soil can serve as both an essential micronutrient, but becomes toxic to flora, fauna and microorganisms at high levels. In small amounts, it is essential for breaking down urea nitrogen into usable ammonia by the enzyme urease. But when it is high in soil, it can accumulate in plates, which can be transferred to humans and animals, and can potentially cause health issues such as dermatitis, lung fibrosis and in some cases, cancer.

Cadmium (Cd):

Notably, cadmium (Cd) was not detected in any of the sampled locations, suggesting that the levels of cadmium are either below detectable limits or absent. Cadmium is a highly toxic element, and its absence in the samples is a positive indication that sludge or other inputs used in these areas do not contribute to cadmium contamination.

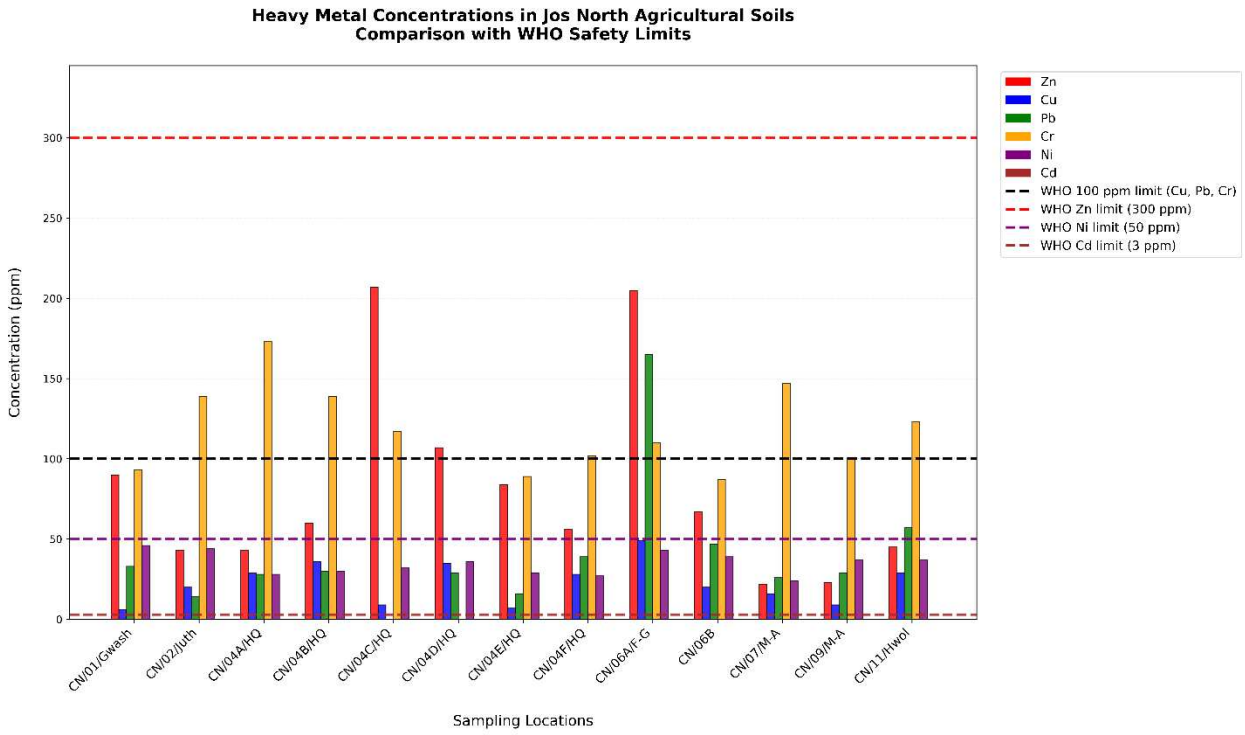

Figure 3: Concentration of heavy metals in sludge-amended agricultural soils

3.2 Heavy Metal Concentrations in Non-Sludge Agricultural Areas

The analysis of heavy metal concentrations in the non-sludge agricultural locations reveals varying levels of zinc (Zn), copper (Cu), lead (Pb), chromium (Cr), nickel (Ni), and cadmium (Cd) (Fig. 4). The concentrations of these elements provide insight into the potential environmental impact and help identify any areas of concern regarding heavy metal contamination.

Zinc (Zn):

The concentration of zinc in the non-sludge areas ranges from 19 ppm in CN/08/M-A to 55 ppm in CN/13/GYEP. The relatively higher concentration in CN/13/GYEP suggests either direct defecation or the application of pesticides (How et al., 2025). However, overall, the zinc levels are moderate across the locations, indicating minimal contamination or external zinc accumulation in these agricultural areas.

Copper (Cu):

Copper concentrations show considerable variation, with levels ranging from 8 ppm in CN/13/GYEP to 50 ppm in CN/05/LAM. The highest value recorded at CN/05/LAM indicates a potential source of copper contamination, which may be due to agricultural practices or proximity to industrial activities (Xia et al., 2024). Conversely, CN/13/GYEP exhibits the lowest copper levels, implying lesser external input or natural soil conditions.

Lead (Pb):

Lead concentrations in the non-sludge areas range between 16 ppm in CN/11/HWO and 39 ppm in CN/10/M-A. The lead concentration in CN/10/M-A is the highest, which could pose environmental and health concerns if it exceeds safe thresholds (Khan et al., 2025). Nonetheless, the variation in lead levels is relatively small, indicating that the sources of lead contamination might be uniform across these regions, though CN/10/M-A stands out as a hotspot for further investigation.

Chromium (Cr):

Chromium concentrations vary widely, with CN/03/JUTH showing an exceptionally high value of 1200 ppm, which is significantly above the concentrations found in other locations. This high chromium level raises concerns about potential environmental contamination, possibly due to industrial runoff or improper waste disposal (Gzar et al., 2025). The lowest concentration of chromium is found in CN/10/M-A, with 101 ppm, which still indicates some level of contamination, but to a lesser extent.

Nickel (Ni):

The concentration of nickel in the study areas ranges from 21 ppm in CN/08/M-A to 68 ppm in CN/11/HWO. The elevated nickel levels in CN/11/HWO suggest external sources, possibly direct defecation or agricultural inputs (Gao et al., 2025). Foodborne metal (loid) contamination from coastal petrochemical industrial zone to countryside and urban zones: Spatial distribution and public health implications. The lower values in CN/08/M-A indicate less environmental impact from nickel contamination in that location.

