
Assessment of Soil, Surface Water, and Food Crop Quality around Municipal Waste Dumpsites in Abakaliki, Southeastern Nigeria

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Abstract

Uncontrolled waste dumpsites can contribute to environmental degradation, particularly in rapidly urbanizing areas where waste management practices are inadequate. This study assessed the physicochemical characteristics and elemental concentrations of soil, surface water, and selected food crops around municipal waste dumpsites in Abakaliki, southeastern Nigeria. Soil, surface water, and food crop samples were collected from selected locations around the Umuoghara, Rice Mill, and Mechanic Village dumpsites and analysed using standard laboratory procedures. Physicochemical parameters were determined using standard analytical methods, while elemental concentrations were quantified using Atomic Absorption Spectrophotometry (AAS). Descriptive statistics and Pollution Index (PI) assessment were used to characterize the measured concentrations and compare elements with applicable environmental benchmarks. The soils were slightly acidic (pH 5.98–6.10) and generally non-saline, while surface water pH ranged from 6.47 to 6.67, with relatively low electrical conductivity and total dissolved solids. Several elements, including Fe, Hg, Cd, Ni, Pb, and Cu, exceeded applicable Nigerian surface water criteria at one or more sampling locations, whereas the measured soil elemental concentrations were below the selected Canadian Council of Ministers of the Environment (CCME, 2007) agricultural soil guideline values for elements with applicable benchmarks. Food crop samples contained measurable concentrations of the analysed elements; however, the limited number of composite crop samples and absence of field replication restricted broader interpretation of crop variability and food safety implications. The PI results indicated exceedances for several individual elements in surface water, while soil values were comparatively lower for elements with available benchmark criteria. The findings suggest that the investigated dumpsite environments warrant continued environmental monitoring and improved waste management, including appropriate disposal practices and effective leachate management. Further spatially replicated and seasonal investigations are recommended to better establish contaminant sources, transport pathways, and potential human-health implications.

Keywords: Environmental quality; Elemental concentrations; Municipal solid waste; Physicochemical characteristics; Pollution Index; Soil; Surface water.

Introduction

Waste generation from domestic, commercial, and industrial activities has become a major global environmental challenge due to rapid population growth, urbanization, and changing consumption patterns. Although several waste management strategies have been developed, no existing method of solid waste disposal is entirely free from environmental risks (Okeyode and Rufai, 2011). In many developing countries, particularly Nigeria, open dumping remains the predominant method of municipal solid waste disposal because of inadequate waste management infrastructure, poor enforcement of environmental regulations, and limited financial resources (Afolagboye et al., 2020; Ayobami and Dokumo, 2020). While dumpsites play an important role in urban sanitation, poorly designed and unmanaged sites have been associated with severe environmental consequences, including soil and water contamination, greenhouse gas emissions, offensive odours, and long-term ecosystem degradation (Fatoba et al., 2020). Consequently, municipal solid waste dumpsites have been identified as major sources of environmental pollution in many urban centres worldwide (Bisht et al., 2024; Rouhani & Hejman, 2025).

Unsecured waste dumpsites pose significant threats to environmental quality and agricultural productivity because rainfall infiltration can contribute to leachate generation, which may facilitate the movement of dissolved and particulate contaminants into surrounding soils and water bodies under favourable environmental conditions. These leachates often contain elevated concentrations of heavy metals, organic pollutants, nutrients, and other contaminants that may persist in the environment for extended periods. Nwawuike and Nwawuike (2024), for example, reported elevated concentrations of mercury and arsenic in cassava cultivated near waste dumpsites, attributing the contamination to bioaccumulation from polluted soils. Similarly, Ubanwa et al. (2021), in their characterization of municipal solid waste in Ibadan, reported that organic waste constituted 53.53% of the total waste stream, followed by paper (23.22%), plastics (8.94%), wood (4.35%), rubber (2.22%), polythene (1.66%), and textiles (1.66%), indicating the predominance of biodegradable waste in the municipal solid waste stream. Karkarna and Mujahid (2020) also reported varying concentrations of Zn, Pb, Cd, Cr, and Ni in soils surrounding dumpsites in Kano, although the mean concentrations remained below the permissible limits established by the World Health Organization (2007) and the Department of Petroleum Resources (2002). Most dumpsites in Nigeria are located within or close to residential communities (Abdus-Salam et al., 2011), and many lack engineered liners, leachate collection systems, or suitable geological barriers capable of preventing contaminant migration. Consequently, In general, the absence of engineered containment systems may increase the potential for contaminants associated with waste decomposition and leachate to migrate into adjacent soil and water systems, depending on local geological, hydrological, and geochemical conditions. Where underlying soils are permeable and hydraulically connected to shallow aquifers, contaminants may migrate over considerable distances, thereby increasing environmental and public health risks (Ubechu et al., 2021).

The migration and persistence of contaminants in the subsurface environment are controlled by complex physical, chemical, and hydrological processes. These processes are particularly significant in areas underlain by permeable soils, weathered formations, fractured rocks, or unconsolidated sediments that facilitate contaminant transport (Chinye-Ikejiunor et al., 2021; Chukwura & Igwe, 2021). In addition to contaminating soil and groundwater, heavy metals can be absorbed by agricultural crops cultivated around waste disposal sites, thereby providing a direct pathway for human exposure through the food chain. Adewoyin et al. (2023) investigated heavy metal concentrations in soils and cassava tubers around the limestone mining area in Ewekoro and reported elevated levels of Fe, Mg, Na, Ag, As, Cd,

Co, Cr, Cu, Mn, Ni, Pb, and Zn relative to recommended standards. Their study demonstrated significant bioaccumulation of toxic metals in cassava grown near polluted environments, with children identified as the most vulnerable population group based on calculated health risk indices. Soil-to-plant transfer factors further confirmed the existence of a food-chain exposure pathway. Likewise, Okeke and Ifemeje (2021) reported elevated concentrations of Pb, Cd, Cr, and Ni in cassava, rice, and okra cultivated around mining areas in Ebonyi State, with concentrations exceeding WHO safety limits. These findings underscore the importance of assessing heavy metal contamination in agricultural soils and food crops located near pollution sources.

Although numerous studies have investigated the environmental impacts of waste dumpsites worldwide, the extent of contamination depends largely on local geological, hydrogeological, climatic, and waste management conditions.

In Abakaliki, investigations of waste-disposal impacts have provided important but fragmented evidence. Anikwe and Nwobodo (2002) evaluated the long-term effect of approximately two decades of municipal waste disposal on soil properties and productivity and compared dump and non-dump soils. They reported differences in particle-size distribution, bulk density, porosity, hydraulic conductivity, organic matter, total nitrogen, cation-exchange capacity, and selected heavy metals, including Pb, Cu, Fe, and Zn. Their findings established that prolonged municipal waste disposal can modify soil properties and increase the concentrations of selected metals in dumpsite soils.

Subsequent studies have examined individual environmental compartments and selected contaminant groups. Njoku (2015) investigated the effects of waste dumpsites on water and air quality in Abakaliki and determined Pb, Zn, Cd, Cu, and Cr in water from rivers near selected dumpsites, with rainwater from a non-dumpsite location used as a control. Obasi et al. (2015), meanwhile, assessed the occurrence of Fe, Ni, Cd, Hg, Mn, Pb, and As in water resources around four open dumpsites in Abakaliki, including boreholes, hand-dug wells, ponds, and streams. Their results demonstrated that concentrations of selected metals varied among the dumpsites and water sources, highlighting differences in the vulnerability of local water resources to waste-disposal impacts.

Soil-focused studies have likewise provided evidence of metal enrichment at Abakaliki dumpsites. Aja et al. (2021) investigated three major dumpsites in Abakaliki using soil samples collected from 0–15 and 15–30 cm depths. The study examined Pb, Cu, Cd, Zn, and Fe together with nitrate, phosphate, and sulphate and applied contamination indices and multivariate statistical techniques. The authors reported spatial and depth-related variations in elemental concentrations and identified environmental risks associated particularly with Pb, Cd, and Cu. Similarly, Onwukeme and Eze (2021) included the Rice Mill dumpsite in Abakaliki in a broader southeastern Nigerian investigation aimed at identifying potential sources of heavy metals in active dumpsites using multivariate statistical approaches.

More recent studies have extended investigations to agricultural areas and human-health implications. A study of the central solid-waste dumpsite in Ebonyi State assessed Pb, Fe, Cu, Zn, Co, Ni, Cd, Cr, Hg, and As in dumpsite soils, surrounding farms, and control sites, together with ecological and human-health risk indices. Other studies in Ebonyi State have examined elemental accumulation in food crops around mining environments. For example, Adewoyin et al. (2023) investigated soils and commonly consumed crops around the Enyigba mining area and reported elevated concentrations of some elements relative to recommended food-safety values. These mining-related studies are relevant to understanding soil-to-crop

transfer in Ebonyi State, but their contaminant sources and environmental settings differ from those of municipal waste dumpsites.

Although previous studies have established the occurrence of selected elemental contaminants in soils and water resources around waste-disposal sites in Abakaliki, the available evidence remains fragmented across environmental media, contaminant groups, and sampling designs. Previous investigations have predominantly focused on dumpsite soils and selected heavy metals (Anikwe & Nwobodo, 2002; Aja et al., 2021), groundwater and other water resources (Obasi et al., 2015), or selected surface-water and air-quality parameters (Njoku, 2015). Other studies in Ebonyi State have examined elemental accumulation in agricultural crops, but largely in mining-affected environments rather than municipal waste dumpsites. Consequently, there remains limited site-specific information on the concurrent occurrence of selected elements in soil, surface water, and food crops around municipal waste dumpsites within Abakaliki. The present study therefore provides a descriptive characterization of these three environmental compartments around selected dumpsites and evaluates the measured concentrations against applicable environmental benchmarks. Given the geological setting of Abakaliki and the absence of comprehensive reference soil and surface-water sampling in the present study, the findings are interpreted as site-specific environmental characterization rather than definitive evidence of contaminant source or causation.

