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Physicochemical Properties and Health Risks of Informal E-Waste Processing at Alaba International Market in Lagos, Nigeria

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Abstract

This study investigated the groundwater quality and health risks associated with informal e-waste processing in the Alaba International Market in Lagos, Nigeria. Twenty-two groundwater samples were collected from hand-dug wells in the market area and analyzed for physicochemical properties and heavy metal concentrations. The results showed that the groundwater quality was poor, with high levels of heavy metals, including cadmium, lead, and chromium. The health index (HI) for children and adults was above the tolerable threshold levels, indicating a potential health risk to the population. Principal component analysis and hierarchical cluster analysis were used to identify the sources of metals in groundwater, and the results showed that informal e-waste processing was a significant source of contamination. The study highlights the need for effective management strategies to mitigate the potential health risks associated with informal e-waste processing and ensure public health and environmental safety.

Keywords

Groundwater-Quality, Health Risks, Informal E-Waste Processing, Alaba International Market, Nigeria

1. Introduction

Electronic waste (e-waste) is the fastest-growing section of the overall waste stream

globally, generating an estimated 50 million metric tons yearly (Kumar et al., 2017; Shevchenko et al., 2019; Maes & Preston-Whyte, 2022). This surge in e-waste is due to the increased disposal of electrical electronic equipment (EEE) within developing countries and the shipment of used materials from the developed world to the developing world (Shevchenko et al., 2019). The short lifespan of EEE and the increasing demand for newer and more efficient technologies have led to the rapid discarding of EEE worldwide (Shahabuddin et al., 2023). Furthermore, the need to bridge the perceived digital divide between developed and developing countries and the trail of global production and consumption have also driven the increased discarding of materials such as mobile phones, refrigerators, and computers (Pickren, 2014; Vassilakopoulou & Hustad, 2021). However, developing countries have become the endpoint of the dumping of waste, receiving about 50% - 80% of EEE collected for recycling in developed countries (Kumar et al., 2017), with China and India being the largest recipients (Vassilakopoulou & Hustad, 2021).

The production and consumption of electronic and electrical equipment (EEE) have increased significantly, leading to a corresponding increase in e-waste. Nigeria receives large volumes of e-waste from developed countries, and most of these second-hand electronics end up in landfills after useful parts have been removed (Forti et al., 2020). The environmental impact resulting from e-waste recycling and disposal has been reported in many countries, including China, Germany, India, Sweden, and Asia (Otache et al., 2014; Borthakur, 2016; Cayumil et al., 2016; Mohammed, 2022). The disposal and recycling of e-waste in an environmentally unsound way can pose significant risks to human health and the environment due to the presence of heavy metals and organic compounds of chlorine and bromine (Fadaei, 2022). Heavy metals are one of the major groundwater contaminants, which can accumulate in living tissues and concentrate through the food chain, and their toxicity depends on the concentration in the environment (Belkhiri et al., 2018; Parvez et al., 2021). Informal e-waste recycling, directly and indirectly, affects human health, with exposure occurring through ingestion, inhalation, and dermal absorption through the skin (Chitrakoot et al., 2018). Exposure to a high concentration of heavy metals can result in acute and chronic health effects, such as damage to the central and peripheral nervous systems, blood, lungs, kidneys, liver, and even death (Ogunkeyede et al., 2019). Studies in China have revealed elevated amounts of heavy metals and persistent toxic substances in the blood of children and workers at e-waste recycling sites (Pradhan & Kumar, 2014; Zeng et al., 2020; Hang et al., 2022).

The improper handling of electronic waste (e-waste) has resulted in significant environmental and health concerns globally. Heavy metal emissions into the environment through e-waste processing activities have been reported to leach into groundwater and soil, posing a risk to human health (Afolayan, 2018; Liang et al., 2022). The toxicity of heavy metals can lead to bioaccumulation through the food chain, resulting in high body loadings of heavy metals and per-

sistent toxic substances in e-waste workers and children (Wierzbowska et al., 2016; Belkhiri et al., 2018; Lin et al., 2022). Studies conducted in Nigeria have revealed high levels of copper, nickel, zinc, and lead, exceeding the European Union limits, in plants and nearby surface water in e-waste dumpsites in Lagos, Benin, and Aba cities (Nnorom, 2009; Senthilnathan & Philip, 2023). Additionally, the mean concentration of copper and lead in printed circuit boards of computer monitors and central processing units was found to be over 50 times higher than the toxicity threshold limit concentration for the metals in developed countries (Olubanjo et al., 2015; Jiang et al., 2019). The Alaba International Market in Lagos, Nigeria, attracts over one million traders daily who engage in informal e-waste processing activities such as burning, dismantling, and releasing hazardous materials into the environment (Isimekhai et al., 2017; Owoso et al., 2018). However, only a few studies have been carried out in Nigeria to determine the levels of heavy metal contaminants in groundwater from e-waste activities, particularly in the Alaba International Market (Isimekhai et al., 2017; Forti et al., 2020).

Therefore, this research will provide invaluable data on the levels of heavy metals in groundwater in the study area. These will also provide information to substantiate the urgent need for actions to address the problems posed by the crude recycling and disposal of hazardous e-waste in Lagos, Nigeria, as well as in other places in which similar activities take place.

The study aims to assess the groundwater quality and health risks associated with informal e-waste processing in Alaba International Market in Lagos, Nigeria. With a focus on the impacts of e-waste activities on groundwater in the area, the following objectives were developed: 1) Quantifying heavy metal levels in groundwater samples from Alaba International Market and its surrounding areas, 2) Interpreting the results of heavy metal analysis and presenting their spatial variability across all the sampling points, and 3) Assessing the potential hazards and health risks posed by heavy metal exposure to human health. The findings of this study will contribute to a better understanding of the effects of informal e-waste processing on groundwater and human health in the Alaba International Market in Lagos, Nigeria.

2. Materials and Methods

2.1. Study Area, Sampling Design and Sample Collection

The study area for this research is Alaba International Market in Ojo Local Government Area, Lagos State, Nigeria. Alaba International Market is the largest electronics market in West Africa and features over 2500 shops that refurbish and sell used electrical and electronic equipment. The market is located in a tropical region with a climate characterized by plenty of rainfall during the wet season (April-October) and a dry season that spans between October-May (Forti et al., 2020). **Figure 1** shows the sample locations where water samples were collected for this study.

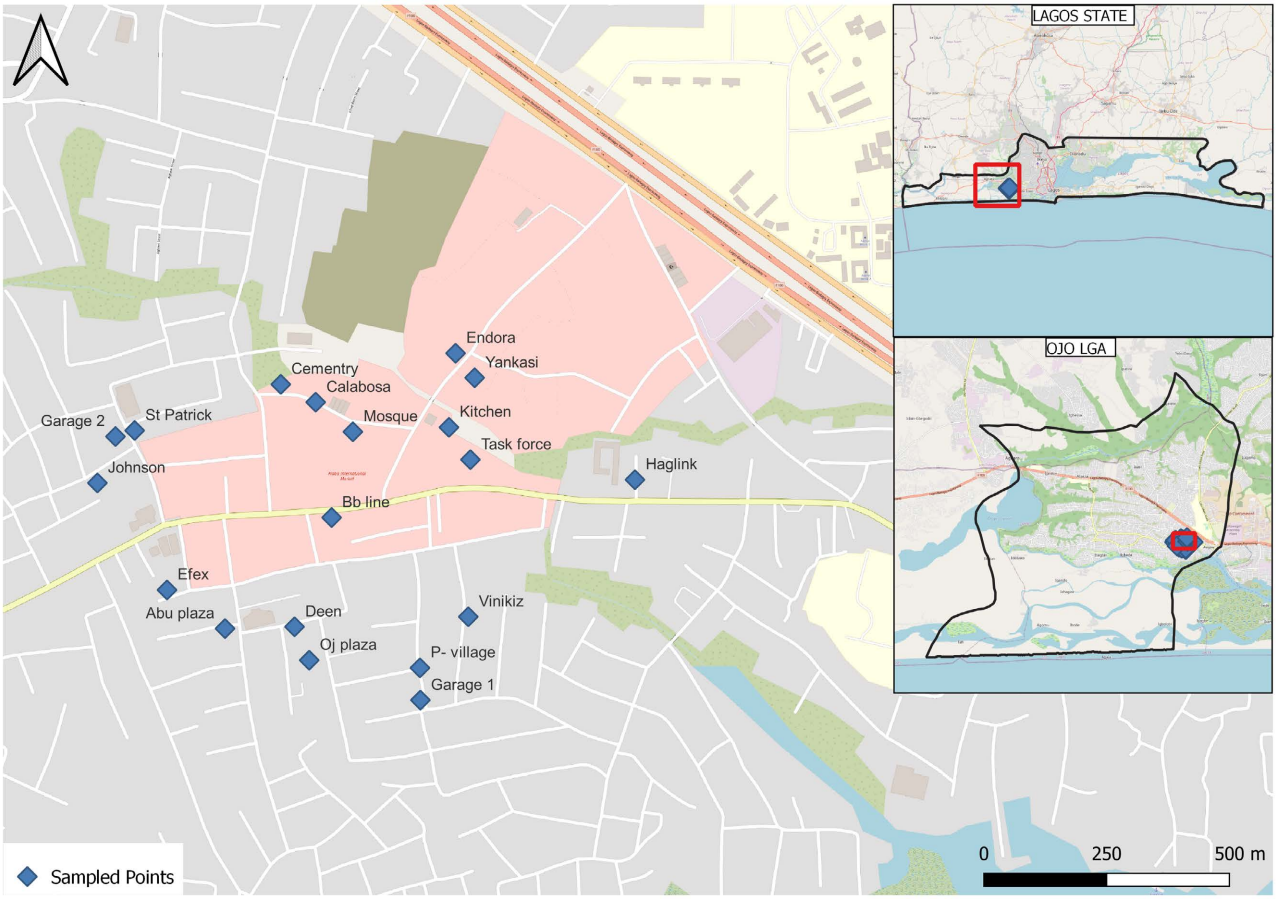


Figure 1. Study areas and sampling points in Alaba, Lagos State.

The sampling design for this study involves the collection of water samples from functioning hand-dug wells in the study sites, which are frequently used for domestic needs such as cooking, washing clothes and plates, bathing, and irrigation of plants for subsistent farming. Plants that were visibly cultivated in the study areas include *Celosia argentea* (locally called Efo riro) and *Telfairia occidentalis* (locally called ugu).