Cadmium (Cd): Cadmium was not detected in any of the non-sludge agricultural areas, which is a positive finding. The absence of cadmium suggests that the soil in these areas is not significantly affected by cadmium contamination, and this element does not pose a threat to the agricultural environment in these locations (Dayananda et al., 2025). From Fig. 4, the results show that certain locations, such as CN/03/JUTH and CN/05/LAM, exhibit elevated levels of heavy metals like chromium and copper, which could be cause for concern. These findings highlight the need for further investigation into the sources of contamination and potential environmental impacts in these non-sludge agricultural areas. However, based on the WHO (1989), FAO (2000), and EEC (2020) permissible limits, all the concentrations of heavy metals are below the permissible limit.

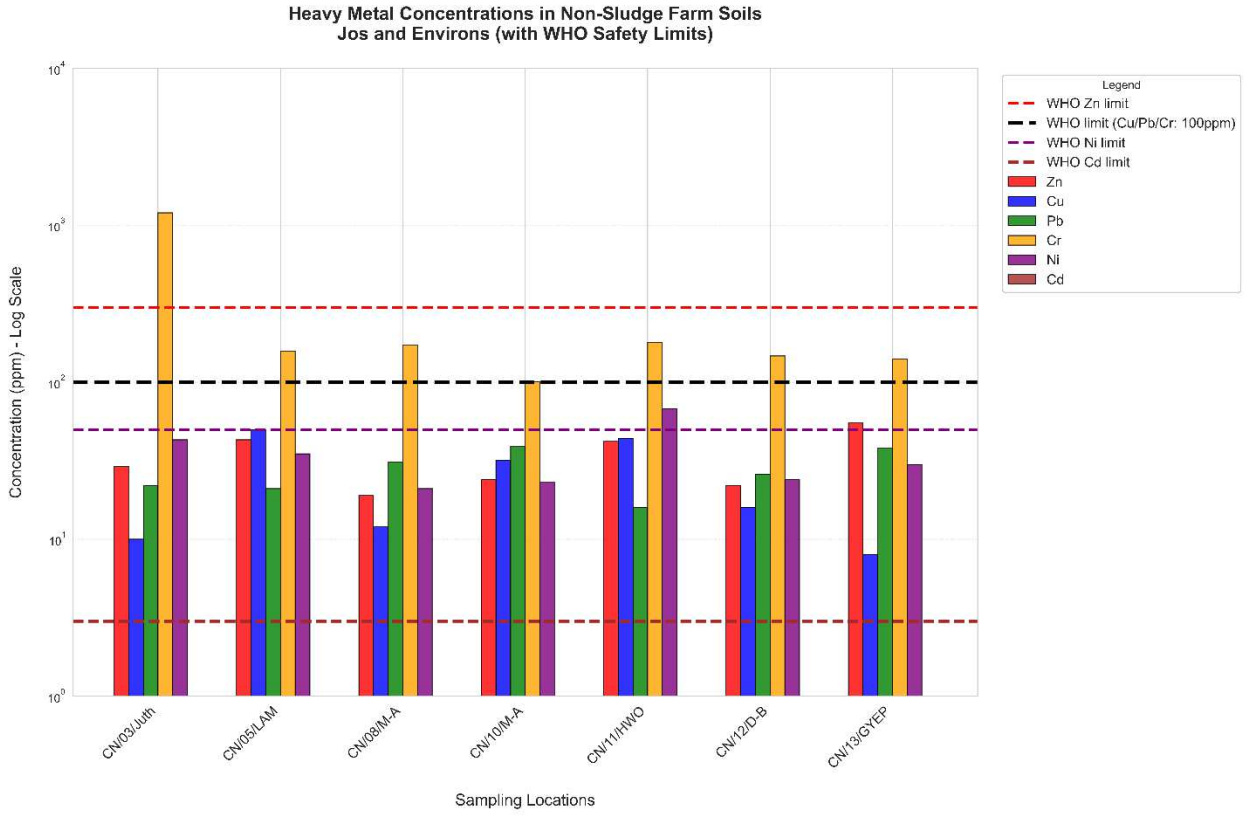

Figure 4: Concentration of heavy metals in farm soils that did not receive sludge application in Jos and environs

3.3. Contamination Factors (CF) for Heavy Metal Concentrations in Sludge Agricultural Areas

Zinc (Zn): The CF values for Zinc range from 0.31 to 2.96. Locations like CN/04D/HQ and CN/06A/F-G have high CF values (2.96 and 2.93, respectively), suggesting significant contamination. These elevated levels may indicate the presence of anthropogenic activities contributing to the enrichment of Zinc in these areas (Fig. 5). Conversely, locations like CN/07/M-A and CN/11/Hwol show low CF values (0.31 and 0.33), suggesting minimal contamination and concentrations closer to natural levels.

Copper (Cu): Copper exhibits CF values between 0.11 and 0.89, with CN/04C/HQ showing the highest value (0.65), which is indicative of moderate contamination. Locations such as CN/02/Juth and CN/04F/HQ show relatively low CF values (0.11 and 0.13, respectively), suggesting minimal contamination, with copper concentrations aligning closely with natural background levels.

Lead (Pb): Lead demonstrates a wide range of CF values from 1.08 to 12.69. Some locations, like CN/09/M-A and CN/06A/F-G, show significant contamination with CF values of 12.69 and 3.00, respectively, which are notably high, reflecting substantial anthropogenic influence. Other locations, such as CN/02/Juth and CN/04D/HQ, exhibit lower CF values (1.08 and 1.23, respectively), which still indicate contamination, but to a lesser degree.

Chromium (Cr): Chromium shows CF values between 0.87 and 1.73, with most locations falling between 1.00 and 1.50. For example, CN/04A/HQ (1.39) and CN/04B/HQ (1.73) exhibit moderate levels of contamination, suggesting some human impact in these areas. Locations like CN/07/M-A and CN/11/Hwol have lower CF values (0.87 and 1.01, respectively), suggesting a lesser degree of contamination and concentrations closer to natural levels.

Nickel (Ni): The CF values for Nickel range from 0.32 to 0.61, with the lowest values found in CN/09/M-A and CN/07/M-A (0.32 and 0.36, respectively), indicating minimal contamination. CN/02/Juth and CN/04A/HQ show higher CF values of 0.59 and 0.61, suggesting that these locations have slightly higher levels of Nickel contamination.