The geological and hydrogeological setting of Abakaliki is also relevant to environmental assessment because the area is situated within the Abakaliki Anticlinorium of the Lower Benue Trough. The area is predominantly underlain by the Albian Asu River Group, including the Abakaliki Shale, which comprises predominantly shale with subordinate sandstone, siltstone, and limestone units. The rocks have experienced significant tectonic deformation, including folding and fracturing associated with the Santonian tectonic event. Fractures and weathered zones may influence secondary porosity, groundwater occurrence, and the movement of dissolved substances; however, the actual mobility of contaminants remains dependent on local soil, hydraulic, geochemical, and structural conditions.

The Abakaliki area is also associated with lead–zinc mineralization hosted within the sedimentary rocks of the Abakaliki Anticlinorium. The presence of naturally occurring metal-bearing geological materials is important when interpreting elemental concentrations in environmental samples because some measured elements may have both geogenic and anthropogenic contributions. Consequently, distinguishing between background geological contributions and possible waste-related enrichment is an important consideration in environmental assessments around Abakaliki dumpsites. Previous studies have similarly recognized the occurrence of metal-bearing formations within the Abakaliki Anticlinorium.

Therefore, the present study assessed the physicochemical characteristics and elemental concentrations of soil, surface water, and selected food crops around major municipal waste dumpsites in Abakaliki, southeastern Nigeria. The study was designed to provide an integrated, site-specific characterization of these environmental compartments and to compare the measured elemental concentrations with applicable environmental guideline values. Specifically, the study aimed to:

- (i) determine the physicochemical characteristics of soil and surface water around the selected municipal waste dumpsites;
- (ii) determine the concentrations of selected elements in soil, surface water, and selected food crops;

- (iii) compare the measured elemental concentrations with applicable national and international guideline values, where available; and
- (iv) assess the environmental implications of the observed physicochemical characteristics and elemental concentrations in relation to the geological and environmental setting of the study area.

Research Questions

The study was guided by the following research questions:

- (i) What are the physicochemical characteristics of soil and surface water around the selected municipal waste dumpsites?
- (ii) What are the concentrations of selected elements in the sampled soil, surface water, and food crops?
- (iii) How do the measured elemental concentrations compare with applicable national and international guideline values?
- (iv) What environmental implications can be inferred from the observed physicochemical characteristics and elemental concentrations considering the geological and environmental setting of the study area?

Geology of the Study Area

The study area is located within the Abakaliki Anticlinorium of the Lower Benue Trough, southeastern Nigeria, and is underlain predominantly by the Abakaliki Shale of the Asu River Group, which was deposited during the Albian Stage of the Lower Cretaceous. The Asu River Group represents the oldest sedimentary succession in the Lower Benue Trough and was deposited unconformably on the Precambrian Basement Complex during the initial marine transgression into the Benue Basin (Burke, 1972). The formation consists predominantly of dark grey to black calcareous shale and mudstone with subordinate siltstone, sandstone, and localized limestone intercalations. The sedimentary sequence has an estimated maximum thickness of approximately 1,500 m (Farrington, 1952; Agumanu, 1989). Kogbe (1989) further described the formation as comprising poorly bedded sandy limestone interbedded with shale and mudstone, reflecting variations in depositional environments during basin evolution.

The Abakaliki Shale has undergone extensive weathering, oxidation, and ferruginization, resulting in the alteration of the original dark shales to pale grey, reddish-brown, yellow, pink, and bluish colours (Orajaka, 1965; Ukpong and Olade, 1979). Structurally, the study area is characterized by intense folding, faulting, and fracturing associated with the Santonian tectonic event that deformed the Lower Benue Trough and produced the Abakaliki Anticlinorium. These structural discontinuities may enhance secondary porosity and permeability and consequently influence groundwater occurrence and the potential movement of dissolved substances in the subsurface. Their presence is therefore relevant when considering the possible mobility of contaminants from waste disposal sites, although actual contaminant transport depends on the local hydraulic gradient, soil properties, degree of weathering, fracture connectivity and geochemical conditions.

The area is also well known for its economically significant lead–zinc mineralization, which is hosted mainly within the dark carbonaceous shales of the Asu River Group. The mineralized veins commonly occur along fracture systems and are closely associated with ironstone bands, silicified zones, and thermally altered (baked) shales, indicating

hydrothermal mineralization processes (Nnabo, 2011). The presence of these naturally occurring metal-bearing formations is particularly relevant to environmental studies because they may contribute to background concentrations of certain heavy metals. Consequently, distinguishing between geogenic and anthropogenic sources of heavy metals is essential when evaluating contamination around waste dumpsites in the study area.

Materials and Methods

Materials

The materials and equipment used for sample collection, preparation, and laboratory analysis are summarized below.

Sampling Equipment

A stainless-steel hand auger was used to collect soil samples at two depth intervals (0–15 cm and 15–30 cm) around the selected waste dumpsites. Surface water samples were collected using pre-cleaned glass bottles fitted with screw caps and Teflon-lined lids to minimize sample contamination. Crop samples (cassava tubers and rice grains) were collected in clean paper bags and heavy-duty Kraft envelopes to prevent contamination during handling and transportation. Surface water samples were transported to the laboratory in insulated coolers containing ice packs to preserve their physicochemical characteristics prior to analysis.

Laboratory Equipment and Consumables

Laboratory analyses were carried out using standard analytical equipment and consumables. Soil samples were dried in a laboratory oven, while plant samples were dried and homogenized using a stainless-steel grinding mill. A 2-mm stainless-steel sieve was used to prepare soil samples for physicochemical and heavy metal analyses. Additional laboratory equipment included filtration apparatus, hot plates, beakers, conical flasks, funnels, volumetric flasks, pipettes, and an analytical balance for sample preparation and reagent measurement.

Elemental concentrations in soil, surface water, cassava, and rice samples were determined using an Atomic Absorption Spectrophotometer (AAS) following standard analytical procedures. All reagents used were of analytical grade, and deionized water was used throughout the laboratory analyses to minimize contamination and ensure analytical accuracy.

The equipment and laboratory facilities employed ensured the proper collection, preparation, preservation, and analysis of samples for the determination of physicochemical characteristics and heavy metal concentrations in the different environmental media.

Sampling Design

A purposive sampling approach was adopted to evaluate the influence of waste dumpsites on the surrounding environment. Three major waste dumpsites within Abakaliki Metropolis were selected based on their size, duration of operation, waste disposal intensity, and proximity to residential areas and agricultural lands. The selected dumpsites comprised the Umuoghara, Rice Mill, and Mechanic Village dumpsites.

Independent samples were collected from each dumpsite to represent the different environmental media. Soil samples were collected at two depth intervals (0–15 cm and 15–30 cm) to assess both surface and subsurface contamination. At each sampling location, several subsamples collected within a radius of approximately 5–10 m were thoroughly homogenized

to form one composite sample representative of that location and depth. Composite sampling was adopted to minimize the effects of small-scale spatial variability and to provide a representative estimate of contaminant concentrations.

Surface water samples were collected as independent grab samples from ponds or drainage channels receiving runoff from each dumpsite using pre-cleaned glass bottles. Food crop samples comprising cassava tubers and rice grains cultivated in the vicinity of the dumpsites were also collected. Cassava tubers were collected from farmland adjacent to the Umuoghara dumpsite, while rice grains were collected from farmland near the Rice Mill dumpsite. In addition, a cassava sample was collected from Mgbabor, a relatively uncontaminated area located away from major waste disposal activities, to serve as the control sample.

In total, six independent composite soil samples (three dumpsites $\times$ two depth intervals), three independent surface water samples, and three independent food crop samples (rice, cassava, and control cassava) were analysed. This sampling design provided representative coverage of the major waste disposal environments and adjacent agricultural areas within the study area and formed the basis for evaluating the physicochemical characteristics and elemental concentrations of soil, surface water, and food crops.

Methods

Study Area Description

The study was conducted within Abakaliki Metropolis, Ebonyi State, southeastern Nigeria, located approximately between latitudes 6°17'00"N and 6°22'00"N and longitudes 8°02'00"E and 8°10'00"E (Figure 1). Abakaliki is the administrative capital of Ebonyi State and has experienced rapid urbanization and population growth over the past few decades, resulting in increased municipal solid waste generation. The metropolis is characterized by a tropical climate with distinct wet and dry seasons, is underlain predominantly by the Abakaliki Shale of the Asu River Group, and is drained by the Ebonyi River and its tributaries. Agriculture, trading, automobile repair, and small-scale industries constitute the major economic activities within the area.

Three major waste dumpsites; Umuoghara, Rice Mill, and Mechanic Village were selected for this study because they represent the principal municipal solid waste disposal sites within the metropolis and have been in continuous operation for more than two decades. The dumpsites were selected based on their operational history, waste disposal intensity, accessibility, and proximity to residential communities, agricultural lands, and surface water bodies, making them suitable for evaluating the environmental impacts of waste disposal activities.

The Umuoghara Dumpsite is located along the Enugu–Abakaliki Expressway and is accessed through the Umuoghara Road. The site has been used for municipal solid waste disposal for over 20 years and receives mixed domestic, commercial, and institutional wastes.

The Rice Mill Dumpsite is situated within the Abakaliki Rice Mill Complex along Old Ogoja Road. The site receives large quantities of rice husk generated from rice processing in addition to municipal solid waste originating from nearby markets, commercial establishments, and residential areas. It has been in operation for more than 30 years.

The Mechanic Village Dumpsite is located along the Enugu–Abakaliki Expressway near the Central Police Station (CPS), Abakaliki. The site has been used for the disposal of municipal and automobile-related wastes for over 20 years. Owing to the presence of vehicle repair workshops, wastes generated at this location are likely to contain petroleum products, spent

lubricants, batteries, scrap metals, and other metal-rich materials that may contribute to elevated heavy metal concentrations in the surrounding environment.

The three dumpsites are well connected by the Enugu–Abakaliki Expressway and collectively represent the major waste disposal environments within Abakaliki Metropolis. Their long operational history and contrasting waste characteristics provide an appropriate basis for assessing the physicochemical characteristics and heavy metal contamination of soil, surface water, and crops in the study area.