The study utilized a purposive sampling technique in selecting the wells for water sample collection. The wells were selected based on their proximity to the e-waste processing sites and the frequency of use by the residents. To ensure representativeness, the selected wells were evenly distributed across the study area. Observable activities during groundwater sample collection are presented in **Table 1**.

In total, twenty-two groundwater samples were randomly collected in March 2019. Twenty of the water samples were collected from functioning hand-dug wells from the study sites. Two control samples were collected from two different locations in Ikeja (Alausa and Opebi). Plastic containers used for water sample collection were first thoroughly washed with distilled water and soaked with diluted acid before use to prevent cross-contamination before sampling. Five (5 mL) of nitric acid (HNO_3) were added to the water sample to prevent precipita-

tion and adsorption of the metal analytes. During the collection, transportation, and analysis of the samples, standard procedures were adopted (Santoyo et al., 2000; Bankole, 2018).

Table 1. Field survey of activities in the Alaba International Market and the geographic positioning of each hand-dug well in the area.

Location	Tag	Well Cover	Activity	Use of Groundwater
Abu plaza	W1	NO	Sales of refurbished EEE	Cooking and washing
Deen	W2	NO	Sales of refurbished EEE	Cooking and washing
Mosque	W3	NO	Sales of office equipment	Cooking and washing
A-line	W4	NO	Sales of phone accessories	Cooking and washing
Vinikiz	W5	NO	Sales of gas cylinder	Washing
Haglink	W6	NO	Restaurant	Cooking, washing and bathing
Garage 1	W7	NO	No activity	Washing
Bb line	W8	YES	Sales of musical instruments	Cooking, washing
Garage 2	W9	NO	Loading of EEE product	Washing and bathing
Johnson	W10	NO	Residential area	Cooking, washing and bathing
Kitchen	W11	NO	Restaurant	Cooking, washing
St Patrick	W12	NO	Sales of refurbished EEE	Cooking and washing and bathing
Calabosa	W13	NO	Sales of refurbished machine parts	Cooking and washing
Cemetery	W14	NO	Sales of refurbished machine parts	Washing and bathing
Oj plaza	W15	YES	Sales of refurbished EEE	Cooking and washing
P-village	W16	YES	Sales of phone products	Washing and bathing
Efex	W17	NO	Residential area	Cooking, washing and bathing
Task force	W18	NO	Dumpsite	Cooking and washing
Yankasi	W19	NO	Dismantling and repair of machine parts	Washing and bathing
Endora	W20	NO	Dismantling and repair of machine parts	Washing and bathing
Control 1	W21	YES	Residential area	Cooking, washing and bathing
Control 2	W22	YES	Residential area	Cooking, washing and bathing

Note: EEE: electrical and electronic equipment.

2.2. Physicochemical Analysis and Preparation of Water Samples for Analysis

To determine pH, total dissolved solids (TDSs), and electrical conductivity (EC), groundwater samples were collected and analyzed using a Hannah hand-held device (model number: HI98194 Waterproof Portable pH/ORP/ISE/TDS/EC/S) in triplicates, with mean and standard deviation recorded. Chloride analysis was conducted at the Lagos State Environmental Protection Agency (LASEPA) using a titrimetric method. The water sample was shaken vigorously, and 100 mL was measured into a 250 mL conical flask, to which potassium chromate (K_2CrO_4) was added as an indicator. The solution was titrated against silver nitrate ($AgNO_3$) until a brick-red colouration was observed, with the volume of titrant used recorded for subsequent calculation of chloride concentration (Zhang, 2007). To determine the total hardness in water samples, a 50 mL sample was measured into a 100 mL conical flask, to which ammonium buffer solution and Erichromeblack-T were added. The solution was titrated using ethylenediaminetetraacetic acid (EDTA) until a light blue colouration was observed, with the titre value recorded for subsequent calculations (Korkmaz, 2017). The digestion of heavy metals in water samples was performed following the method utilized by Nielsen (2017), which involved mixing a 100 mL water sample with 5 mL of concentrated nitric acid and heating with an electric hotplate until precipitation occurred. The resultant concentrate was filtered with filter paper, diluted with distilled water, and transferred to a clean-labelled test tube for analysis using an Atomic Absorption Spectrophotometer. A blank solution was prepared for comparison to ensure the accuracy of the results. Heavy metals and Macronutrients in this study include copper (Cu), manganese (Mn), iron (Fe), nickel (Ni), cadmium (Cd), silver (Ag), lead (Pb), chromium (Cr), calcium (Ca^{2+}) and sodium (Na^{+}) were determined using the atomic absorption spectrometer (AAS). Metal concentrations in the sample solution from the AAS were calculated using the expression in Equation (1) as found in (Isimekhai et al., 2017). Furthermore, a triplicate analysis of all heavy metal concentrations was presented in this study.

As in

$$\text{Metal concentration}\left(\text{mg/L}\right) = \left(A \times B\right)/C. \quad (1)$$

where, A = Instrumental reading in (mg/L), B = Final volume of digested sample solution after making up to the mark (mL), and C = Initial sample volume taken (mL).

2.3. Analysis of the Water Sample Using an Atomic Absorption Spectrophotometer (AAS)

In this study, digested water samples were analysed using an atomic absorption spectrophotometer (AAS) model 2380 (Buck Scientific, USA). The AAS was turned on by connecting it to the readout device and running acetylene gas through the nebulizer hose in combination with compressed air collected using an air com-

pressor. Sample identity, sample mass, and dilution factor values were imputed, along with the concentration and number of standard solutions for the element of interest to aid the calibration graph of absorbance against concentration. The aspirator was inserted into the beaker containing de-ionized water, followed by the introduction of the blank, standard solution, and digested samples into the nebulizer and subsequently introduced into the flame. The results of the analysis were read out and recorded on the readout device.

2.4. Data Quality Control

Analytical-grade chemicals were used in this study to prepare and analyse the groundwater samples. All sample containers were pre-cleaned with a 10% nitric acid solution (v/v), rinsed with deionized water, and air-dried to prevent metal absorption from the container surfaces. Electrometric instruments were calibrated with standard solutions before collecting samples for the field investigation. A blank reagent was analyzed in each batch to verify the procedure. The instrument detection limits for each chemical parameter were 0.3 µg/L of As; 0.4 µg/L of Pb; 0.005 mg/L of Na, K and Fe; 0.001 mg/L of Ca^{2+}; 0.05 mg/L of Mg^{2+}; and 0.001 mg/L of SO_4^{2-}, NO_3^- and Cl (Ngo et al., 2021). Moreover, the working performance standard was well-checked for at least one spike sample and duplicated after running every 20 samples. The percentage recovery was within the 90% - 110% range while checking the duplicate revealed a level lower than 10%.

2.5. Statistical Analysis

Mean, standard deviation and health risk calculations were performed using Microsoft Excel, 2016. Pearson's correlation analysis was performed using the statistical package for the social sciences (SPSS), PASW Statistic Base 18 for Windows. Principal component analysis (PCA), and cluster analysis (CA) were carried out using XLSTAT add-in to Excel. Geospatial Analysis using the Inverse distance weighting method was performed using R programming software.

2.6. Geospatial Analysis

Unobserved extent of environmental exposures can be statistically estimated on a spatial scale using several geostatistical approaches. For instance, a pollutant measured at a location can be estimated spatially across an area by spatial interpolation processes. Although kriging and inverse distance weighted (IDW) methods of interpolation have been identified as the most extensively used in water quality, IDW has been chosen over kriging as the preferred approach (Khouni et al., 2021).

Khouni et al. (2021) also opined that inverse distance weighted (IDW) interpolation assumes that the nearer a sample point is to the cell whose value is to be estimated, the more closely the cell value will resemble the sample points value. The method uses a linear combination of weights at known points to estimate unknown location values.

2.7. Exposure Risk Assessment

The average daily intakes (ADDs) of As and Pb were investigated via two routes, including ingestion and dermal contact, and classified by age groups, such as children and adults. The deterministic risk was calculated using the USEPA health risk assessment guide, as found in (Gao et al., 2004). Hazard index (HI) was used to measure the non-carcinogenic metals that can affect children and adults in the market. If HI does not exceed unity (HI < 1) no carcinogenic risk was assumed to occur at the site and if HI > 1, it implies that there is a non-carcinogenic health risk to health effect over a lifetime exposure.

3. Results and Discussion

3.1. Physicochemical Properties of Groundwater Samples Analyzed

Table 2 presents the results of the physicochemical analysis of the groundwater samples. The mean pH value of the samples was 7.24 ± 0.15, with 77% of the samples falling within the permissible limits of 6.5 - 8.5 for groundwater as defined by the WHO (2020). The turbidity in the samples ranged from 0.13 - 99.8 NTU, with five samples (W4, W5, W7, W15, and W16) exceeding the permissible limit of 5 NTU (Ebrahimi et al., 2016). Of the samples, 23% had turbidity above the permissible limit, with W5, W7, and W16 showing particularly high levels (99.8 ± 0.00, 99.8 ± 0.00 and 99.1 ± 1.15). The electrical conductivity levels were below the permissible limit of 400 µS/cm for all study locations (Qureshi et al., 2021). Additionally, the concentrations of total dissolved solids, total hardness, and chloride were below the WHO permissible limits of 1000 mg/L, 500 mg/L, and 250 mg/L, respectively, for all 22 wells (Meride & Ayenew, 2016; World Health Organization, 2011, 2017).

The high turbidity levels in the groundwater were similar to those found in the southern districts of Sindh Province of Pakistan by Memon et al. (2011), where turbidity units ranged from 0.4 - 1650 NTU. The chloride concentrations ranged from 25.3 - 240 mg/L, with all samples falling within the permissible limit of 250 mg/L. The total hardness levels ranged from 32.7 to 22 mg/L, with 91% of the samples having levels above the permissible limit of 100 mg/L. Although, WHO recognizes no health impact due to the hardness of water, Balakrishnan et al. (2011) found that water with hardness levels between 150 and 300 mg/L may cause kidney and heart problems. The calcium concentration in all samples ranged from 0.14 - 7.41 mg/L, with an average of 2.90 ± 0.35 mg/L, which is within the permissible limit of 200 mg/L set by the WHO. The sodium concentration in the groundwater samples ranged from 0.78 - 3.59 mg/L, with an average of 2.27 ± 0.36 mg/L, and all samples were within the prescribed limit. While the pH levels and most of the physicochemical parameters in the groundwater samples were within permissible limits, the high turbidity levels and TDS concentrations in some of the samples are concerning. These findings suggest a need

Table 2. Physicochemical properties of groundwater samples.