Fig. 5 reveals that most locations exhibit low to moderate contamination across the metals studied, with Lead and Zinc being the most frequently elevated elements. Specifically, locations like CN/09/M-A and CN/06A/F-G show significantly higher contamination for certain metals, particularly Lead, which could suggest pollution from anthropogenic activities such as industrial

or agricultural processes. These findings highlight areas where further investigation into the sources and impact of contamination is warranted, especially in regions with higher CF values for metals like Lead and Zinc.

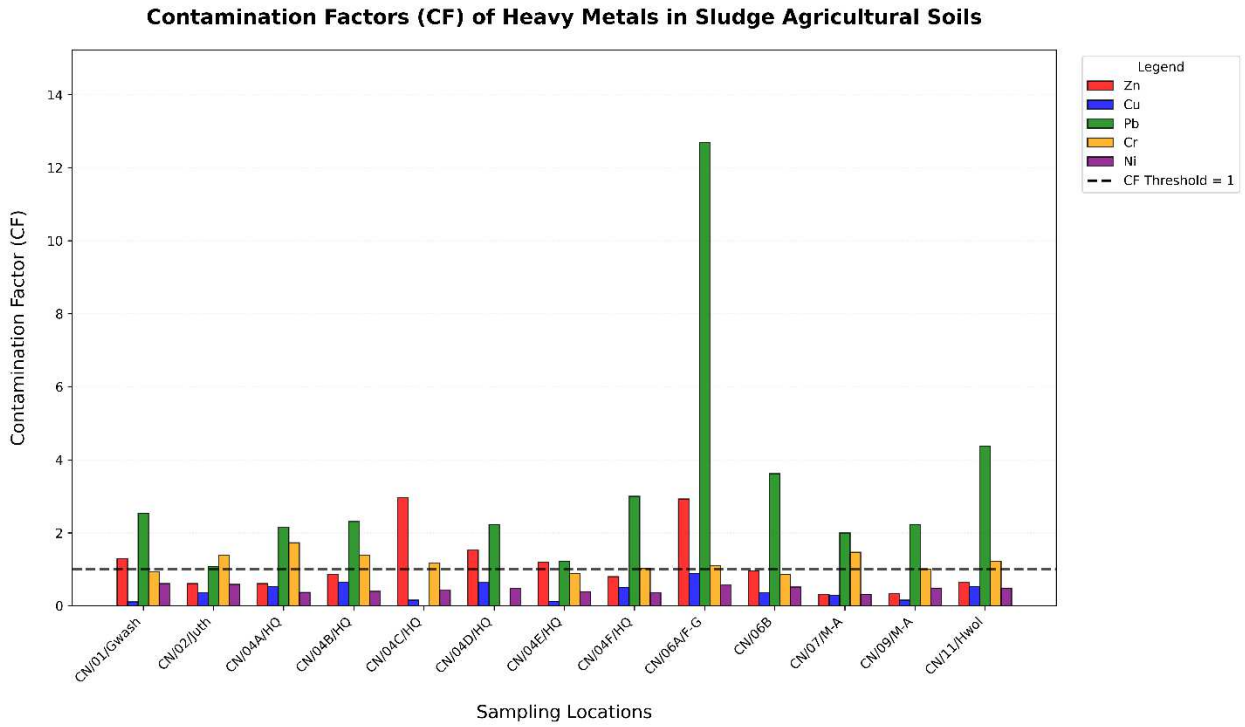

Figure 5: Contamination Factors (CF) for Heavy Metal Concentrations in Sludge Agricultural Soils

3.4. Contamination Factors (CF) for Heavy Metal Concentrations in Non-Sludge Agricultural soils

The data showed that in CN/03/Juth, Chromium (Cr) shows a notably high CF of 12.00, indicating significant contamination relative to its crustal abundance, alongside Lead (Pb), which also shows contamination with a CF of 1.692 (Fig. 6). This could imply that anthropogenic sources contribute to elevated levels of these metals in this area. Additionally, in locations like CN/08/M-A and CN/13/GYEP, Lead (Pb) exhibits CF values of 2.385 and 2.923, respectively, highlighting potential enrichment and contamination concerns. Conversely, Nickel (Ni) maintains CF values below 1 in most locations, suggesting that it remains close to natural levels with minimal contamination. Moreover, specific locations such as CN/11/HWO and CN/12/D-B present CF

values above 1 for multiple metals, indicating higher contamination levels across several heavy metals at these sites. Zinc (Zn) and Copper (Cu), however, generally register CF values below 1 across most locations, which points to concentrations within expected natural ranges and little evidence of contamination.

Overall, the CF values in Fig. 6 highlight areas with potential pollution, particularly for Chromium and Lead, which consistently show elevated values across several locations. These findings suggest the need for further investigation into contamination sources and potential environmental impacts, especially in sites where multiple metals exceed natural background levels.