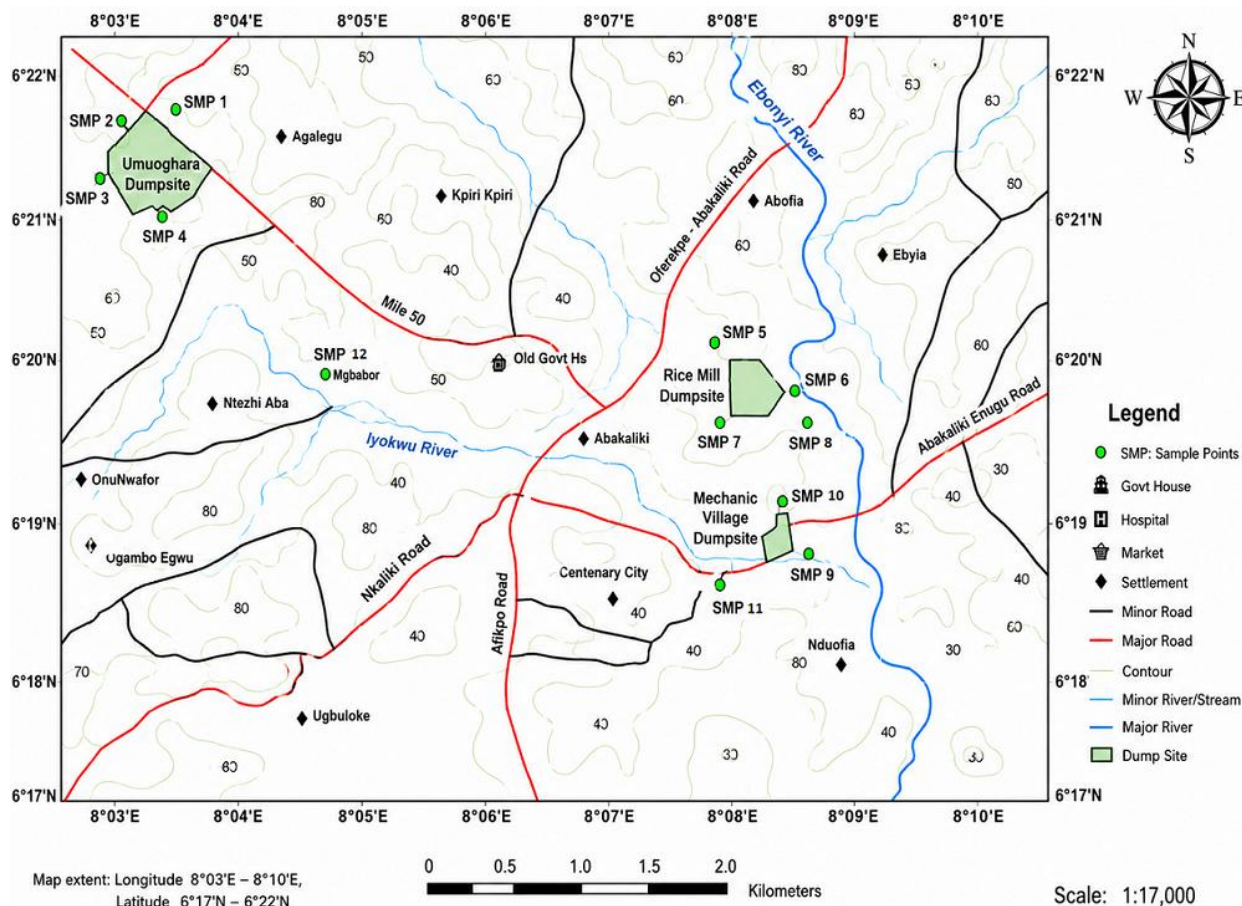


Figure 1. Location map of the study area showing the dumpsites and sample points within the study area

Soil Sampling

Soil samples were collected from the Umuoghara (SSL1), Rice Mill (SSL2), and Mechanic Village (SSL3) waste dumpsites within Abakaliki Metropolis. At each dumpsite, soil was initially collected from two depth intervals, 0–15 cm and 15–30 cm, using a stainless-steel hand auger after removing surface litter and other foreign materials. At each depth, five subsamples were collected within an approximately 5–10 m radius following a zigzag sampling pattern.

The five subsamples collected at each depth were thoroughly homogenized to obtain a depth-specific composite material. The resulting materials from the 0–15 cm and 15–30 cm intervals were subsequently combined and thoroughly homogenized at each dumpsite to produce one final composite soil sample representing the combined 0–30 cm sampled soil layer. Thus, the two depth intervals were not retained as separate samples for elemental analysis. The final elemental dataset therefore comprised three composite soil samples: SSL1

(Umuoghara), SSL2 (Rice Mill), and SSL3 (Mechanic Village), with each representing the combined 0–30 cm soil layer at the respective dumpsite.

This composite approach was adopted to obtain an integrated representation of the near-surface soil within the sampled 0–30 cm profile and to minimize small-scale spatial variability. Because the two depth intervals were combined before elemental analysis, the resulting dataset does not permit separate assessment of elemental concentrations or vertical distribution between the 0–15 cm and 15–30 cm soil layers.

Approximately 1 kg of each final composite soil sample was placed in a labelled polyethylene bag and transported to the laboratory. The samples were air-dried at room temperature, gently disaggregated using a porcelain mortar and pestle, and passed through a 2-mm stainless-steel sieve for physicochemical analysis. A representative portion was subsequently pulverized and passed through a 0.5-mm sieve prior to elemental analysis using Atomic Absorption Spectrophotometry (AAS). Sampling equipment was thoroughly cleaned with distilled water and dried between successive sampling locations to minimize cross-contamination.

Surface Water Sampling

Surface water samples were collected as independent grab samples from ponds and drainage channels located in the vicinity of the Umuoghara (WSL1), Rice Mill (WSL2), and Mechanic Village (WSL3) waste dumpsites. One surface water sample was collected from each sampling location, resulting in a total of three independent water samples for laboratory analysis. The samples therefore represent site-specific observations rather than replicated measurements within each dumpsite.

Approximately 1 L of water was collected at a depth of 5–10 cm below the water surface using pre-cleaned glass bottles fitted with Teflon-lined screw caps. Prior to sample collection, each bottle was rinsed three times with the sample water to minimize contamination. The collected samples were immediately labelled, placed in insulated coolers containing ice packs, transported to the laboratory, and stored at 4 °C until analysis.

Samples intended for elemental analysis were preserved by acidifying them with concentrated nitric acid (HNO₃) to pH < 2, in accordance with American Public Health Association (APHA, 2017) standard procedures. This preservation step minimized adsorption of dissolved elements onto container walls and inhibited microbial activity prior to laboratory analysis.

One grab sample was collected from each sampling location; therefore, no within-site field replication was undertaken. The sampling design provided one observation for each of the three surface-water locations and was used for site-specific assessment of the measured physicochemical and elemental parameters.

Cassava Tuber Sampling

Cassava tubers were collected from cultivated farmland located adjacent to the Umuoghara waste dumpsite (CS1). In addition, a control cassava sample (CS2) was collected from cultivated farmland at Mgbabor, a location situated away from the major waste disposal activities considered in this study. Thus, two composite cassava samples were obtained for laboratory analysis.

At each sampling location, several mature and apparently healthy cassava tubers were randomly harvested and combined to obtain one representative composite sample. The tubers

were placed in clean polyethylene bags, appropriately labelled, and transported to the laboratory. The samples were thoroughly washed with tap water followed by deionized water to remove adhering soil particles and other surface impurities. The tubers were then peeled, sliced into small chips, and oven-dried at 60 °C to constant weight. The dried samples were ground into a fine powder using a stainless-steel grinder, thoroughly homogenized, and stored in labelled airtight glass containers until elemental analysis.

Rice Grain Sampling

Rice grains were collected from cultivated farmland located adjacent to the Rice Mill waste dumpsite (RS1). One composite rice grain sample was obtained for laboratory analysis.

At the sampling location, mature rice panicles were randomly harvested from several plants within the cultivated field and combined to obtain one representative composite sample. The harvested grains were placed in clean polyethylene bags, appropriately labelled, and transported to the laboratory. The samples were air-dried at room temperature, manually dehulled to obtain the rice grains, and further dried to constant weight. The dried grains were ground into a fine powder using a stainless-steel grinder, thoroughly homogenized, and stored in labelled airtight glass containers until elemental analysis.

Elemental Analysis of Soil, Surface Water, and Crop Samples

Elemental concentrations in soil, surface water, cassava tubers, and rice grains were determined using an Agilent FS240AA Atomic Absorption Spectrophotometer (AAS). The laboratory reported the analysis elements as being conducted according to the procedures of the American Public Health Association (APHA, 1995). The analysed elements included Pb, Cd, Cr, Zn, Cu, Ni, Fe, Ba, V, Hg, and As.

The analytical principle of AAS is based on the aspiration and atomization of the sample in a flame, followed by measurement of the absorption of element-specific radiation by the atomized element. Element-specific wavelengths were used for the determination of the respective analytes.

Analysis of Soil Samples

Approximately 2 g of each dried and prepared composite soil sample was weighed into a digestion flask, and 20 mL of the acid mixture was added. The acid mixture comprised concentrated nitric acid (HNO₃), perchloric acid (HClO₄), and concentrated sulphuric acid (H₂SO₄), prepared in the proportions specified in the laboratory procedure (650 mL HNO₃, 80 mL HClO₄, and 20 mL H₂SO₄). The samples were heated until a clear digest was obtained. The resulting digest was subsequently diluted with distilled water to a final volume of 100 mL.

The prepared soil digests were analysed using an Agilent FS240AA Atomic Absorption Spectrophotometer. The concentrations of Pb, Cd, Cr, Zn, Cu, Ni, Fe, Ba, V, Hg, and As were determined using the analytical procedures adopted by the laboratory. Reference metal solutions were prepared daily from single-element stock solutions, and calibration curves were established for the individual elements using the corresponding reference solutions. The laboratory identified the solid-sample digestion procedure as being based on Adrian (1993).

Analysis of Surface-Water Samples

Surface-water samples were thoroughly mixed by shaking, after which 100 mL of each sample was transferred into a 250-mL glass beaker. Five millilitres of concentrated nitric acid (HNO₃) was added, and the mixture was heated to boiling until the volume was reduced to

approximately 15–20 mL. Concentrated HNO_3 was subsequently added in 5-mL increments as required until the residue was completely dissolved. The mixture was allowed to cool, transferred to an appropriate volumetric container, and made up to 100 mL with metal-free distilled water.