Sample	Appearance	pH	Turbidity (NTU)	Electrical Conductivity (μS/cm)	Total Dissolved Solids (mg/L)	Total Hardness (mg/L)	Chloride (mg/L)
W1	Slightly cloudy	7.00± 0.30	0.6 ± 0.10	0.89 ± 0.00	438 ± 0.00	263 ± 4.24	73.5 ± 3.54
W2	Colourless	7.37 ± 0.15	0.6 ± 0.10	1.7 ± 0.00	851 ± 0.00	388 ± 11.3	228 ± 6.08
W3	Colourless	5.4 ± 0.30	2.07 ± 0.45	1.01 ± 0.00	499 ± 0.58	181 ± 3.06	137 ± 7.00
W4	Slightly cloudy	6.27 ± 0.25	6.7 ± 0,10	0.49 ± 0.00	238 ± 0.00	143 ± 13.0	49 ± 0.00
W5	Cloudy	7.4 ± 0.10	99.8 ± 0.00	1.37 ± 0.00	681 ± 0.58	263 ± 24.0	145 ± 1.15
W6	Colourless	7.67 ± 0.06	0.8 ± 0.00	0.51 ± 0.00	246 ± 0.58	137 ± 5.03	65.5 ± 7.78
W7	Cloudy with brownish colour	6.83 ± 0.15	99.8 ± 0.00	0.88 ± 0.00	432 ± 1.73	174 ± 2.28	142 ± 4.51
W8	Colourless	6.8 ± 0.00	2.53 ± 0.35	0.49 ± 0.00	237 ± 0.58	110 ± 10.6	85.3 ± 8.08
W9	Colourless	8.2 ± 0.10	0.4 ± 0.10	0.84 ± 0.00	409 ± 0.00	253 ± 6.11	79 ± 7.07
W10	Colourless	8.17 ± 0.06	0.4 ± 0.10	1.03 ± 0.00	507 ± 0.00	223 ± 3.06	95.7 ± 3.21
W11	Clear	8.27 ± 0.15	0.5 ± 0.10	1.13 ± 0.00	560 ± 0.00	222 ± 10.6	139 ± 4.62
W12	Colourless	8.23 ± 0.06	1.97 ± 0.21	0.7 ± 0.00	341 ± 0.00	200 ± 4.00	74.7 ± 6.11
W13	Clear	5.87 ± 0.67	0.8 ± 0.10	1.27 ± 0.01	628 ± 0.58	291 ± 12.7	166 ± 3.06
W14	Colourless	5.73 ± 0.21	0.17 ± 0.06	0.98 ± 0.00	482 ± 0.00	257 ± 9.90	96 ± 4.00
W15	Cloudy with yellow colour	7.87 ± 0.06	7.6 ± 0.44	0.47 ± 0.01	220 ± 0.71	144 ± 4.00	33 ± 1.41
W16	Slightly cloudy	7.8 ± 0.10	99.1 ± 1.15	1.23 ± 0.00	610 ± 0.00	240 ± 11.1	179 ± 4.51
W17	Colourless	7.8 ± 0.00	3.6 ± 0.26	0.72 ± 0.00	353 ± 0.00	163 ± 13.3	71 ± 2.65
W18	Clear	7.93 ± 0.15	3.97 ± 0.42	1.01 ± 0.00	496 ± 0.00	229 ± 10.1	112 ± 1.73
W19	Clear	6.87 ± 0.25	0.47 ± 0.06	1.86 ± 0.00	935 ± 0.00	367 ± 6.43	240 ± 3.79
W20	Colourless	7.27 ± 0.12	0.27 ± 0.15	1.38 ± 0.01	689 ± 0.00	370 ± 15.6	152 ± 3.06
Control 1	Colourless	6.73 ± 0.06	0.2 ± 0.10	0.33 ± 0.00	0.16 ± 0.00	70 ± 5.66	36 ± 2.65
Control 2	Colourless	5.8 ± 0.20	0.13 ± 0.06	0.11 ± 0.00	0.05 ± 0.00	32.7 ± 7.02	25.3 ± 7.57

for further monitoring and treatment of the groundwater in the study area to ensure safe and healthy drinking water.

3.2. Heavy Metal Concentration in Groundwater Samples Analyzed

The result of the heavy metal and macronutrients analysis in groundwater samples from hand-dug wells in the Alaba International Markets are presented in Table 3. The concentration of Calcium (Ca) from groundwater samples from the Alaba International Market that was analyzed indicated that all samples in the twenty sites and the two control sites were below the WHO permissible

Table 3. Heavy metal properties of groundwater sample.

Sample	Ca	Na	Mn	Fe	Ni	Cd	Ag	Pb	Cr
W1	2.93 ± 0.32	1.79 ± 0.10	0.01 ± 0.01	0.14 ± 0.04	0.02 ± 0.00	BDL	BDL	0.01 ± 0.00	0.13 ± 0.00
W2	7.41 ± 1.22	2.6 ± 0.89	0.01 ± 0.00	0.05 ± 0.01	0.01 ± 0.00	BDL	0.01 ± 0.00	BDL	0.07 ± 0.00
W3	3.05 ± 0.87	2.08 ± 1.10	BDL	BDL	BDL	BDL	BDL	0.01 ± 0.00	0.02 ± 0.00
W4	2.98 ± 0.19	1.97 ± 0.34	0.01 ± 0.00	0.18 ± 0.02	0.01 ± 0.01	BDL	BDL	0.01 ± 0.01	0.05 ± 0.04
W5	5.39 ± 0.54	2.67 ± 0.78	0.03 ± 0.03	1.72 ± 0.64	0.01 ± 0.01	BDL	BDL	0.01 ± 0.00	0.01 ± 0.00
W6	1.4 ± 0.42	2.08 ± 1.36	0.05 ± 0.04	0.01 ± 0.01	0.02 ± 0.01	BDL	0.01 ± 0.00	BDL	0.01 ± 0.00
W7	3.39 ± 1.30	2.2 ± 0.57	0.03 ± 0.01	0.97 ± 0.45	0.01 ± 0.01	BDL	BDL	0.01 ± 0.01	0.1 ± 0.00
W8	1.99 ± 0.57	2.29 ± 0.63	0.06 ± 0.04	0.07 ± 0.01	0.02 ± 0.00	BDL	BDL	0.01 ± 0.00	0.06 ± 0.05
W9	1.7 ± 0.49	3.09 ± 1.12	0.01 ± 0.01	0.04 ± 0.00	0.01 ± 0.01	0.01 ± 0.01	BDL	BDL	BDL
W10	1.43 ± 0.33	2.28 ±0.28	0.00 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.00	BDL	BDL
W11	2.46 ± 0.79	2.03 ± 0.99	0.03 ± 0.01	0.2 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	BDL	0.03 ± 0.00	0.01 ± 0.00
W12	1.81 ± 0.68	2.07 ± 0.73	BDL	0.02 ± 0.00	0.01 ± 0.00	0.01 ± 0.01	BDL	BDL	BDL
W13	2.07 ± 0.26	2.05 ± 0.24	BDL	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.00	BDL	0.01 ± 0.00
W14	3.26 ± 0.19	3.59 ± 0.58	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.01	0.01 ± 0.01	BDL	BDL	BDL

Continued

W15	5.04 ± 0.95	1.63 ± 0.41	0.04 ± 0.01	1.4 ± 0.08	0.01 ± 0.01	BDL	BDL	0.01 ± 0.00	0.04 ± 0.00
W16	2.75 ± 0.69	2.40 ± 0.44	0.02 ± 0.00	0.51 ± 0.12	0.02 ± 0.01	BDL	0.01 ± 0.00	0.01 ± 0.00	0.03 ± 0.02
W17	1.93 ± 0.07	1.69 ± 0.17	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	BDL	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.00
W18	2.04 ± 0.50	2.31 ± 0.41	0.02 ± 0.00	0.05 ± 0.00	0.01 ± 0.00	0.01 ± 0.01	BDL	0.01 ± 0.01	BDL
W19	2.33 ± 0.09	2.23 ± 0.66	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.01	BDL	BDL	BDL	BDL
W20	2.71 ± 0.46	2.43 ± 1.19	0.03 ± 0.02	BDL	0.01 ± 0.01	BDL	0.01 ± 0.01	BDL	0.02 ± 0.01
Control 1	0.63 ± 0.03	2.19 ± 0.95	BDL	0.02 ± 0.01	0.02 ± 0.00	BDL	BDL	BDL	0.01 ± 0.00
Control 2	0.14 ± 0.07	0.78 ± 0.34	0.01 ± 0.01	BDL	0.01 ± 0.00	BDL	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00
WHO PL	100	200	0.4	0.3	0.07	0.003	0.1	0.01	0.05
PL Source	WHO, 2011	WHO, 2017	WHO, 2017	WHO, 2017	WHO, 2017	WHO, 2017	WHO, 2020	WHO, 2017	WHO, 2017

Note: BDL: below detection limits; PL: permissible limits.

limits of 200 mg/L (Sarath Prasanth et al., 2012), with the concentration of calcium ranging from 0.14 - 7.41 mg/L with an average mean of 2.90 ± 0.35 mg/L. The concentration of sodium (Na) in groundwater samples in this study ranged between 0.78 - 3.59 mg/L with an average of 2.27 ± 0.36 mg/L which was below the WHO permissible limit of 200 mg/L. The concentration of Manganese (Mn) in this study ranged from 0.01 - 0.06 mg/L with a mean value of 0.02 ± 0.01 mg/L which was less than the WHO permissible limit of 0.4 mg/L. The concentration of iron (Fe) in groundwater samples from the sampled locations ranged from 0.01 - 1.72 mg/L with a mean value of 0.27 ± 0.17 mg/L. Where 50% of the groundwater samples were greater than the permissible limit of 0.03 mg/L. The concentration of nickel (Ni) in the groundwater of the study area was within the range of 0.01 - 0.02 mg/L with an average value of 0.01 ± 0.00 mg/L. The permissible level of Ni in groundwater as specified by WHO is 0.07 mg/L, which is higher than the values for Ni in all the samples analyzed. The Cadmium (Cd)

concentration present in sampled water was 0.01 mg/L in locations W9 to W14 and location W18. All other locations were below the detection limits. The concentration of Cd in this study was found to be greater than the permissible limit of 0.003 mg/L for groundwater by the WHO standards at sites W9 - W14, and W18. Silver ions analyzed in the water samples were generally less than the permissible limits of 0.1 mg/L as 64% of the samples analyzed were below the detection limits. In groundwater samples from Alaba International Market, lead (Pb) concentrations ranged from below the detection limit to 0.03 ppm. W11 had a concentration of 0.03 ppm, while W1, W3, W4, W5, W7, W8, W15 to W18 had a concentration of 0.01 ppm. The informal market-based processing of e-waste components may be responsible for the detection of lead in some of the sites' groundwater samples. The mean concentration of Chromium (Cr) ranged from 0.01 - 0.13 mg/L with an average of 0.03 ± 0.01 mg/L. Twenty-three (23%) of the groundwater samples were found greater than the permissible limit of 0.05 mg/L for groundwater. From the present study, heavy metal concentrations in groundwater samples from the Alaba International Market varied. In all studied areas, Ca and Na concentrations were within the WHO-acceptable levels. Manganese and Ni values were also found to be within acceptable ranges. Nevertheless, Cd, Pb, and Cr values were found to exceed WHO-permitted limits in some of the studied locations. Cadmium concentrations, for example, were above the allowable limit in locations W9 - W14 and W18, while Pb was identified in several groundwater samples from the sites, possibly due to the informal market-based processing of e-waste components.