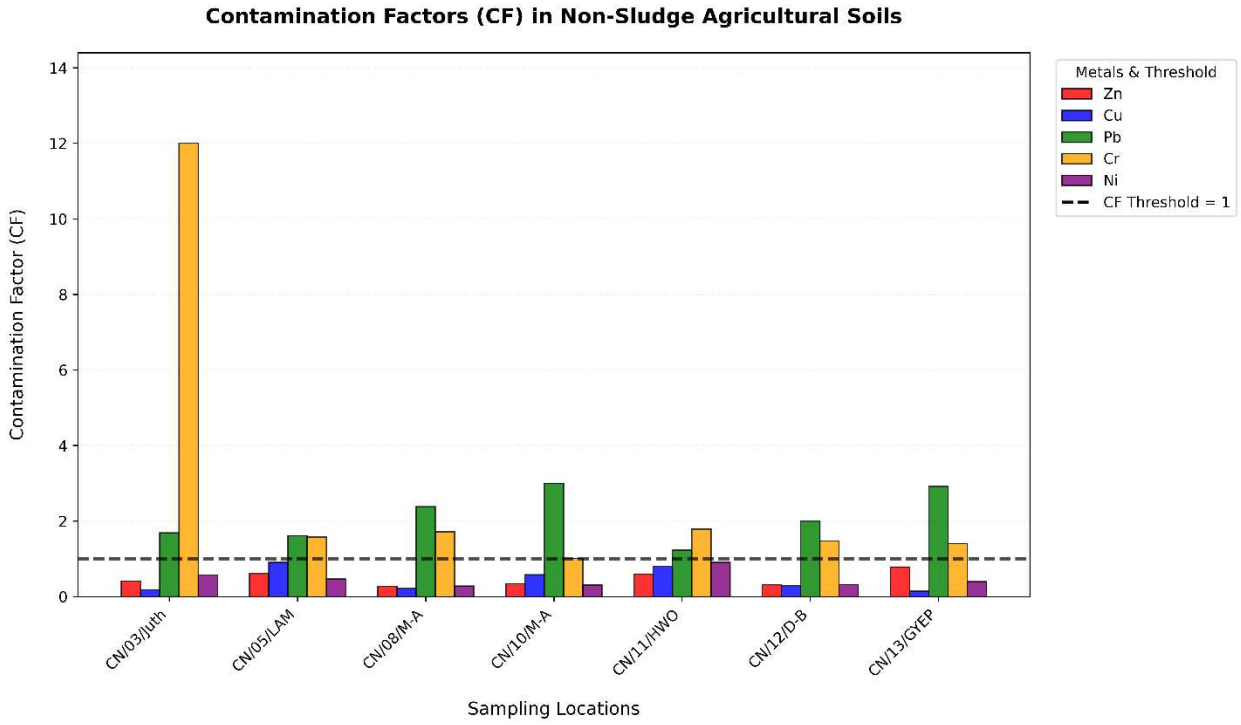

Figure 6: Contamination Factors (CF) for Heavy Metal Concentrations in Non-Sludge Agricultural Soils

3.5. Geoaccumulation Index for Heavy Metal Concentrations in Sludge Agricultural Soils

Zinc (Zn):

Igeo values for Zn range from -1.56 (CN/07/M-A) to 0.59 (CN/04C/HQ). Locations CN/04C/HQ, CN/06A/F-G, and CN/04D/HQ show Igeo values close to 0, indicating unpolluted to moderately polluted conditions. Other locations mostly have negative Igeo values, suggesting they are unpolluted for Zn.

Copper (Cu):

Igeo values for Cu range from -4.04 (CN/04C/HQ and CN/09/M-A) to -0.42 (CN/04B/HQ). All Igeo values are negative, indicating an unpolluted state for Cu across all locations. The lower values at CN/04C/HQ and CN/09/M-A suggest particularly low contamination levels for Cu in these areas.

Lead (Pb):

The Igeo values for Pb show a wide range, from -1.23 (CN/04E/HQ) to 3.62 (CN/06A/F-G). Location CN/06A/F-G has an Igeo of 3.62, indicating it falls within the category of "heavily polluted" for Pb, which suggests significant contamination. Locations such as CN/11/Hwol and CN/06B also have positive Igeo values (1.24 and 1.11, respectively), indicating "moderate" to "considerable" contamination. Other locations display values close to or below zero, indicating lower contamination levels or unpolluted status for Pb.

Chromium (Cr):

Igeo values for Cr vary from -0.97 (e.g., CN/09/M-A and CN/06A/F-G) to 0.23 (CN/04A/HQ). Most locations have negative Igeo values, suggesting an unpolluted state. Only a few locations, such as CN/04A/HQ and CN/07/M-A, show values close to zero or slightly positive, suggesting they may be in the unpolluted to moderately polluted range, indicating minimal contamination of Cr.

Nickel (Ni):

Igeo values for Ni range from -1.28 (CN/01/Gwash) to -0.40 (CN/04D/HQ). All values for Ni are negative, indicating that none of the locations show significant contamination for Ni and are considered unpolluted according to the Igeo classification.

(Fig. 7), The Igeo values indicate that lead (Pb) is the primary contaminant of concern at specific locations (notably CN/06A/F-G and CN/11/Hwol), while other metals (Zn, Cu, Cr, Ni) show minimal to no contamination across the surveyed locations. This suggests targeted pollution sources, possibly related to industrial or anthropogenic activities, contributing to elevated lead levels at certain sites.

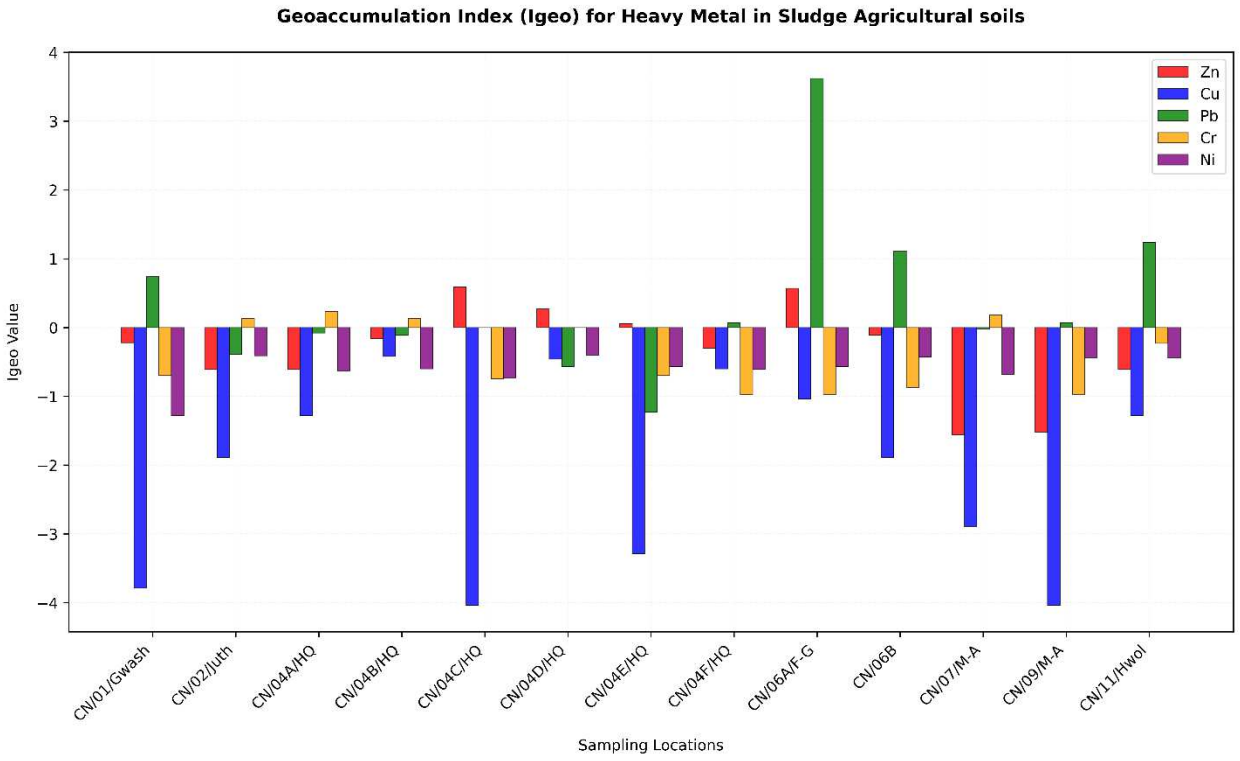

Figure 7: Geoaccumulation Index for Heavy Metal Concentrations in Sludge Agricultural Soils

3.6. Geoaccumulation Index (Igeo) Analysis for Heavy Metal Concentrations in Non-Sludge Agricultural Soils

Most locations, except for specific cases, fall under "low contamination" across the metals (Zn, Cu, Cr, Ni) based on Igeo (Fig. 8). Some locations show moderate contamination (Pb in CN/03/Juth and CN/08/M-A). Pb in CN/08/M-A has considerable contamination; otherwise, this category is less common (Fig. 8). Cr in CN/03/Juth exhibits very high contamination, suggesting an enrichment of chromium in this location.