The prepared solutions were analysed using an Agilent FS240AA Atomic Absorption Spectrophotometer. The concentrations of Pb, Cd, Cr, Zn, Cu, Ni, Fe, Ba, V, Hg, and As were determined using the analytical procedures adopted by the laboratory. Reference metal solutions were prepared daily from single-element stock solutions by dilution with water containing 1.5 mL of concentrated nitric acid per litre. A calibration blank was prepared using the same reagents without the metal stock solutions, and calibration curves were established by plotting the absorbance of the standards against their corresponding concentrations.

Analysis of Food Crop Samples

Approximately 2 g of the dried and powdered cassava tuber and rice grain composite samples was weighed into a digestion flask and 20 mL of the acid mixture was added. The acid mixture consisted of concentrated nitric acid (HNO_3), perchloric acid (HClO_4), and concentrated sulphuric acid (H_2SO_4), prepared in the proportions specified by the laboratory procedure (650 mL HNO_3 , 80 mL HClO_4 , and 20 mL H_2SO_4). The samples were heated until clear digests were obtained. Following digestion, the digests were cooled and diluted with distilled water to a final volume of 100 mL.

The prepared solutions were subsequently analysed using the Agilent FS240AA Atomic Absorption Spectrophotometer. The elemental concentrations of Pb, Cd, Cr, Zn, Cu, Ni, Fe, Ba, V, Hg, and As were determined according to the analytical procedures adopted by the laboratory. Reference metal solutions were prepared daily, and calibration curves were established for the individual elements using the corresponding reference solutions.

Preparation of Reference Solutions and Calibration

Reference metal solutions were prepared daily from single-element stock solutions by dilution with water containing 1.5 mL of concentrated nitric acid per litre. A calibration blank was prepared using the same reagents but without the metal stock solutions. Calibration curves for the individual elements were prepared by plotting the absorbance of the reference solutions against their corresponding concentrations.

Instrumental Analysis

Following digestion or sample preparation, the solutions were introduced into the Agilent FS240AA Atomic Absorption Spectrophotometer for elemental determination. The samples were aspirated into an oxidizing air–acetylene flame for atomic absorption measurement. Instrumental operating conditions were selected according to the requirements of the individual analytes and the manufacturer's operating recommendations.

Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control procedures were applied during sample preparation and instrumental analysis to minimize contamination and maintain consistency of the analytical measurements. Laboratory glassware and sample-contact materials were thoroughly cleaned before use, and distilled or deionized water was used for sample preparation and dilution.

Reference metal solutions were prepared daily from single-element stock solutions by appropriate dilution with water containing concentrated nitric acid. A calibration blank

containing the reagents used for standard preparation but excluding the metal stock solutions was prepared for instrumental calibration. Calibration curves for the individual elements were established by plotting absorbance against the corresponding concentrations of the reference solutions.

Instrument calibration and operating conditions were checked before sample analysis, and the Agilent FS240AA Atomic Absorption Spectrophotometer was operated according to the analytical requirements of the respective elements and the manufacturer's recommendations.

The available laboratory documentation did not provide sufficient information to independently verify analyte-specific limits of detection and quantification, certified reference material identity and recovery data, numbers of procedural blanks and duplicate samples, or detailed digestion-batch information. These parameters were therefore not reported as quantitative QA/QC results in this study. Similarly, recovery and precision values were not independently reported where supporting laboratory records were unavailable.

Statistical Analysis

The analytical dataset was organized according to sample matrix and sampling location. Descriptive statistics were used to summarize the measured physicochemical parameters and elemental concentrations for the individual soil and surface water samples. Because only one final composite soil sample was available from each dumpsite, one grab water sample was collected from each water-sampling location, and food-crop sampling was limited to individual composite samples, the dataset did not provide sufficient independent replication for robust inferential statistical testing within or among sampling locations.

Accordingly, elemental concentrations were primarily presented as individual site-specific values and, where appropriate, as ranges to describe the observed variation among the sampled locations. Soil, surface-water, and food-crop datasets were analysed separately because the matrices differ in their physical and chemical characteristics and their elemental concentrations were expressed on different bases (mg/kg for soil and crop samples and mg/L for surface-water samples).

Comparisons of measured elemental concentrations with applicable guideline or benchmark values were performed descriptively to identify concentrations exceeding the selected reference values. The results were interpreted in relation to the sampling design and the limitations associated with the absence of field replication and local reference samples.

Data organization and graphical presentation were performed using Microsoft Excel 2020, while IBM SPSS Statistics version 25 was used where required for descriptive statistical calculations.

Results

Physicochemical Characteristics of Soil Samples

The physicochemical characteristics of soil samples collected from the Umuoghara (SSL1), Rice Mill (SSL2), and Mechanic Village (SSL3) dumpsites are presented in Table 1 and Figure 2. Soil pH ranged from 5.98 to 6.10, indicating slightly acidic conditions across the study area. Electrical conductivity varied between 190 and 197 $\mu\text{S}/\text{cm}$, while salinity ranged from 0.023 to 0.123 psu. Total dissolved solids (TDS) ranged from 195 to 243 mg/L, with the highest value recorded at the Rice Mill dumpsite (SSL2). Exchangeable sodium concentrations ranged from 0.1298 to 0.1462 mEq/kg, whereas calcium and magnesium

concentrations varied from 0.0832–0.0978 mEq/kg and 0.1054–0.1267 mEq/kg, respectively. Cation exchange capacity (CEC) ranged from 0.3319 to 0.3707 cmol(+)/kg, while sodium adsorption ratio (SAR) values ranged from 0.113 to 0.120. Collectively, only minor variations in the measured physicochemical parameters were observed among the three sampling locations. The graphical comparison presented in Figure 2(a–i) further illustrates the spatial variation of the individual physicochemical parameters across the investigated dumpsites.

Table 1. Physicochemical Characteristics of Soil Samples around the Selected Dumpsites

Parameter	SSL1	SSL2	SSL3	Unit
Electrical Conductivity	197	190	196	µS/cm
Temperature	37	36	36	°C
Salinity	0.104	0.023	0.123	Psu
PH	6.04	5.98	6.10	–
Total Dissolved Solids (TDS)	195	243	221	mg/L
Sodium (Na ⁺)	0.1298	0.1462	0.1367	mEq/kg
Calcium (Ca ²⁺)	0.0967	0.0978	0.0832	mEq/kg
Magnesium (Mg ²⁺)	0.1054	0.1267	0.1167	mEq/kg
Cation Exchange Capacity (CEC)	0.3319	0.3707	0.3366	cmol/kg
Sodium Adsorption Ratio (SAR)	0.112653	0.120062	0.11781	–

Note: SSL1 = Umuoghara Dumpsite; SSL2 = Rice Mill Dumpsite; SSL3 = Mechanic Village Dumpsite. EC = Electrical Conductivity; TDS = Total Dissolved Solids; CEC = Cation Exchange Capacity; SAR = Sodium Adsorption Ratio.

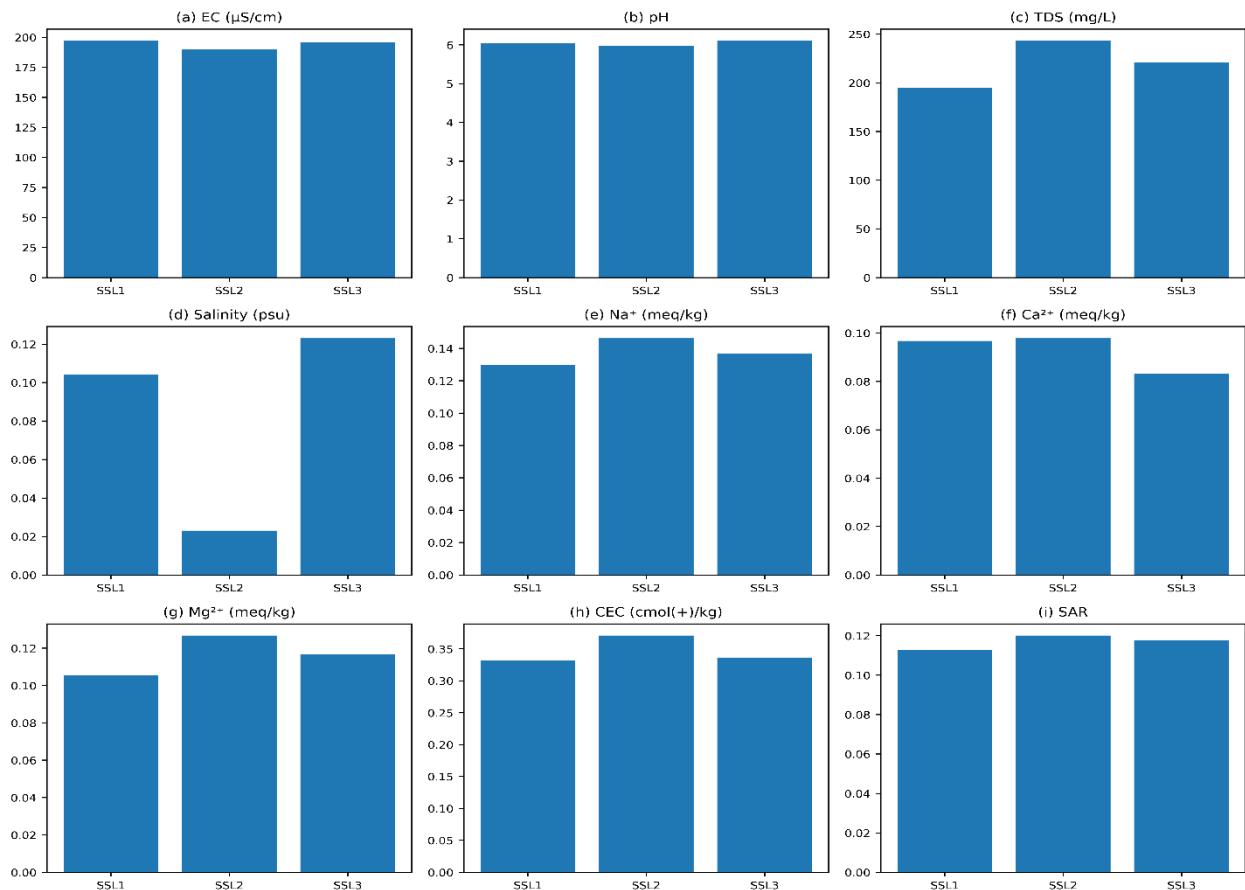


Figure 2 (a-i). Physicochemical characteristics of soil samples collected from the Umuoghara (SSL1), Rice Mill (SSL2), and Mechanic Village (SSL3) dumpsites.