The concentrations of heavy metals in groundwater around the Alaba International Market were compared to those reported in other studies. The concentration of Ca in this study was lower than that recorded in surface and pond water bodies around e-waste dump sites of Guzape, Karmo, and Kubuwa areas of Abuja, where the authors recorded Ca concentrations of 30.7, 35.4, and 24.8 mg/L respectively (Mukate et al., 2019). The concentration of Na in water samples contaminated by anthropogenic activities in rural east-central Illinois ranged from 0.8 to 12 mg/L, which was higher than what was reported in the present study (Balogun-Adeleye et al., 2022). Panno et al. (2006) reported Pb concentrations in groundwater exceeding the WHO permissible limits for drinking water, with Pb concentrations ranging from 0.001 to 5.458 mg/L, which is higher than the Pb concentrations reported in the present study. Adeyi and Oyeleke (2017) reported cadmium concentrations ranging from 0.001 to 0.060 mg/L in groundwater samples collected around informal e-waste recycling sites in Lagos, Nigeria. The Mg concentration in groundwater around e-waste processing sites at Guiyu in the Guangdong Province of China was higher than that reported in this study and ranged from 0.11 to 0.43 mg/L (Wang & Guo, 2006). The concentration of Fe in this study was higher than the Fe in groundwater samples around metal recycling sites at Ikorodu-Shagamu road, Lagos, Nigeria, where the Fe concentration observed was at 0.3 mg/L (Oyeku & Eludoyin, 2010). The concentration of Ni in e-waste processing sites in Karachi, Pakistan, as recorded by Ra-

feeq (2021), was 0.032 mg/L, which was higher than what was recorded in this study. The concentration of Cr in the groundwater around the Vihar industrial area in East Delhi, India when analyzed was higher than the concentrations of Cr in the present study and was at 0.29 mg/L (Panwar & Ahmed, 2018). The Ag concentrations in this study were higher than those recorded in groundwater around the Subriso East Rock Waste dump area located in the Hwini-Butre and Benso in Ghana, where the concentrations of Ag recorded were below the detection limits of the AAS machine used for analysis (Krampah et al., 2019).

The majority of the groundwater in the wells was close to the surface, and heavy metals were found in the water samples. The presence of Ca, Mn, Fe, Ni, Cd, Ag, Pb, and Cr in the groundwater could be attributed to the activities of informal handling of e-waste materials around the sampled sites. Heavy metals from e-waste can contaminate groundwater in various ways. Leaching of heavy metals into the soil and subsequently into groundwater is one possible way. Additionally, heavy metals can be deposited onto the ground and eventually into groundwater through atmospheric deposition, which occurs when heavy metals are released into the air during the burning or incineration of electronic waste (Ackah, 2017). Another way heavy metals can be transported to groundwater is through surface water runoff from e-waste dumping sites or landfills (Sivaramanan, 2013). It is worth noting that compounds like Ca and Mg can be found in groundwater surrounded by metamorphic and sedimentary rock types such as limestone, dolomite, gypsum, marble, and certain types of schist. In informal e-waste processing environments, Ca and Mg can be found in soil and possibly groundwater through e-waste materials such as battery-powered electronic gadgets, such as laptops, cell phones, cameras, and circuit boards as part of the solder used to connect components to the board). Sodium in groundwater can originate from the natural breakdown of rocks and minerals, such as feldspar and mica. In coastal regions, like Lagos, the high soil salinity can potentially cause the presence of sodium ions in groundwater. However, the presence of Na in electronic devices that utilize capacitors, which are electrical energy storage components, and displays, such as televisions and computer monitors can also lead to the presence of Na in water systems when washed away in water systems or leached into groundwater. E-waste materials contain toxic components that, if not properly disposed of, can be hazardous to human health and the environment.

Manganese, iron and nickel are typical components of electronic gadgets and can leach into groundwater from e-waste disposal sites. Cadmium, Silver, Lead, and Chromium are some elements that are commonly used in electronics and can be discharged into the environment during informal processing.

3.3. Pearson's Correlation Analysis of Heavy Metals in Groundwater Samples Analyzed

Pearson's correlation analysis was used to check the possible relationships be-

tween the parameters determined. Correlation of the physicochemical parameters and heavy metal in groundwater indicated positive correlations among samples as shown in Table 4.

Table 4 shows correlation coefficients ranging from very strong positive correlations to weak positive correlations. Very strong positive correlations (r = 0.992, 0.940, 0.935, 0.932, and 0.930 $p \leq 0.05$) were observed between TDS/EC, Cl/EC, TH/TDS, TH/EC, and Cl/TDS, respectively. Strong positive correlations (r = 0.808, 0.542, $p \leq 0.05$) were established between chloride/TH and Fe/Ca. Moderate correlations (r = 0.716, 0.542, 0.526, 0.523, 0.511, 0.508, 0.466, 0.465, 0.455, 0.393, 0.387, 0.379, 0.370, 0.366, 0.314, 0.312, 0.310, 0.306, $p \leq 0.95$) were observed between Fe/Turbidity, Fe/Ca, Ca/TDS, Na/TH, Ca/TH, Ca/EC, Ca/Cl, Na/EC, Na/TDS, Ni/Mn, Cr/Ca, Fe/Mn, Cd/Na, Na/Cl, Na/Ca, Ca/Tur, Pb/Fe, and Pb/Mn. Weak positive correlations (r = 0.287, 0.264, 0.236, 0.231, 0.225, 0.218, 0.213, 0.203, 0.199, 0.198, 0.197, 0.197, 0.196, 0.187, 0.173, 0.168, 0.164, 0.164, 0.152, 0.150, 0.134, 0.127, 0.122, 0.121, 0.117, 0.110, 0.107 $p \leq 0.95$) were observed between Cl/Turbidity, Cd/pH, Cr/Turbidity, −6pH/Turbidity, Cr/Pb, Mn/Turbidity, Cr/Fe, Cr/Ni, TDS/Turbidity, Ni/Na, Mn/pH, Cr/Mn, EC/Tur, Cd/TH, Fe/pH, Mn/Ca, Ag/Cl, TH/pH, Pb/pH, Na/Tur, Ag/TH, TDS/pH, Ag/TDS, Cd/TDS, Ag/EC, EC/pH, and Cd/EC, respectively.

These positive correlations suggest that the metals in groundwater have common sources, and their accumulation may have resulted from anthropogenic activities in the market.

Table 4. Pearson's correlation coefficient analysis between physicochemical characteristics and heavy metals in groundwater.

	pH	Turbidity	EC	TDS	TH	Cl	Ca	Na	Mn	Fe	Ni	Cd	Ag	Pb	Cr
pH	1														
Turbidity	0.094	1													
EC	0.110	0.196	1												
TDS	0.127	0.199	0.992	1											
TH	0.164	0.030	0.932	0.935	1										
Cl	−0.003	0.287	0.940	0.930	0.808	1									
Ca	0.058	0.312	0.508	0.526	0.511	0.466	1								
Na	0.089	0.150	0.465	0.455	0.523	0.366	0.314	1							
Mn	0.197	0.218	−0.154	−0.106	−0.158	−0.077	0.168	0.069	1						
Fe	0.173	0.716	0.042	0.055	−0.047	0.015	0.542	0.010	0.379	1					
Ni	0.068	0.058	−0.259	−0.281	−0.183	−0.237	−0.203	0.198	0.393	−0.093	1				
Cd	0.264	−0.283	0.107	0.121	0.187	−0.015	−0.246	0.370	−0.281	−0.286	−0.120	1			
Ag	0.060	−0.043	0.117	0.122	0.134	0.164	−0.094	−0.234	−0.089	−0.277	0.055	−0.111	1		
Pb	0.152	0.231	−0.099	−0.067	−0.241	−0.051	0.098	−0.302	0.306	0.310	−0.150	−0.049	−0.307	1	
Cr	−0.145	0.236	−0.049	−0.027	0.013	0.020	0.387	−0.181	0.197	0.213	0.203	−0.480	−0.143	0.225	1

3.4. Source Correlation Analysis of Heavy Metals in Groundwater Using Principal Component Analysis and Clustering Analysis

Principal component analysis was used in this study to identify the sources of metals in groundwater. These sources could be natural, anthropogenic or mixed (both natural and anthropogenic). Table 5 indicated that seven factors affected the variables. Out of the seven factors, only five accounted for the total variability in the data as shown in the scree plot. However, only two loading factors out of the five were used to show the most variable data (p: 0.5%). Principal component analysis (PCA) revealed the total cumulative variance for the two factors in groundwater.

The hierarchical cluster analysis results in this study showed by the dendrogram grouped the observations into three clusters. The classification showed similarities in the sources of the observations with W1, W6, and W16 grouped as Cluster 1, W2, W3, W4, W9, W10, W12, W13, W14, W17 to W22 all grouped as Cluster 2, and W5, W7, W11, and W15 grouped as Cluster 3 as shown in Figure 2.

This shows that Cluster 1 is from a natural source, Cluster 2 resulted from the anthropogenic source, while cluster three was a result mixed source (both natural and anthropogenic activities). The dendrogram established that Cluster 1 had similar sources different from Cluster 2 and Cluster 3.