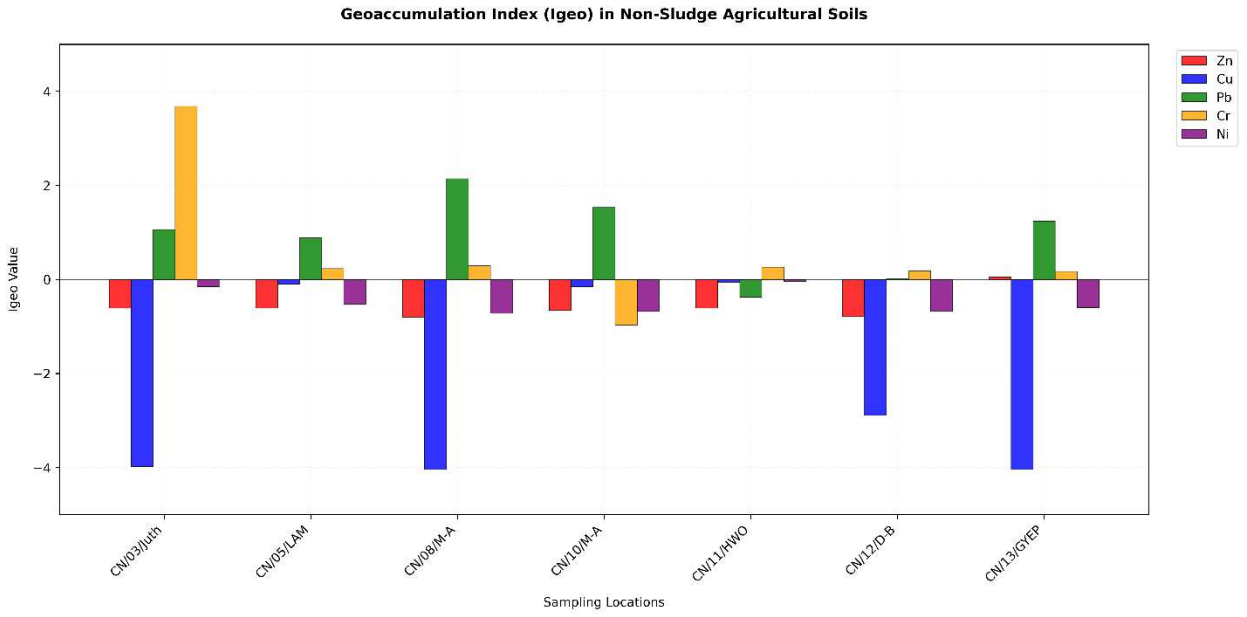

Figure 8: Geoaccumulation Index (Igeo) Analysis for Heavy Metal Concentrations in Non-Sludge Agricultural Soils

3.7. Pollution Load Index (PLI) Heavy Metal Concentrations in Sludge Agricultural Areas

Most locations exhibit PLI values well below 2, suggesting that they are either unpolluted or only moderately polluted. For instance, CN/02/Juth with a PLI of 0.81 and CN/04A/HQ with a PLI of 0.84 fall into the "unpolluted-to-moderately polluted" category, indicating relatively low contamination levels. Similarly, locations such as CN/01/Gwash (PLI = 1.12), CN/04B/HQ (PLI = 0.90), and CN/06B (PLI = 1.06) also show moderate pollution levels, but their pollution levels are not alarming. In contrast, CN/06A/F-G has the highest PLI value of 2.06, which falls into the "moderately polluted" category, pointing to a higher degree of contamination, particularly from metals like lead (Pb) and zinc (Zn), which likely contributed to the overall pollution. CN/11/Hwol

(PLI = 1.13) is another location with relatively higher pollution, especially for metals like lead and chromium. Interestingly, several locations, including CN/04C/HQ, CN/04D/HQ, and CN/07/M-A, have values suggesting minimal contamination or moderate contamination. Locations such as CN/06A/F-G and CN/11/Hwol, which showed higher PLI values, might require more attention due to the higher risk of pollution, potentially influencing local ecosystems and human health.

While the majority of locations did not exceed the "moderately polluted" threshold, the variation in PLI values provided insight into the varying levels of environmental pollution across these locations, with some areas showing a need for mitigation measures to address pollution from heavy metals.