Physicochemical Characteristics of Surface Water Samples

The physicochemical characteristics of surface water samples collected from the Umuoghara (WSL1), Rice Mill (WSL2), and Mechanic Village (WSL3) dumpsites are presented in Table 2 and Figure 3. Electrical conductivity ranged from 43.20 to 65.10 $\mu\text{S}/\text{cm}$, with the highest value recorded at the Mechanic Village dumpsite (WSL3). Water temperature remained constant at 28°C across all sampling locations. Salinity was 0.01 psu at all sites, indicating freshwater conditions. The pH values ranged from 6.47 to 6.67, with only the Rice Mill sample (WSL2) recording a value slightly below the lower World Health Organization (WHO) (2022) guideline limit of 6.5. Total dissolved solids (TDS) ranged from 14.20 to 27.20 mg/L, which were substantially below the WHO permissible limit of 500 mg/L. The graphical comparison presented in Figure 3(a-e) illustrates the variation in physicochemical parameters among the three sampling locations.

Table 2. Physicochemical Characteristics of Surface Water Samples around the Selected Dumpsites Compared with Nigerian Environmental Surface-Water Criteria

Parameter	WSL1	WSL2	WSL3	Nigerian Surface-Water Criterion (2011)	Unit
Electrical Conductivity	49.20	43.20	65.10	Not specified	μS/cm
Temperature	28	28	28	≤0.3°C increase above natural background*	°C
Salinity	0.01	0.01	0.01	Not specified	psu
pH	6.61	6.47	6.67	6.5–8.5	—
Total Dissolved Solids (TDS)	27.20	14.20	22.18	Not specified	mg/L

Note: WSL1 = Umuoghara dumpsite; WSL2 = Rice Mill dumpsite; WSL3 = Mechanic Village dumpsite.

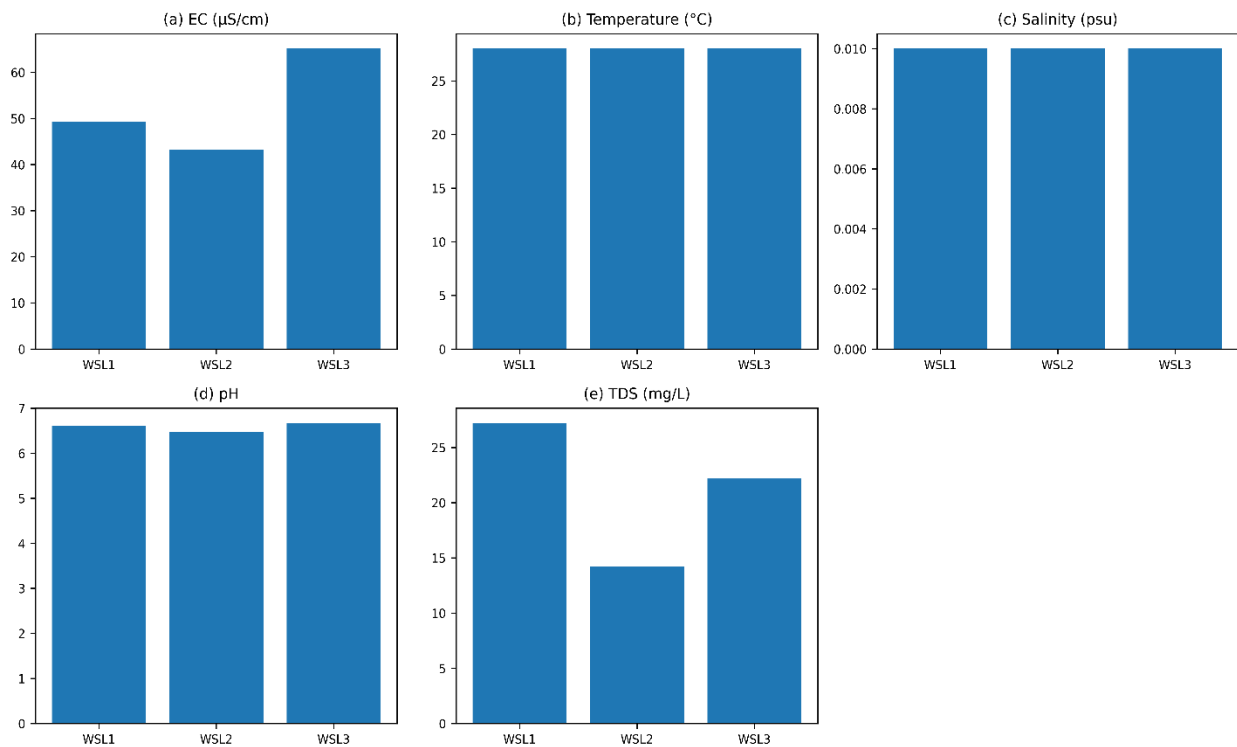


Figure 3 (a-e). Physicochemical characteristics of surface water samples collected from the Umuoghara (WSL1), Rice Mill (WSL2), and Mechanic Village (WSL3) dumpsites.

Distribution of Major and Trace Elements in Soil Samples

The concentrations of the analysed elements in soil samples collected from the Umuoghara (SSL1), Rice Mill (SSL2), and Mechanic Village (SSL3) dumpsites are presented in Table 3 and Figure 4. Among the analysed elements, iron (Fe) and nickel (Ni) exhibited the highest concentrations across the three sampling locations, whereas sodium (Na), arsenic (As), chromium (Cr), mercury (Hg), lead (Pb), cadmium (Cd), copper (Cu), barium (Ba), and

vanadium (V) occurred at comparatively lower concentrations. Zinc (Zn) concentrations ranged from 1.6933 to 3.6232 mg/kg, with the highest concentration recorded at the Mechanic Village dumpsite (SSL3). Iron concentrations varied from 5.0776 to 6.0602 mg/kg, while nickel concentrations ranged from 3.873 to 6.927 mg/kg. The concentrations of zinc (Zn), mercury (Hg), chromium (Cr), arsenic (As), lead (Pb), cadmium (Cd), copper (Cu), and nickel (Ni) were all below the corresponding Canadian Council of Ministers of the Environment (CCME, 2007) agricultural soil quality guideline values. No CCME (2007) agricultural soil quality guideline values are available for iron (Fe), sodium (Na), barium (Ba), or vanadium (V). The graphical comparison presented in Figure 4 illustrates the distribution of major and trace elements across the investigated dumpsites.

Table 3. Concentrations of Major and Trace Elements in Soil Samples around the Selected Dumpsites

Metal (mg/kg)	SSL1 (Umuoghara dumpsite)	SSL2 (Rice Mill dumpsite)	SSL3 (Mechanic Village dumpsite)	CCME (2007) Agricultural Soil Guideline (mg/kg)
Iron (Fe)	5.0776	6.0602	5.1030	–
Sodium (Na)	0.0064	0.1243	0.1477	–
Zinc (Zn)	1.6933	3.1806	3.6232	200
Mercury (Hg)	0.020	0.010	0.034	6.6
Chromium (Cr)	0.011	0.008	0.012	64
Arsenic (As)	0.003	0.010	0.007	12
Lead (Pb)	0.018	0.035	0.035	70
Cadmium (Cd)	0.040	0.032	0.034	1.4
Copper (Cu)	0.037	0.011	0.089	63
Nickel (Ni)	6.927	3.873	4.465	45
Barium (Ba)	0.055	0.086	0.048	–
Vanadium (V)	0.013	0.006	0.009	–

Note: – = No guideline value is provided by the Canadian Council of Ministers of the Environment (CCME, 2007) for this parameter/element.

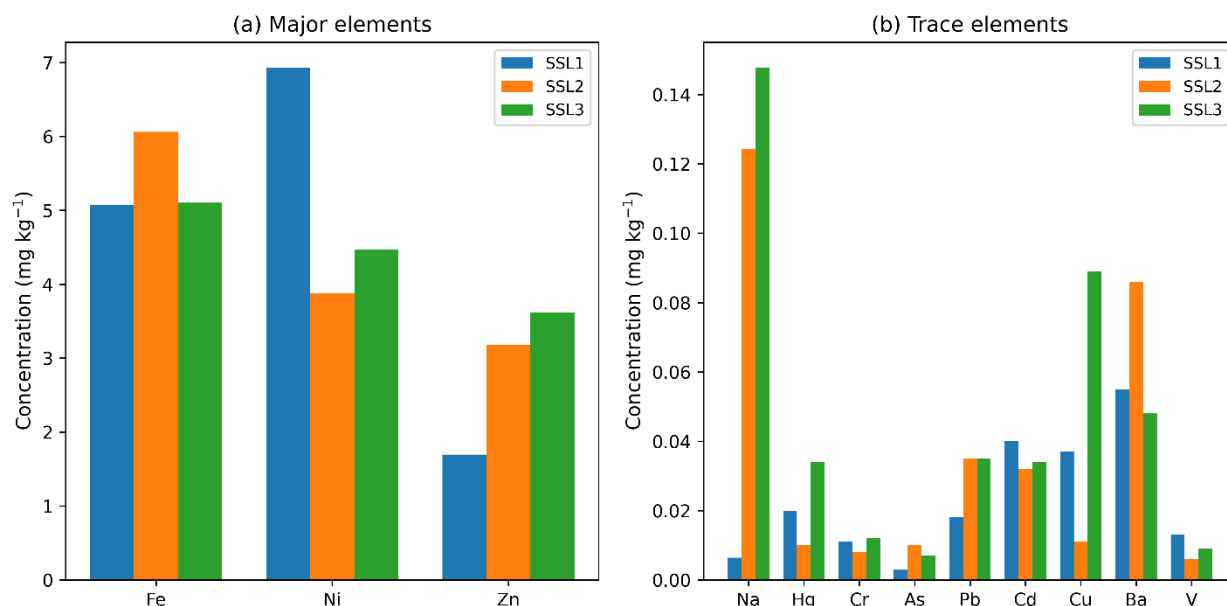


Figure 4. Distribution of major (a) and trace (b) elements in soil samples collected from the Umuoghara (SSL1), Rice Mill (SSL2), and Mechanic Village (SSL3) dumpsites. The classification is based on the measured concentrations of the analysed elements; sodium (Na) is included among the trace elements because of its comparatively low concentrations.