3.5. Spatial Distribution of Heavy Metals

Figure 3 depicts the spatial variations of groundwater properties and heavy metals. Samples collected from the Southern part of the market had high concentrations of Ca, Cr, Pb and Fe, while the Northern parts of the market had more concentration of Cd and Na. Mn and Ni were detected more in samples collected more in the W6 and W8. Ag was detected despondently across W2, W6, W10, W13, W16, W17, and W20.

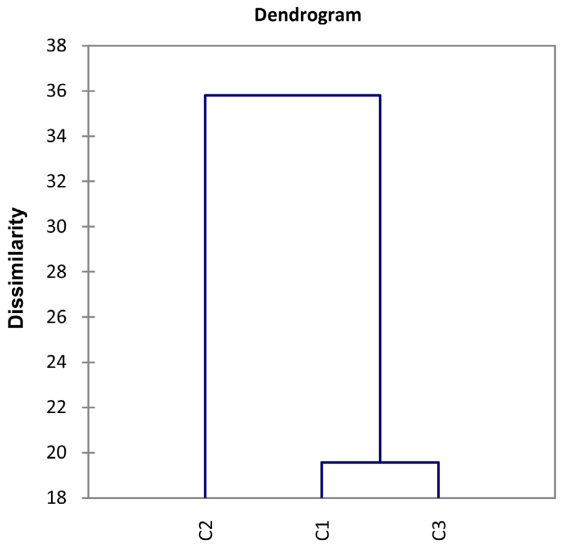
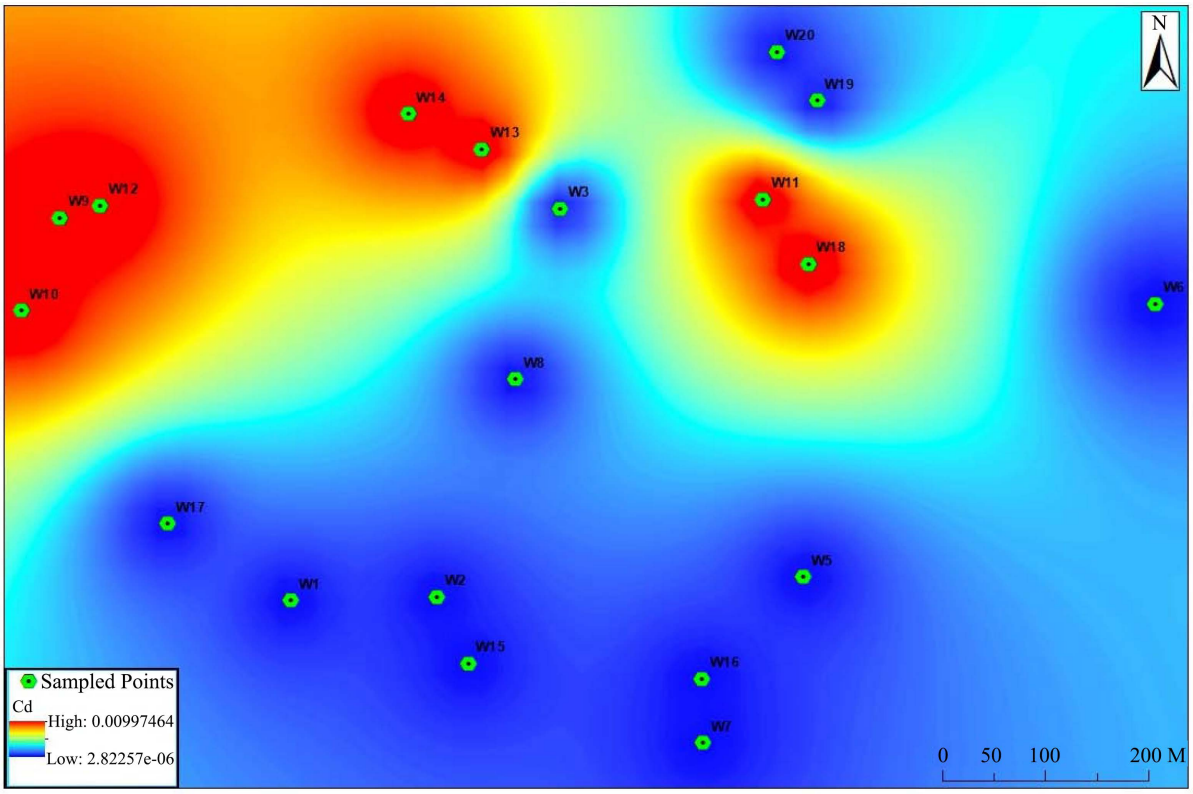
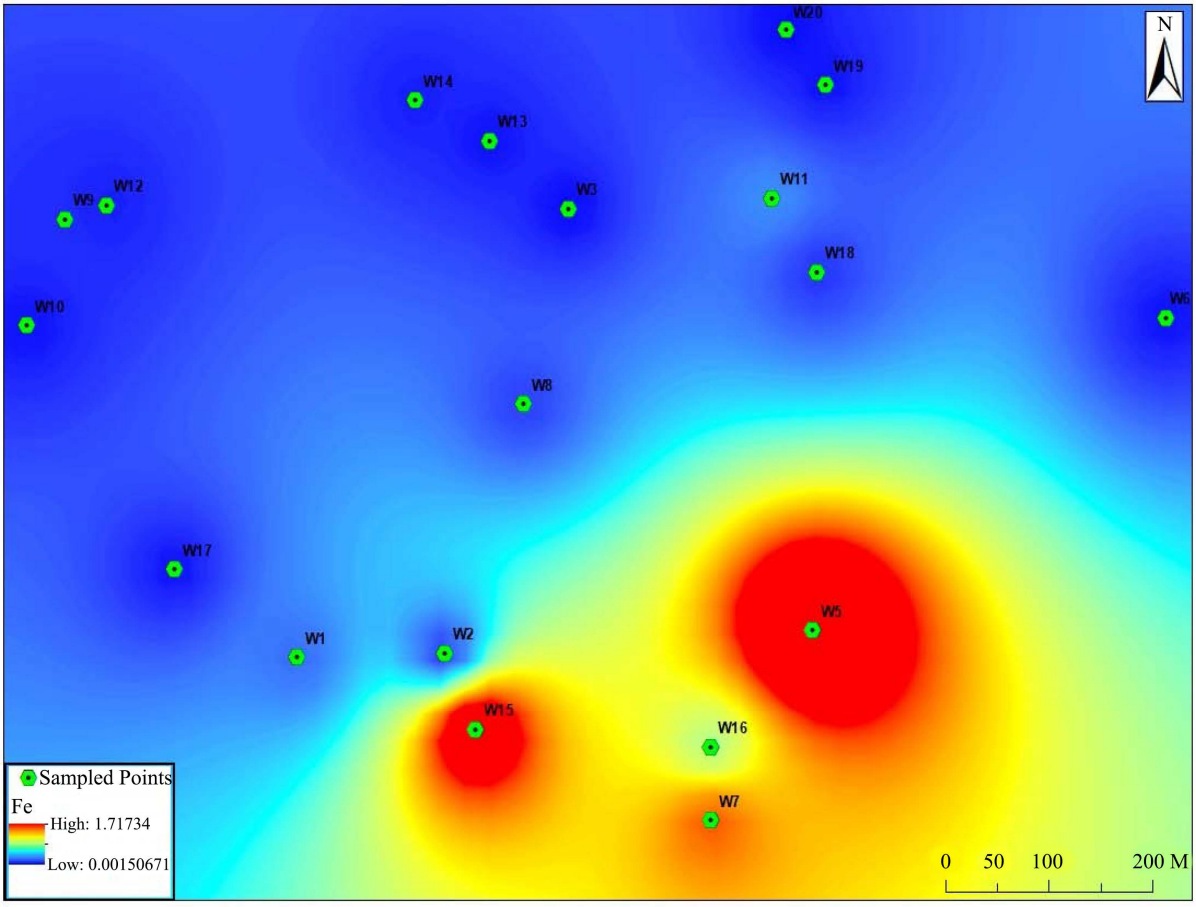
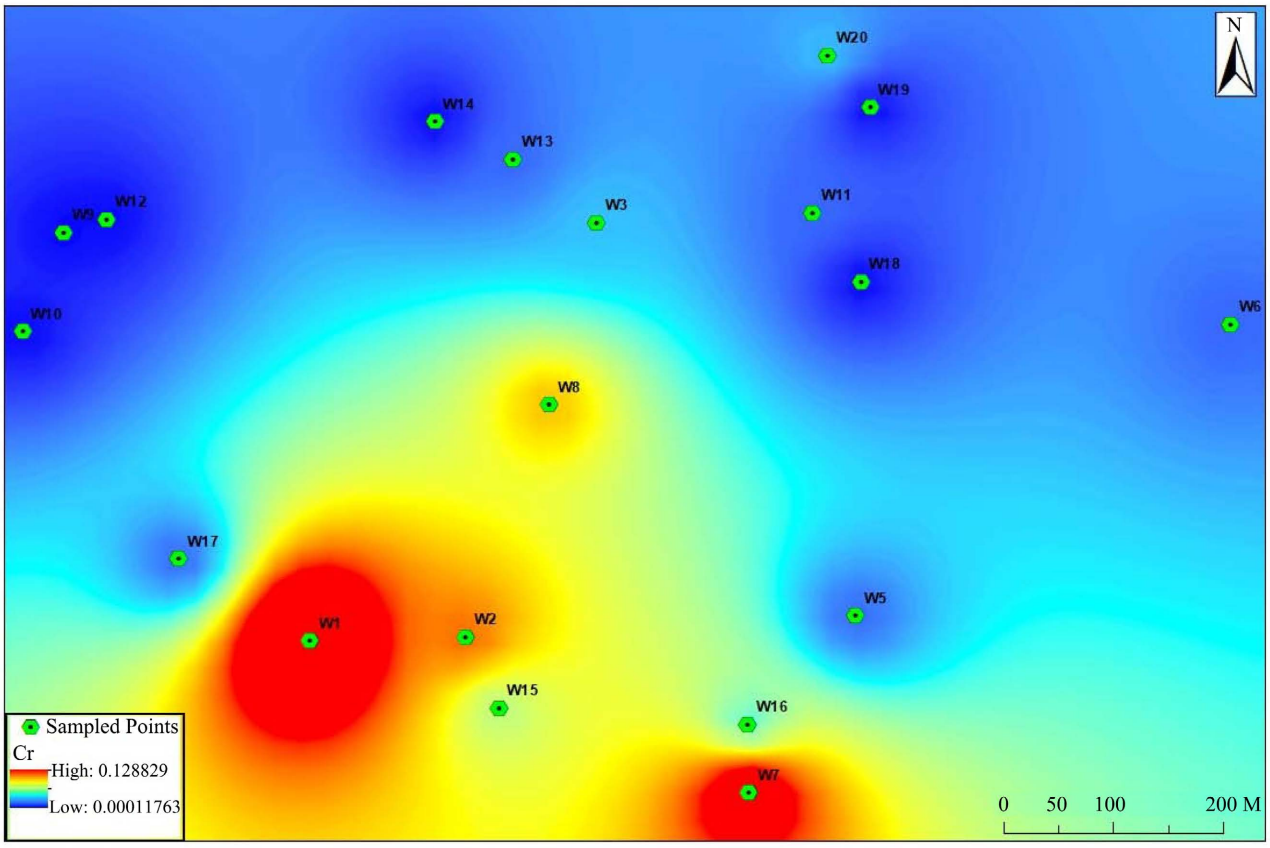
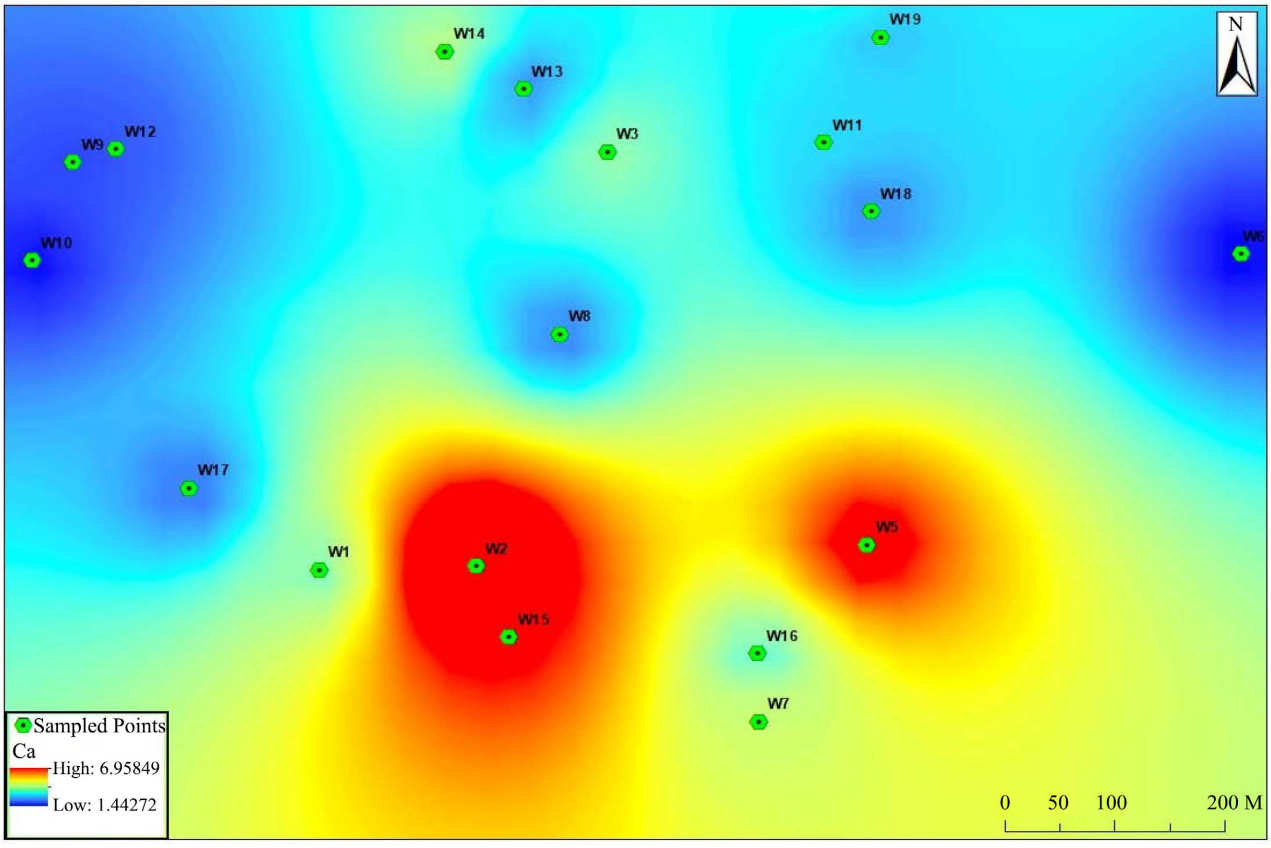