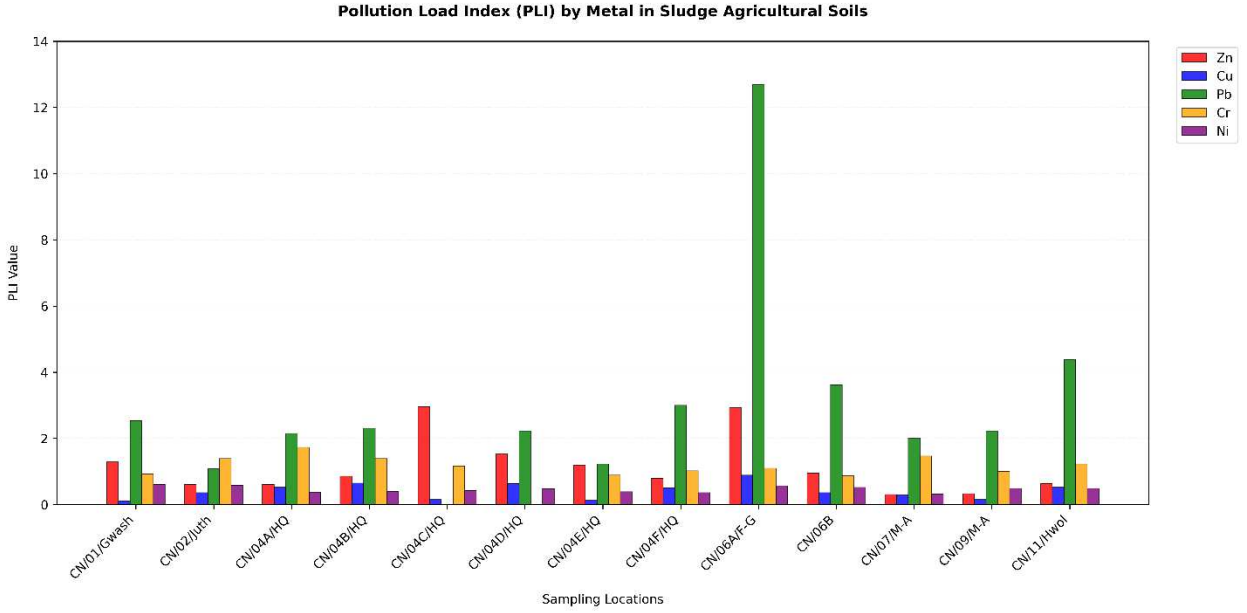

Figure 9: Pollution Load Index (PLI) Heavy Metal Concentrations in Sludge Agricultural Soils

Pollution Load Index (PLI) Heavy Metal Concentrations in Non-Sludge Agricultural Areas

From Fig. 10, CN/03/Juth shows the highest PLI of 1.694, largely influenced by the significantly high contamination factor for Chromium (12.00), indicating a very high level of contamination at this site. Similarly, CN/11/HWO has a PLI of 1.030, which is also indicative of moderate pollution due to its relatively higher CFs for Copper (0.800) and Nickel (0.907). On the other hand, CN/05/LAM and CN/08/M-A have lower PLIs of 0.857 and 0.738, respectively, reflecting a less polluted or moderately polluted state. Locations such as CN/10/M-A and CN/12/D-B exhibit PLIs

of 0.806 and 0.699, respectively, indicating that they are also moderately polluted, though not to the extent of CN/03/Juth. Lastly, CN/13/GYEP has a PLI of 0.911, suggesting a slight to moderate pollution level, with significant contributions from Lead (Pb) and Chromium (Cr). The results showed that most of the locations fall into the category of moderate pollution, with CN/03/Juth standing out as the most polluted site based on the high contamination factors. The Pollution Load Index provided a useful overall measure of pollution, highlighting areas where contamination by heavy metals is significant and requires attention.

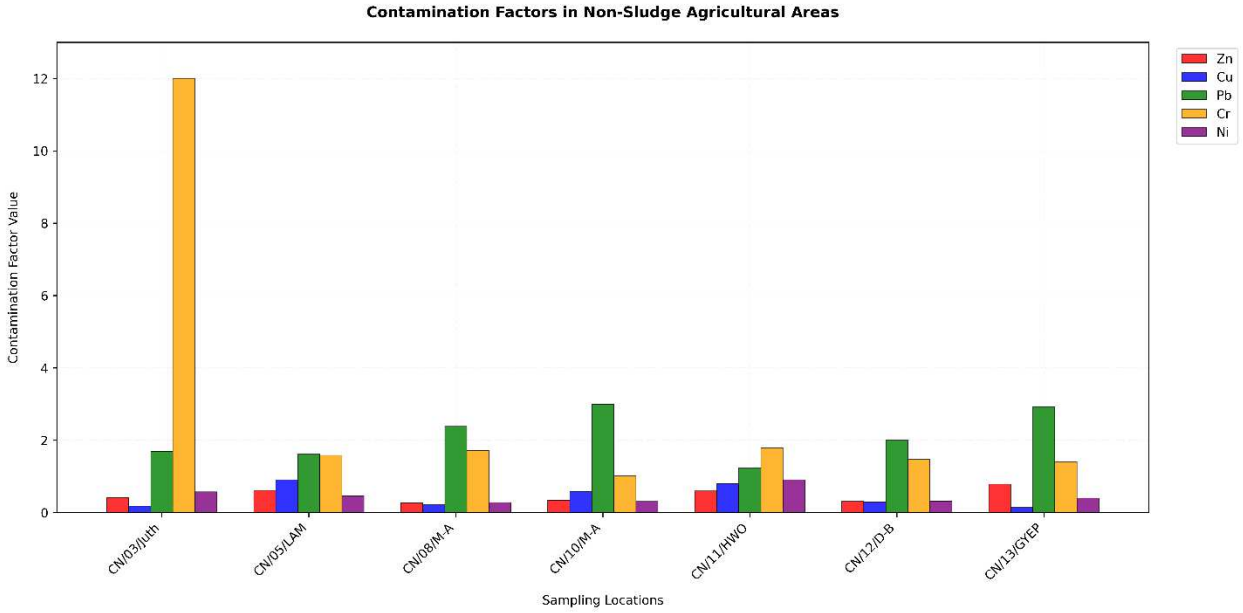

Figure 10: Pollution Load Index (PLI) Heavy Metal Concentrations in Non-Sludge Agricultural Areas

Comparison and Analysis of Pollution Load Index (PLI) for Locations with and without Sludge Application

The Pollution Load Index (PLI) values calculated for the locations with and without sludge application provide important insights into the environmental impact of sludge application on trace elements in agricultural lands. The comparison of the Pollution Load Index (PLI) between locations with and without sludge application revealed notable differences and some similarities. Locations that received sludge generally show higher PLI values, indicating a greater degree of

contamination. For example, CN/06A/F-G with sludge has the highest PLI value of 2.06, primarily due to the extremely high contamination factor for lead (Pb), suggesting that sludge application may have contributed to higher levels of pollution in certain areas. On the other hand, CN/03/Juth (without sludge) has a lower PLI of 1.69, though it also has a notable higher Pb contamination factor. There are several locations where the PLI is relatively similar between sludge and non-sludge locations, such as CN/02/Juth (sludge) with a PLI of 0.81 and CN/05/LAM (no sludge) with a PLI of 0.857, which implies that the impact of sludge application might not always lead to significant pollution increase. Lead (Pb) is a key contributor to the PLI differences, as seen in locations like CN/06A/F-G, where Pb contamination is exceptionally high. Zinc (Zn) and copper (Cu) also contribute, but to a lesser extent compared to Pb. Locations with high chromium (Cr) contamination, such as CN/03/Juth, also influence the PLI. Sludge application appears to increase the variability in pollution levels. Locations with extremely high Pb contamination (e.g., CN/06A/F-G) show substantially higher PLI values compared to those without sludge, suggesting that sludge may have contributed to higher pollution levels in some cases, particularly to metals like Pb. While sludge application can lead to increased pollution, the overall effect on the Pollution Load Index is variable. Some locations showed higher PLI values due to Pb contamination; others, however, do not exhibit a drastic difference. Hence, it was clear that other factors, such as the type of sludge and its specific metal content, played a crucial role in determining the pollution load in agricultural soils.