Elemental Concentrations in Surface Water Samples

The concentrations of the analysed elements in surface water samples collected from the Umuoghara (WSL1), Rice Mill (WSL2), and Mechanic Village (WSL3) dumpsites are presented in Table 4 and Figure 5. Among the analysed elements, nickel (Ni) and iron (Fe) recorded the highest concentrations across the three sampling locations. Nickel concentrations ranged from 4.154 to 4.455 mg/L across WSL3 and WSL1, respectively, and exceeded the applicable Nigerian surface water criterion of 0.01 mg/L at all three sampling locations. Iron concentrations ranged from 0.2282 to 2.9374 mg/L, with the highest concentration recorded at the Rice Mill dumpsite (WSL2), exceeding the Nigerian surface water criterion of 0.05 mg/L.

Zinc (Zn) concentrations ranged from 0.3114 to 1.1161 mg/L and exceeded the Nigerian surface water criterion of 0.01 mg/L at all three sampling locations. Similarly, mercury (Hg), lead (Pb), cadmium (Cd), and copper (Cu) exceeded their respective Nigerian surface water criteria in all three sampling locations. Arsenic (As), with concentrations ranging from 0.000 to 0.004 mg/L, remained below the applicable criterion of 0.05 mg/L.

Chromium (Cr) concentrations ranged from 0.012 to 0.058 mg/L across the three surface water sampling locations. The highest concentration was recorded at the Mechanic Village dumpsite (WSL3), while the lowest occurred at the Umuoghara dumpsite (WSL1). No applicable criterion was identified in the cited Nigerian regulation for sodium (Na), barium (Ba), and vanadium (V); therefore, these elements were not assessed against a Nigerian surface water criterion.

The graphical comparison in Figure 5 illustrates the spatial distribution and concentration patterns of the analysed elements across the three investigated surface water samples.

Table 4. Comparison of Element Concentrations in Surface Water with Nigerian Environmental Surface-Water Criteria

Metal (mg/L)	WSL1 Umuoghara	WSL2 Rice Mill	WSL3 Mechanic Village	Nigerian Fisheries/Recreation Criterion (mg/L)	Exceedance
Iron (Fe)	0.2282	2.9374	0.3346	0.05	Yes
Sodium (Na)	0.0148	0.0006	0.0031	—	—
Zinc (Zn)	0.3114	1.1161	0.3456	0.01	Yes
Mercury (Hg)	0.015	0.012	0.022	0.001	Yes
Chromium (Cr)	0.012	0.027	0.058	0.001	Yes
Arsenic (As)	0.001	0.000	0.004	0.05	No
Lead (Pb)	0.016	0.022	0.019	0.01	Yes
Cadmium (Cd)	0.022	0.086	0.033	0.005	Yes
Copper (Cu)	0.016	0.022	0.034	0.001	Yes
Nickel (Ni)	4.455	4.382	4.154	0.01	Yes
Barium (Ba)	0.034	0.027	0.056	—	—
Vanadium (V)	0.007	0.017	0.014	—	—

Note: “—” indicates that no applicable criterion was identified in the cited Nigerian surface-water regulation.

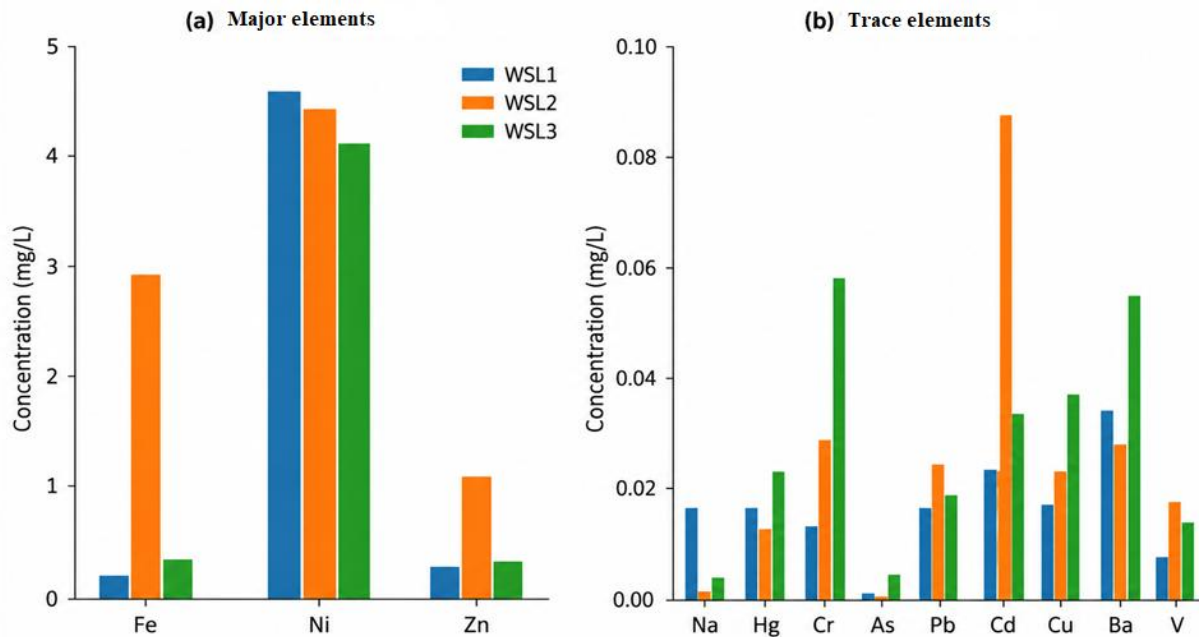


Figure 5. Distribution of major (a) and trace (b) elements in surface water samples collected from the Umuoghara (WSL1), Rice Mill (WSL2), and Mechanic Village (WSL3) dumpsites. The classification is based on the measured concentrations of the analysed elements.

Elemental Concentrations in Food Crop Samples

The concentrations of the analysed elements in food crop samples collected from the Rice Mill dumpsite (RS1), Umuoghara dumpsite (CS1), and the control location at Mgbabor (CS2) are presented in Table 5 and Figure 6. Among the analysed elements, iron (Fe), nickel (Ni), and zinc (Zn) exhibited the highest concentrations across the food crop samples. Iron concentrations ranged from 1.6550 to 3.4341 mg/kg, with the highest concentration recorded in cassava collected from the Umuoghara dumpsite (CS1). Nickel concentrations varied between 3.378 and 5.482 mg/kg, with the highest concentration observed in the control cassava sample (CS2). Zinc concentrations ranged from 0.7187 to 1.9960 mg/kg, with the highest concentration recorded in rice collected from the Rice Mill dumpsite (RS1). Among

the trace elements, copper (Cu) exhibited the highest concentration (0.067 mg/kg) in the rice sample, whereas arsenic (As) showed the lowest concentrations (0.001–0.002 mg/kg) across all food crop samples. The graphical comparison presented in Figure 6 illustrates the distribution of major and trace elements among the analysed food crop samples.

Table 5. Elemental Concentrations in Food Crop Samples around the Selected Dumpsites

Metal (mg/kg)	RS1 (Rice – Rice Mill dumpsite)	CS1 (Cassava – Umuoghara dumpsite)	CS2 (Cassava – Control, Mgbabor)
Iron (Fe)	2.9283	3.4341	1.6550
Sodium (Na)	0.0976	0.0154	0.0113
Zinc (Zn)	1.9960	1.5463	0.7187
Mercury (Hg)	0.013	0.014	0.010
Chromium (Cr)	0.027	0.035	0.022
Arsenic (As)	0.001	0.002	0.001
Lead (Pb)	0.016	0.034	0.026
Cadmium (Cd)	0.040	0.022	0.023
Copper (Cu)	0.067	0.038	0.019
Nickel (Ni)	3.467	3.378	5.482
Barium (Ba)	0.076	0.027	0.025
Vanadium (V)	0.010	0.020	0.024

Note: NL = No guideline limit specified.

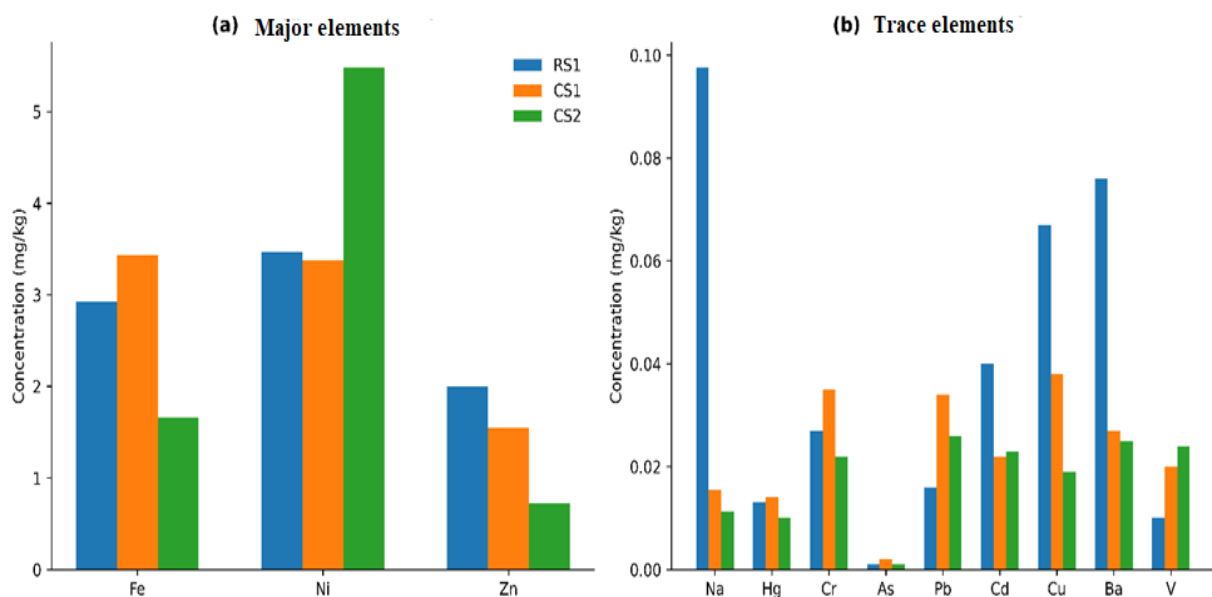


Figure 6. Distribution of major (a) and trace (b) elements in food crop samples collected from the Rice Mill dumpsite (RS1), Umuoghara dumpsite (CS1), and the control location at Mgbabor (CS2). The classification is based on the measured concentrations of the analysed elements.