Figure 2. Dendrogram for the heavy metals obtained by the furthest neighbour method.


N
W20
W19
W14
W13
W12
W9
W3
W11
W18
W10
W6
W8
W17
W5
W1
W2
W15
W16
W7
Sampled Points
Cd
High: 0.00997464
Low: 2.82257e-06
0 50 100 200 M


N
W20
W19
W14
W13
W12
W9
W3
W11
W18
W10
W6
W8
W17
W5
W1
W2
W15
W16
W7
Sampled Points
Fe
High: 1.71734
Low: 0.00150671
0 50 100 200 M


N
W20
W19
W14
W13
W12
W9
W3
W11
W18
W10
W6
W8
W17
W5
W1
W2
W15
W16
W7
Sampled Points
Cr
High: 0.128829
Low: 0.00011763
0 50 100 200 M


N
W19
W14
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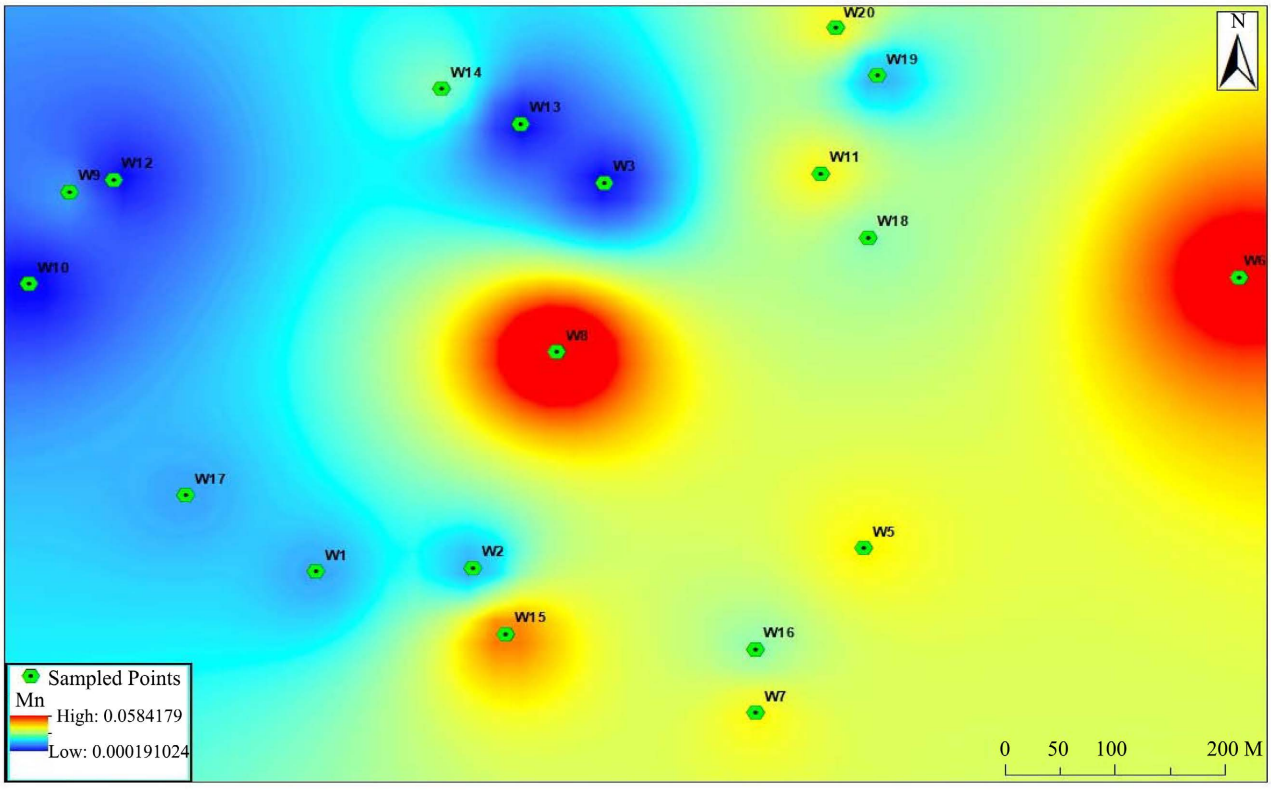
W12
W9
W3
W11
W18
W10
W6
W8
W17
W5
W1
W2
W15
W16
W7
Sampled Points
Ca
High: 6.95849
Low: 1.44272
0 50 100 200 M