The analysis of the Contamination Factor (CF), Geoaccumulation Index (Igeo), and Pollution Load Index (PLI) provides a comprehensive view of heavy metal contamination across different locations, highlighting key differences between sludge and non-sludge application areas. For CF, metals like lead (Pb) and zinc (Zn) showed higher values across many locations, indicating notable contamination, particularly in areas where sludge was applied. The Igeo analysis corroborates these findings, showing categories from unpolluted to moderately polluted, with lead (Pb) and zinc (Zn) again standing out as more significant pollutants, especially in sludge-applied fields. In contrast, non-sludge areas showed lower Igeo values, suggesting reduced metal accumulation. The Pollution Load Index (PLI) reflects overall pollution across multiple metals. Sludge-applied locations consistently displayed higher PLI values, some above the threshold of 1, indicating moderate to elevated pollution levels. Non-sludge locations generally had PLI values under 1, suggesting minimal contamination. This comparison underscores that sludge application

contributes to increased heavy metal levels in soil, with potential implications for environmental quality and soil health. Sludge-applied areas exhibit higher metal contamination, as evidenced by elevated CF, Igeo, and PLI values for certain metals, especially lead (Pb) and zinc (Zn). Non-sludge fields demonstrate lower contamination levels, highlighting the role of sludge in elevating metal concentrations and its associated environmental impact.

Parasitology

Eggs of certain parasites were found in 3 out of the 20 samples analyzed (Fig. 11), and these parasites are all roundworms (Toxocara and Ascaris lumbricoides) that can affect both humans and animals (Van Sluijs et al., 2025). The parasitological examination of the samples revealed the presence of parasitic eggs in 3 out of the 20 samples analyzed. Specifically, the eggs of **Toxocara** were identified in the sample from Mista Ali (CN/09/HM/MISTA ALI), and eggs of **Ascaris lumbricoides** were found in two samples from Mista Ali (CN/10/CONTROL/MISTA ALI and CN/07/HM/MISTA ALI). The presence of these parasitic eggs indicates contamination, likely due to poor sanitation practices, the presence of animal faeces, or environmental conditions conducive to the survival of these parasites (Nath et al., 2025). The majority of the samples (17 out of 20) did not show any parasitic presence, suggesting that in these locations, either the environmental conditions are less favorable for parasite survival, or that the parasite survival rate reduces outside its host or that sanitation measures are relatively more effective. However, the presence of parasites in 15% of the samples (3 out of 20) signifies a notable prevalence, which warrants attention due to the potential health risks associated with parasitic infections.

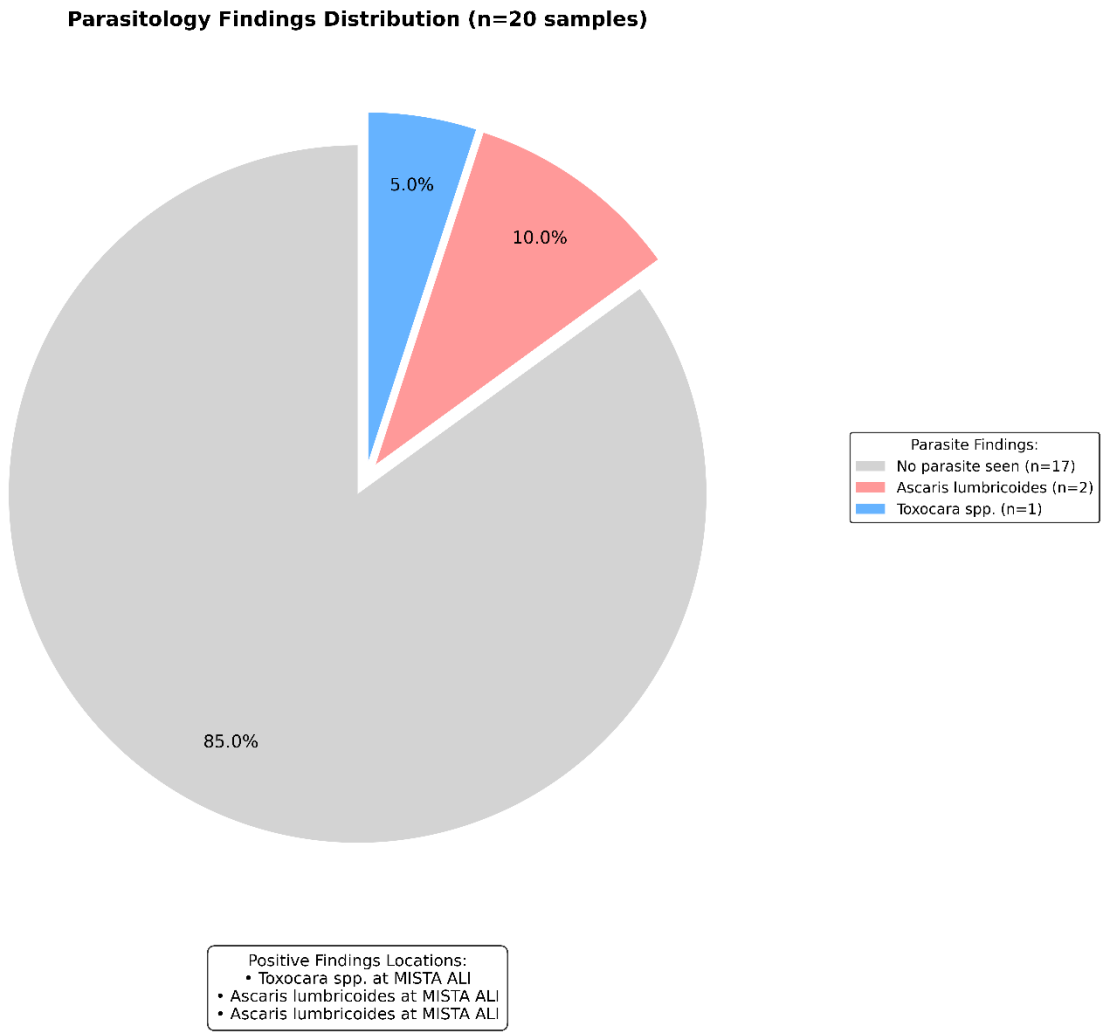

Figure 11: Microscopic (PARASITOLOGY) findings distribution (Prevalence = 3/20 * 100% = 15%)