Descriptive Statistics of Physicochemical Parameters and Elemental Concentrations

Descriptive statistics for the physicochemical parameters and elemental concentrations determined in the soil and surface-water samples are presented in Supplementary Table S1. For soil and surface water, mean $\pm$ standard deviation (SD) values were calculated from the three sampling locations to summarize the measured values across the investigated sites. For food crops, the results are presented as individual measured concentrations rather than pooled mean $\pm$ SD because the crop dataset comprised three composite samples representing different crop types and sampling locations (RS1, CS1, and CS2), with no field replication. Accordingly, the crop results are interpreted descriptively and should not be considered estimates of within population variability.

Pollution Index Assessment

The Single-Factor Pollution Index (PI) was used to provide a parameter-specific comparison between the measured concentrations of individual elements and their corresponding environmental benchmark values. The index was calculated as:

$$PI_i = \frac{C_i}{S_i}$$

Where (PI_i) is the single-factor pollution index for element (i), (C_i) is the measured concentration of the element, and (S_i) is the corresponding reference or guideline concentration. The single-factor approach evaluates each pollutant independently rather than providing a composite pollution index for the entire environmental medium. The relationship ($PI_i = \frac{C_i}{S_i}$) is used in established single-factor pollution-index applications. The selected soil, and surface water guideline values were used as the reference concentrations.

Accordingly, the surface-water PI calculations were restricted to elements for which an applicable criterion was available in the selected Nigerian regulatory framework. Sodium (Na), barium (Ba), and vanadium (V) were therefore not assigned PI values where no applicable criterion was identified. For the elements with applicable criteria, PI values were interpreted as a measure of exceedance relative to the selected benchmark. A PI value below 1 indicates that the measured concentration is below the selected benchmark, whereas a value greater than 1 indicates exceedance. Where the descriptive low, moderate, and high categories were applied, $PI < 1$, $1 \leq PI < 3$, and $PI \geq 3$ were used, respectively, as an index-classification scheme rather than as regulatory classifications of surface-water quality. The category thresholds were therefore interpreted separately from the Nigerian environmental standards.

Pollution Index assessment was not performed for the food-crop samples because comprehensive, element-specific food-safety limits were not available for all of the analysed elements and crop types. Food-crop elemental concentrations were therefore evaluated separately by comparing individual measured concentrations with applicable food-safety or health-based standards where such standards were available.

The calculated PI values are presented in Supplementary Tables S2 (a–b). Because the soil, surface-water, and food-crop matrices have different physical and chemical characteristics, units, benchmark values, and exposure pathways, PI values were interpreted within each environmental medium and were not used to rank the media according to an overall level of contamination.

Discussion

Physicochemical Characteristics of Soil

The physicochemical characteristics of soils samples around the investigated dumpsites indicate that the soils were slightly acidic, with pH values ranging from 5.98 to 6.10. These values are below the commonly cited optimum range for many agricultural soils but are within the range that can occur naturally in weathered tropical soils. The slightly acidic conditions may also be influenced by the decomposition of organic waste and associated biochemical processes. Soil pH is one the important factors that controls the mobility and availability of several metallic elements because changes in acidity can affect their solubility, adsorption, and retention in soil. However, the present measurements represent the sampled conditions and do not by themselves establish that waste decomposition was the specific cause of the observed pH values.

Electrical conductivity (EC) ranged from 190 to 197 $\mu\text{S}/\text{cm}$, while salinity ranged from 0.023 to 0.123 psu and total dissolved solids (TDS) from 195 to 243 mg/L. These values indicate relatively low soluble-salt concentrations and no pronounced salinity under the conditions sampled. The highest TDS value was recorded at the Rice Mill dumpsite (SSL2), which may possibly reflect differences in the composition and degree of decomposition of materials deposited at the site. Conversely, the relatively narrow range of EC among the three locations suggests that substantial differences in the concentration of soluble ions were not evident from the measurements obtained.

The measured exchangeable sodium, calcium, and magnesium concentrations, together with the CEC and SAR values, indicate low sodium-related soil degradation potential under the sampled conditions. The relatively low CEC may indicate a limited capacity for retaining exchangeable cations, however, CEC is influenced by soil mineralogy, organic matter, clay content, and pH. Therefore, the observed CEC values may be described as characteristics of the sampled soils rather than as direct evidence of enhanced contaminant migration. Similarly, although soil pH can influence metal mobility, the present physicochemical measurements alone cannot establish the extent to which metals were transported through the soil profile.

Although the investigated soils did not show pronounced salinity or sodicity based on the measured parameters, nevertheless, the slightly acidic conditions are environmentally relevant because soil acidity can influence the behaviour and availability of some metallic contaminants. The findings are broadly consistent with previous studies in Nigeria. Anikwe and Nwobodo (2002), for example, reported changes in soil properties associated with long-term municipal waste disposal in Abakaliki. Other studies have similarly documented variations in physicochemical properties and metal distributions around waste-disposal areas. These comparisons provide regional context for the present findings, although differences in soil type, waste composition, sampling design, and duration of waste deposition should be considered when comparing results among sites.

Physicochemical Characteristics of Surface Water

The measured physicochemical characteristics of the surface water samples are presented in Table 2. The pH values ranged from 6.47 to 6.67, while electrical conductivity ranged from 43.2 to 65.1 $\mu\text{S}/\text{cm}$. Total dissolved solids ranged from 14.20 to 27.20 mg/L, and salinity was 0.01 psu at the three sampling locations. Temperature was 28°C at all locations.

The measured pH values indicate that the sampled waters were slightly acidic to near neutral. The lowest pH was recorded at the Rice Mill dumpsite (WSL2), whereas the highest occurred at the Mechanic Village dumpsite (WSL3). The observed pH conditions may influence the chemical behaviour and mobility of some metallic elements; however, the available measurements cannot establish the specific processes responsible for the differences among locations.

The EC, TDS, and salinity values indicate low concentrations of dissolved salts in the sampled waters. Conductivity was highest at the Mechanic Village dumpsite (65.1 $\mu\text{S}/\text{cm}$), while the highest TDS was recorded at the Umuoghara dumpsite (27.20 mg/L). These differences indicate some spatial variation in dissolved ionic constituents among the sampling locations. However, because only one surface-water sample was collected from each location, the observed differences should be regarded as site-specific measurements rather than evidence of persistent spatial or temporal trends.

The measured physicochemical parameters were generally within the cited benchmark values used for comparison in this study. Due to the limited sample size, the physicochemical results provide a snapshot of the measured conditions at the time of sampling rather than a comprehensive assessment of water quality over time.

The relatively favourable physicochemical measurements also do not preclude the presence of individual chemical contaminants. In the present study, several elemental concentrations exceeded the applicable Nigerian environmental surface-water criteria despite the relatively low EC, TDS, and salinity values. This demonstrates the importance of assessing physicochemical characteristics alongside elemental concentrations rather than using general physicochemical parameters alone to characterize the environmental quality of surface waters around dumpsites.

Previous studies have reported that waste disposal areas can influence surrounding surface water chemistry and contribute contaminants to receiving waters. Such studies provide useful contextual support for interpreting the present findings, however, the current study did not directly measure leachate flow, contaminant flux, or hydrological connectivity between the dumpsites and the sampled surface waters. Therefore, the observed elemental concentrations were discussed as measured environmental conditions associated spatially with the investigated dumpsite areas, rather than being attributed exclusively to dumpsite-derived leachate.

Distribution of Major and Trace Elements in Soil Samples

The distribution of major and trace elements in soils around the investigated dumpsites showed spatial variation among the three sampling locations. The measured concentrations of the analysed elements were below the corresponding Canadian Council of Ministers of the Environment (CCME, 2007) agricultural soil quality guideline values, where applicable. This comparison indicates that the measured concentrations did not exceed the selected regulatory benchmarks at the time of sampling; however, it does not by itself establish the absence of contamination, enrichment, or influence from waste-disposal activities.

Among the analysed elements, iron (Fe) and nickel (Ni) exhibited relatively higher concentrations, whereas arsenic (As), chromium (Cr), mercury (Hg), lead (Pb), cadmium (Cd), copper (Cu), barium (Ba), and vanadium (V) occurred at comparatively lower concentrations. The relatively higher Fe concentrations may partly reflect the natural geochemical characteristics of the study area, including the ferruginous nature of the weathered materials associated with the shale-derived terrain. Contributions from discarded

metallic materials, construction debris, and other waste materials may also be possible; however, the present dataset does not permit the relative contribution of natural and anthropogenic sources to be established.

The relatively higher concentrations of Ni and Zn at some of the investigated locations may be associated with differences in waste composition and site-specific environmental conditions. Potential sources of these elements in municipal waste include metal-containing materials, batteries, vehicle components, and other discarded materials. Nevertheless, source attribution cannot be confirmed from concentration data alone, particularly in the absence of local background concentrations and source-specific measurements.

The observed spatial variation in elemental concentrations among the investigated dumpsites may reflect differences in waste composition, disposal practices, soil properties, and local geochemical conditions. Anikwe and Nwobodo (2002) reported changes in soil properties and elemental composition associated with long-term municipal waste disposal in Abakaliki, while Alloway (2013) noted that the distribution and mobility of trace elements in soils are influenced by factors including parent material, soil pH, organic matter, and other soil properties.

Collectively, the measured soil elemental concentrations were below the selected CCME (2007) agricultural soil guideline values for the elements with applicable standards. This finding were interpreted as a benchmark exceedance assessment rather than direct evidence that the soils are unaffected by dumpsite activities. Because local background concentrations were not determined, the extent of natural versus anthropogenic enrichment could not be established. Future investigations incorporating uncontaminated reference soils and a larger number of spatially replicated samples would provide a stronger basis for evaluating elemental enrichment and distinguishing natural geochemical contributions from potential waste-related inputs.