W20
W19
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W13
W12
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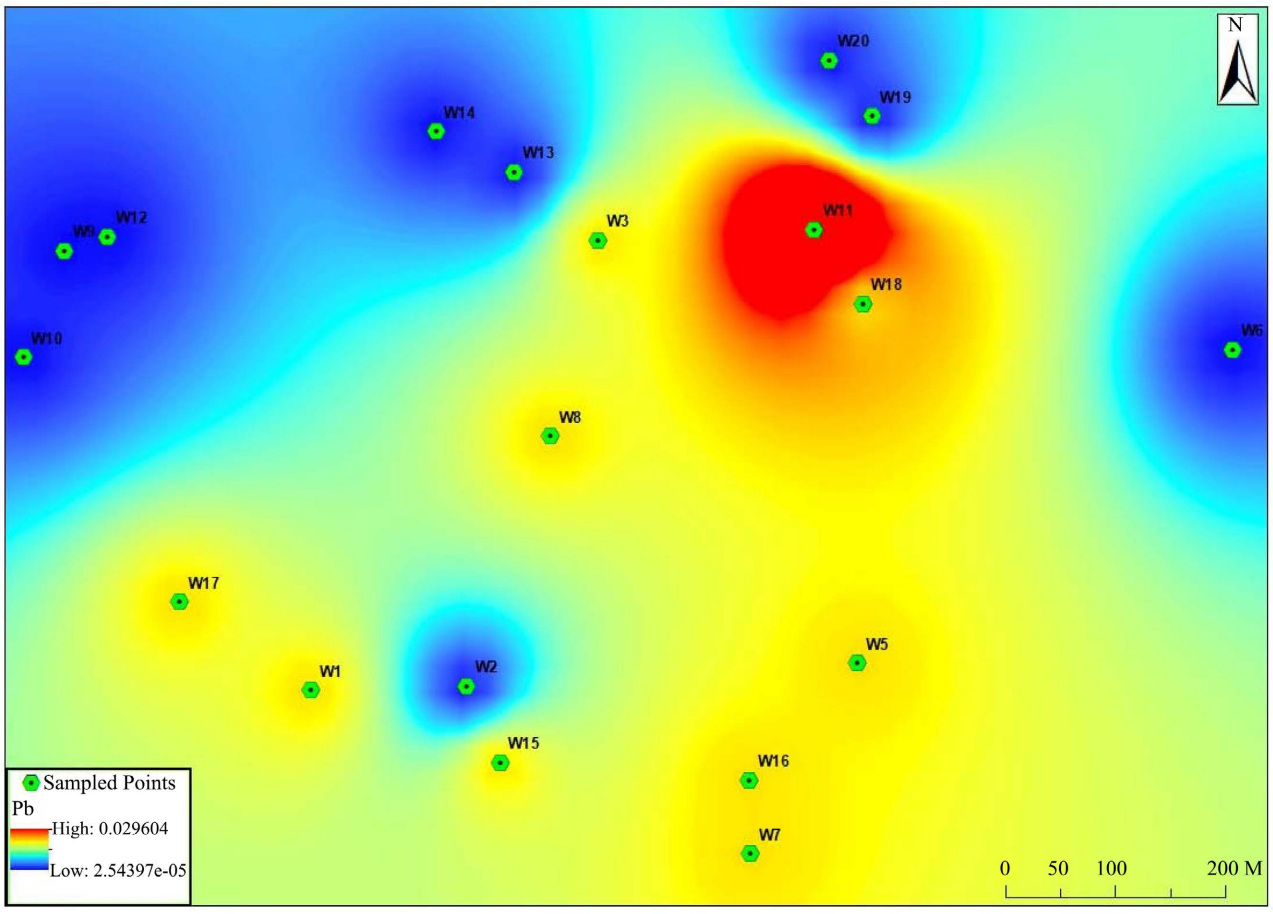
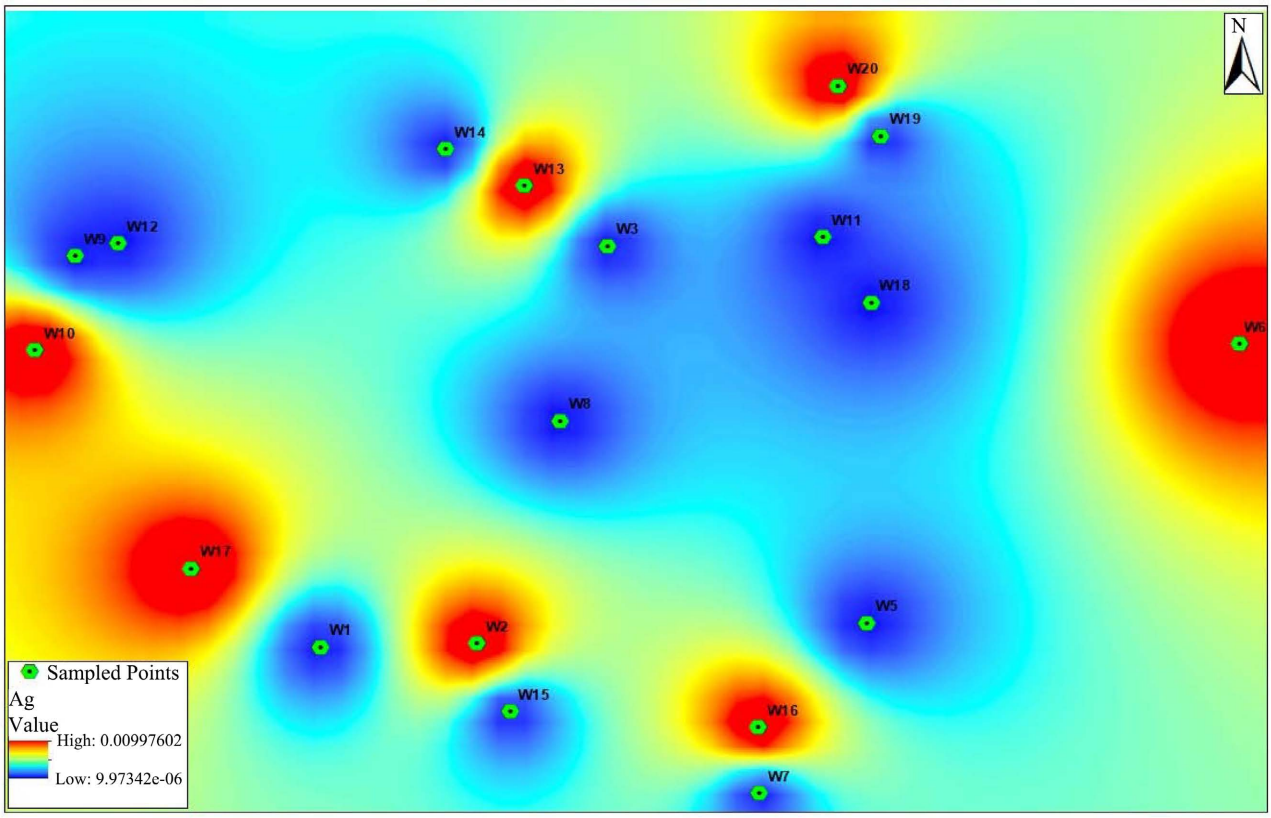
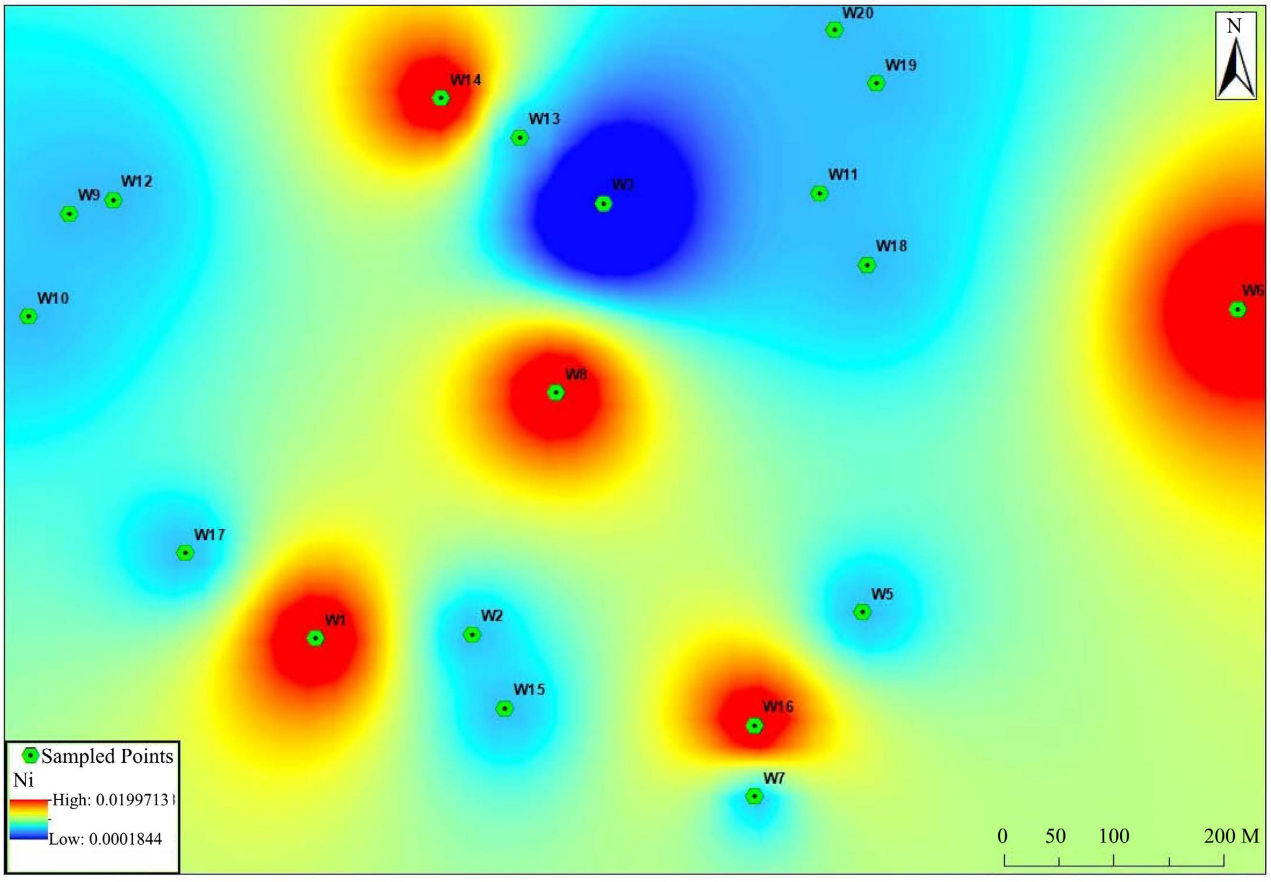
W3
W11
W18
W10
W8
W17
W5
W1
W2
W15
W16
W7
N
Sampled Points
Mn
High: 0.0584179
Low: 0.000191024
0 50 100 200 M


W20
W19
W14
W13
W12
W9
W3
W11
W18
W10
W8
W17
W5
W1
W2
W15
W16
W7
N
Sampled Points
Pb
High: 0.029604
Low: 2.54397e-05
0 50 100 200 M


N
W20
W19
W14
W13
W12
W9
W3
W11
W18
W10
W8
W17
W5
W1
W2
W15
W16
W7
Sampled Points
Ag
Value
High: 0.00997602
Low: 9.97342e-06


N
W20
W19
W14
W13
W12
W9
W3
W11
W18
W10
W8
W17
W5
W1
W2
W15
W16
W7
Sampled Points
Ni
High: 0.0199713
Low: 0.0001844
0 50 100 200 M