BACTERIOLOGY

The bacteriological analysis of 20 soil samples (Fig. 12) revealed the presence of seven distinct bacterial pathogens (Escherichia coli, Bacillus subtilis, Pseudomonas aeruginosa, Bacillus licheniformis, Klebsiella aerogenes, Micrococcus, and Enterobacter aerogenes), with Escherichia coli being the most prevalent. Detected in 8 out of 20 soil samples (40%), its presence suggests significant faecal contamination, particularly concerning in agricultural areas where sludge is used as manure (Vaz-Moreira et al., 2025). Escherichia coli originates from the intestines of warm-blooded animals, including humans, and its presence in soil indicates potential health risks, especially if such contaminated soil is used for growing food crops.

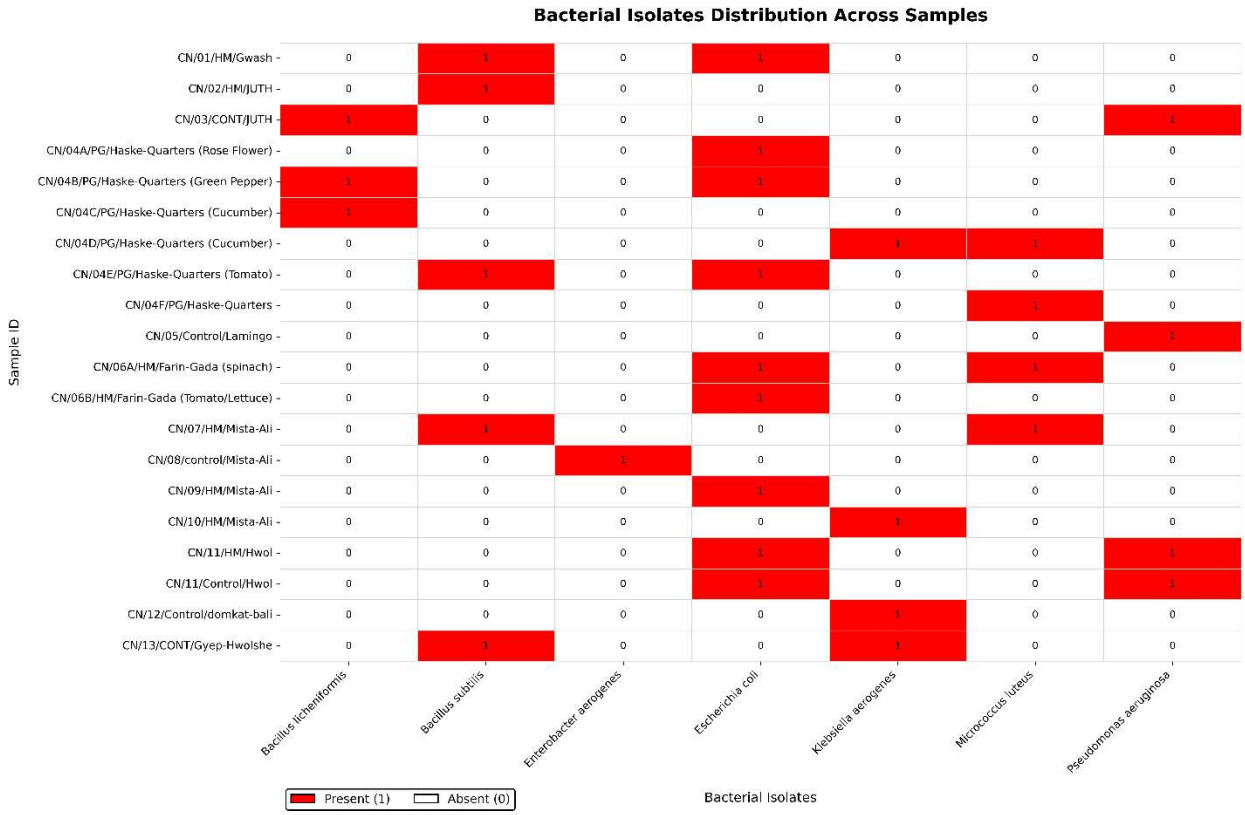

Figure 12: Laboratory findings; BACTERIOLOGY (PREVALENCE Escherichia coli = 8/20 x 100% = 40%, Bacillus subtilis = 4/20 x 100% = 20%, Pseudomonas aeruginosa = 4/20 x 100% = 20%, Bacillus licheniformis = 3/20 x 100% = 15%, Klebsiella aerogenes = 4/20 x 100% = 20%, Micrococcus = 4/20 x 100% = 20%, Enterobacter aerogenes = 1/20 x 100% = 5%)

CONCLUSION

This study has extensively evaluated the risks and benefits of sewage sludge application in agriculture determining the concentration and distribution of heavy metals (e.g., Pb, Zn, Cr, Ni) and pathogenic organisms (bacteria and parasites) in soils amended with sludge in the Jos region and have presented a comparative assessment between sludge-amended and non-sludge farms and have evaluate environmental safety and sustainability. The research findings underscore the potential risks associated with using untreated sludge as manure in agriculture.

Heavy metals such as Cd, Cr, Hg, Pb, and Zn are present in reasonably safe concentrations but, the significant increase in Zinc concentration in sludge-amended soils suggests a potential for

phytotoxicity, which could negatively impact plant growth and soil fertility with continues accumulation.

Furthermore, the presence of pathogenic parasites and bacteria such as Escherichia coli in the soil poses a threat to public health, particularly if these soils are used to grow food crops.

The study's comparison between sludge-amended and non-amended soils confirms that the concentration of heavy metals as well as pathogens in sludge-amended soils is higher than in soils that did not receive sludge application. This study highlights the need for careful management and monitoring of sludge use in agriculture. While sludge can be a valuable source of nutrients and organic matter, its application must be carefully controlled to prevent heavy metal accumulation over time as well as pathogen accumulation and contamination. Policies regarding sludge use and treatments (e.g., composting, liming, drying), enacted or alternative management strategies which must be adhered to and closely monitored by all stakeholder (farmers, regulators, public health agencies)

However, the study limitations included small sample size, the use of only XRF, lack of seasonal data, and pathogen detection limited to microscopy/culture.

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