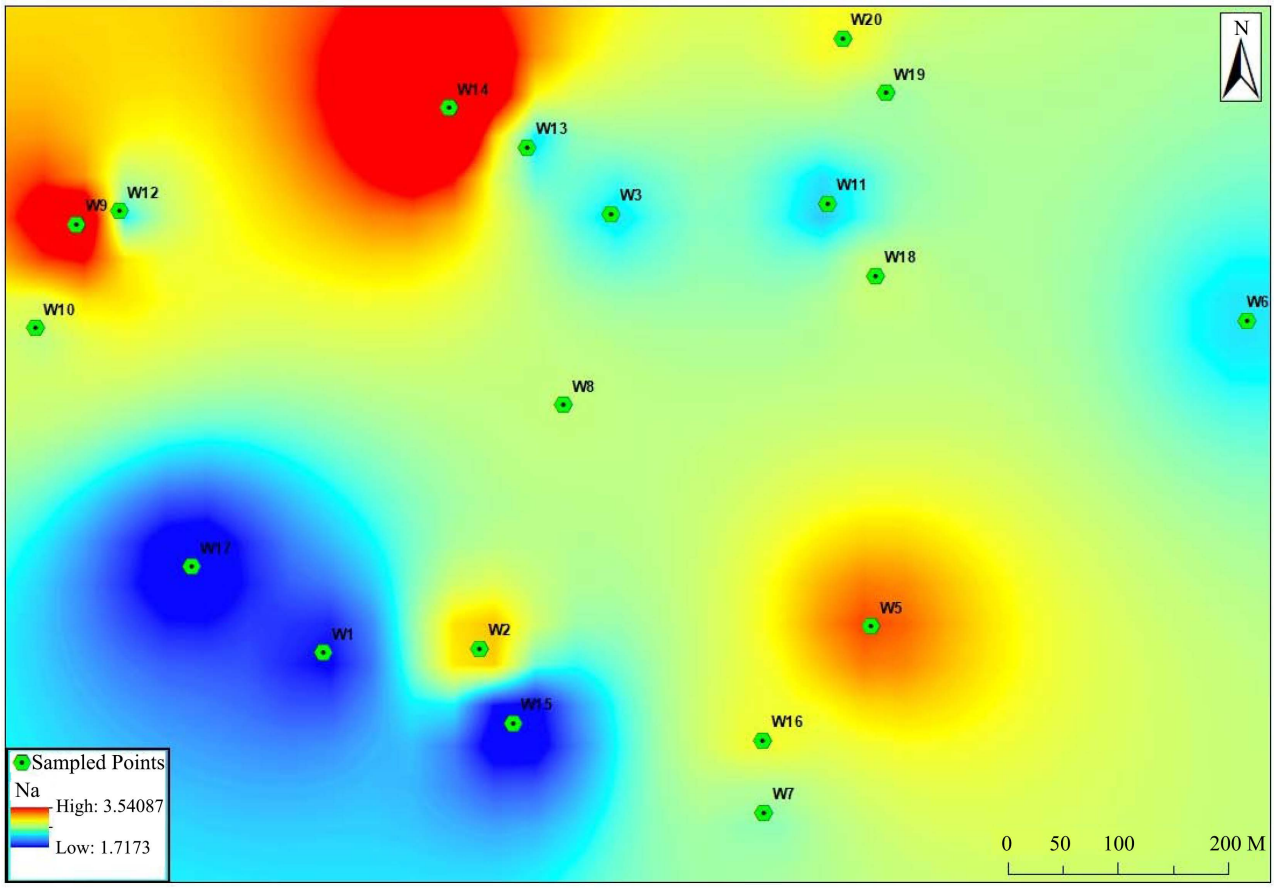


Figure 3. Spatial distribution of heavy metal concentration in groundwater at the Alaba International Market.

Table 5. Eigenvalues table for variables.

	F1	F2	F3	F4	F5	F6	F7
Eigenvalue	2.216	1.470	1.046	0.845	0.698	0.415	0.310
Variability (%)	31.661	21.007	14.939	12.071	9.964	5.927	4.431
Cumulative (%)	31.661	52.667	67.607	79.678	89.643	95.569	100.000

The spatial representation of the metals from all the sampled points as depicted in Figure 3 revealed that the concentration of heavy metals was lower in the southern region parts of the electronic market. If there is an inevitable need to dig a well around the study area, it is advisable to use water with less treatment around the southern region to avoid health effects.

3.6. Health Risk Assessment of Heavy Metals

Figure 4 showed the non-carcinogenic risk of metals for both children and adults. The HI for both children (3.7E+12) and adults (1.51E+12) are greater than 1. This means that the health risk will impact the children more than the adults. This observation proves that e-waste activities possess a serious potential hazard to children in Alaba International Market (Isimekhai et al., 2017). The carcino-

genic risk as revealed by the indices of potential cancer or cumulative carcinogenic risk (R_{total}) for carcinogenic metals for children and adults is represented in Figure 5. The results showed that the cancer risk values were higher than 1.0E−04 indicating unacceptable high-dose exposure risk for both children (3.30E+08) and the adults (6.18E+08).

Groundwater contamination with Calcium, Sodium, Manganese, Iron, Nickel, Cadmium, Silver, Lead, and Chromium can have adverse health and environmental implications for both children and adults. Calcium and Sodium are essential minerals that are required for healthy bone and cardiovascular system function, respectively. However, excessive levels of these minerals in groundwater can cause hypertension and kidney damage in adults, while in children, high calcium levels may lead to developmental delays. Manganese is another essential mineral that is needed for proper brain development, but high levels in groundwater can cause neurological and behavioural problems (Dibal et al., 2019; Rapant et al., 2017). Nickel, Cadmium, Silver, and Chromium are toxic metals that can cause dystrophic changes in the liver, heart, and kidneys, and also carcinogenic effects, even at low exposure levels (Navas-Acien et al., 2007; Obasi & Akudinobi, 2020).

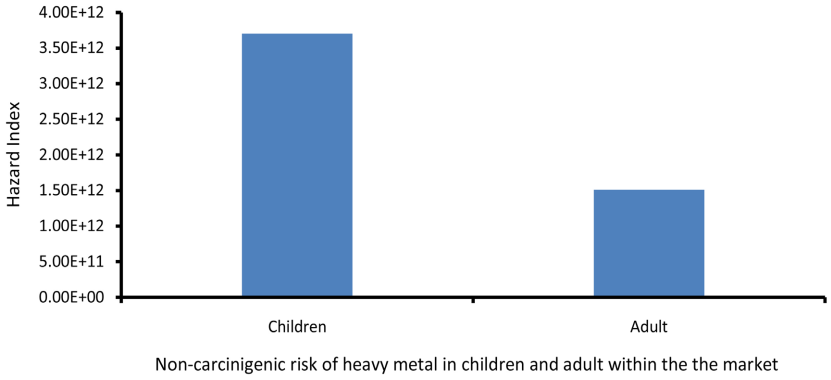


Figure 4. Hazard index for people within the market.

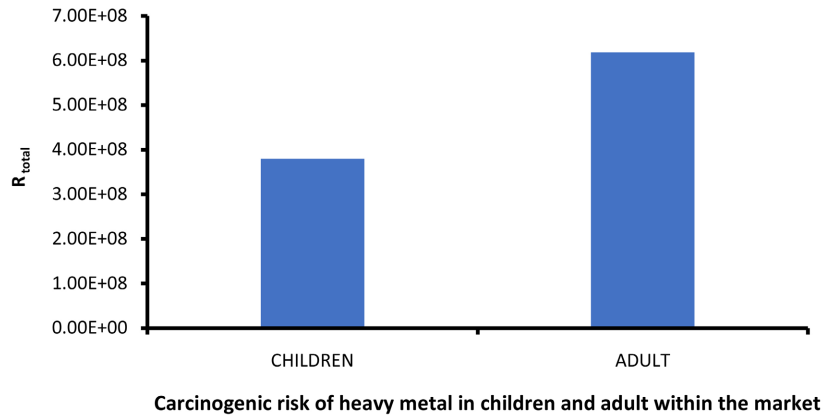


Figure 5. Total carcinogenic risk of heavy metals in children and adults within the market.

Exposure to lead, even at low levels, can lead to developmental delays and neurological problems in children, while in adults, it can cause high blood pressure and kidney damage. Therefore, it is essential to monitor and regulate the levels of these minerals and metals in groundwater to ensure the health and well-being of the population.

4. Conclusion

In this study, we analyzed the physicochemical properties and heavy metal concentrations of groundwater samples collected from hand-dug wells in the Alaba International Market area, Nigeria. The results revealed that the mean pH value of the samples complied with the WHO permissible limit. However, a significant percentage (23%) of the samples exceeded the permissible turbidity limit, indicating potential water quality issues. Moreover, a majority (91%) of the samples exhibited total hardness levels above the acceptable limit, which could pose health risks, including kidney and heart problems. Heavy metal and macronutrient analysis indicated that the concentrations of calcium, sodium, manganese, iron, nickel, and silver ions were within the permissible limits set by WHO. Nevertheless, the concentrations of cadmium and chromium exceeded the limits at certain sampling locations, while lead was detected in some groundwater samples, likely originating from the informal market-based deconstruction of e-waste components. Pearson's correlation analysis demonstrated positive correlations among samples, suggesting common sources of metals, possibly from anthropogenic activities in the market. Principal component analysis and hierarchical cluster analysis identified anthropogenic activities in the market as contributors to the accumulation of heavy metals in groundwater, emphasizing the necessity of effective management strategies to mitigate potential health risks. The spatial distribution analysis showed that certain heavy metals were distributed differently across the study area, with specific metals concentrated in different districts, such as Cd, Mn, Ca, and Ag in the south-eastern district, and Na, Fe, and Ni in the north-west section. The western part of the Alaba market area had higher concentrations of Cr and Pb due to sales of refurbished electronic products. The study further highlighted that informal e-waste dismantling activities could lead to heavy metal contamination in soil, leaching into groundwater and posing health hazards. Thus, continuous monitoring of groundwater quality is crucial to ensure public health and environmental safety. Proper handling and disposal of e-waste are essential to prevent environmental contamination and protect human health. Additionally, implementing measures to reduce the environmental and health risks associated with e-waste dismantling activities is necessary. The study emphasized the importance of effective management strategies, particularly concerning potential health risks to children in the Alaba International Market area, requiring immediate prioritization.

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Environmental Protection Agency (LASEPA) for making available the kits used in conducting the physicochemical parameters of this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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