Elemental Concentrations in Surface Water

The elemental concentrations measured in the surface water samples showed substantial variation among the three investigated dumpsites. Several elements exceeded the applicable Nigerian environmental surface water criteria, while others remained below the available reference values. Among the analysed elements, nickel (Ni) recorded the highest concentrations, ranging from 4.154 to 4.455 mg/L, with the highest value occurring at Umuoghara (WSL1) and the lowest at Mechanic Village (WSL3). These concentrations were substantially higher than the applicable Nigerian surface water criterion of 0.01 mg/L. Cadmium (Cd), mercury (Hg), lead (Pb), copper (Cu), zinc (Zn), and iron (Fe) also exceeded their respective applicable criteria at one or more sampling locations.

The relatively high Ni concentrations require particular consideration because the available laboratory results indicate substantially elevated concentrations relative to the selected environmental criterion. Potential sources of Ni in waste-disposal environments include metallic materials, batteries, electronic waste, automobile components, and other Ni-containing discarded materials. However, the present study did not include source-specific measurements or background surface water samples; consequently, the observed Ni concentrations may not be attributed exclusively to municipal waste disposal on the basis of the concentration data alone.

Cadmium, mercury, and lead also exceeded their respective applicable environmental criteria at the investigated locations. These elements can occur in batteries, electronic materials, pigments, metal-containing products, and other components of municipal solid waste. The

spatial differences among WSL1, WSL2, and WSL3 may reflect differences in waste composition, site characteristics, and other local environmental conditions, although the available dataset does not permit definitive source apportionment.

Iron exceeded its applicable criterion at the Rice Mill dumpsite (WSL2), whereas the highest measured chromium concentration occurred at the Mechanic Village dumpsite (WSL3). The relatively high concentrations of several elements demonstrate that measured elemental concentrations in the sampled surface waters warrant environmental attention, even though several of the physicochemical parameters were relatively low. However, the present study does not provide direct evidence of leachate transport into the sampled waters because leachate composition, contaminant flux, groundwater connectivity, and hydrological transport pathways were not directly measured. The results were therefore interpreted as a characterization of elemental concentrations in surface waters associated spatially with the investigated dumpsite areas rather than as definitive evidence of a dumpsite-to-water contaminant transport pathway.

The findings emphasize the importance of integrating physicochemical and elemental analyses when characterizing surface waters around unsecured waste-disposal sites. Further investigations incorporating field duplicates, certified reference materials, procedural blanks, documented dilution factors, expanded temporal sampling, and independent confirmation of unusually high Ni concentrations would strengthen confidence in the reported elemental concentrations and help distinguish natural background contributions from potential anthropogenic inputs.

Elemental Concentrations in Food Crops

The elemental concentrations measured in the rice and cassava samples are presented as site-specific observations of elemental occurrence in the sampled edible crop tissues. The measured concentrations varied among the crop samples and elements. Among the analysed elements, iron (Fe) generally occurred at relatively higher concentrations, with the highest value recorded in cassava collected near the Umuoghara dumpsite (CS1). The relatively high Fe concentration may reflect contributions from the natural geochemical characteristics of the study area, including the ferruginous nature of the underlying soils, as well as soil-to-plant transfer. However, the present data do not permit the relative contributions of geogenic and anthropogenic sources to be distinguished.

Zinc (Zn) was highest in rice collected near the Rice Mill dumpsite (RS1). As an essential micronutrient, Zn can be taken up by plants from soil, and its concentration in edible tissues may be influenced by soil properties, elemental availability, plant species, and other environmental factors. Similarly, Pb, Cd, Hg, Cr, and As were detected at varying concentrations in the analysed crop samples. The occurrence of these elements demonstrates their presence in the sampled plant tissues, but the limited number of samples does not allow the extent or consistency of their transfer from soil to crops to be established.

Notably, Ni recorded its highest concentration in the comparative/control cassava sample (CS2) rather than in the cassava collected near the Umuoghara dumpsite (CS1). This observation is important because it indicates that proximity to a dumpsite alone does not adequately explain the spatial variation in elemental concentrations in the sampled crops. The result may reflect differences in natural soil geochemistry, background elemental concentrations, soil properties, plant uptake characteristics, or other site-specific factors. Because a corresponding background soil sample was not collected at the CS2 location,

however, the present data cannot establish a specific geogenic source for the Ni concentration.

Collectively, the food crop results provide evidence of the occurrence and spatial variation of the analysed elements in the sampled rice and cassava tissues, but they do not provide sufficient evidence to conclude on the health conditions of the crops for human consumption at the population level. The absence of field replication, the small number of crop samples, the lack of comprehensive commodity-specific permissible limits for all analysed elements, and the absence of a dietary exposure assessment limit the extent to which health implications can be inferred. Further studies involving replicated crop sampling, corresponding background soils, crop-specific food-safety benchmarks, and quantitative dietary exposure assessment would provide a stronger basis for evaluating potential human-health implications.

Environmental Implications

The findings provide evidence of measurable variation in the physicochemical and elemental characteristics of soil, surface water, and sampled agricultural crops around the investigated dumpsites. Several elemental concentrations in the surface-water samples exceeded the applicable Nigerian environmental surface-water criteria, whereas the measured soil concentrations remained below the selected soil guideline values for elements with applicable standards. These findings demonstrate the occurrence of elevated elemental concentrations in some sampled environmental media; however, the results were interpreted as exploratory rather than as a definitive evidence that the observed concentrations were caused exclusively by the dumpsites.

The relatively elevated concentrations of Fe, Hg, Pb, Cd, Ni, and other elements in some surface water samples may be associated with differences in local waste composition, soil and water chemistry, background geochemical conditions, or other site-specific environmental processes. Waste materials such as batteries, electronic components, metal-containing materials, and automobile-related wastes represent plausible sources of some of these elements in municipal waste environments. However, because waste composition was not analytically characterized and leachate was not directly sampled, these potential sources remain hypotheses rather than confirmed sources. Similarly, the study did not establish upstream/downstream concentration gradients or quantify contaminant fluxes and therefore cannot directly demonstrate transport of contaminants from the dumpsites into the sampled surface waters.

The Single-Factor Pollution Index indicated that several surface-water elemental concentrations exceeded their selected environmental reference values, while the soil PI values were below 1 for the elements with applicable reference values. These indices provide parameter-specific comparisons with selected benchmarks and were interpreted separately for each environmental medium. They were not used to establish an overall ranking of soil and surface water because the media differ in their characteristics, units, reference values, and exposure pathways.

The slightly acidic soil conditions may influence the mobility and availability of some elements. Similarly, rainfall and surface runoff may potentially influence contaminant movement in the study environment. However, because contaminant transport, leachate composition, groundwater connectivity, and temporal variations were not directly investigated, these processes were regarded as potential mechanisms rather than demonstrated transport pathways.

The analysed food crops contained measurable concentrations of several elements. The relatively high Ni concentration observed in the comparative cassava sample, rather than the cassava collected near the Umuogbara dumpsite, further demonstrates that proximity to a dumpsite alone does not explain all observed elemental variation. Background geochemistry, soil properties, plant-specific uptake mechanisms, and other environmental factors may contribute to the observed concentrations.

The findings therefore highlight the value of integrated monitoring of soil, surface water, and agricultural crops around unsecured waste-disposal areas. Improved waste management, including waste segregation, controlled disposal, appropriate landfill engineering, and leachate management, may help reduce potential environmental exposure pathways. However, further site-specific monitoring and source-oriented investigations are required to determine the relative contribution of dumpsite activities and natural background processes to the observed elemental concentrations.

Limitations of the study

This study has several limitations that were considered when interpreting the findings.

First, the study employed a purposive sampling design with a relatively small number of environmental samples and no environmental reference sites for soil and surface water. The findings therefore provide site-specific information for the investigated dumpsites rather than been generalized to other dumpsites or agricultural areas in Abakaliki. The cassava sample from Mgbabor (CS2) served only as a comparative crop sample and was not accompanied by corresponding reference soil and surface water samples.

Secondly, the study was limited by the temporal and spatial coverage of water and crop sampling. Surface water samples were collected at a single sampling time, with one sample per location, while the crop dataset comprised only three composite samples, with no crop sample available from the Mechanic Village dumpsite. Consequently, seasonal variation, temporal changes, and field-scale variability in water and crop elemental concentrations were not be assessed.

Third, direct contaminant sources and transport pathways were not investigated. The study did not directly measure leachate composition, contaminant flux, groundwater connectivity, upstream/downstream gradients, or hydrological transport pathways. Therefore, the observed elemental concentrations cannot establish a direct causal relationship between dumpsite activities and the sampled environmental media. Potential sources and transport mechanisms discussed in the study are regarded as plausible interpretations rather than demonstrated pathways.

Finally, the soil and statistical datasets imposed analytical limitations. Although soil materials were initially collected from 0–15 and 15–30 cm intervals, the two depths were combined at each dumpsite before elemental analysis; consequently, vertical elemental distribution could not be evaluated. In addition, the pooled correlation analysis cannot be established because of the small sample size and heterogeneity of soil, water, and crop matrices. The study therefore emphasizes descriptive results and benchmark comparisons rather than statistical source attribution.

Collectively, the findings are regarded as a site-specific environmental characterization and screening assessment. More extensive spatially replicated, seasonal, background-controlled, and source-oriented investigations would be required to establish contaminant sources, transport pathways, temporal trends, and potential human-health risks.

Conclusions

This study assessed the physicochemical characteristics and elemental concentrations of soil, surface water, and selected food crops around municipal waste dumpsites in Abakaliki, southeastern Nigeria. The investigated soils were generally slightly acidic and non-saline, while the measured physicochemical characteristics of the surface water were generally within the applicable Nigerian surface-water criteria, except for a marginally lower pH at WSL2. The elemental results showed that several elements in the surface-water samples exceeded applicable Nigerian surface-water criteria, particularly Fe, Hg, Cd, Ni, Pb, and Cu at one or more sampling locations. In contrast, the measured soil elemental concentrations were below the selected CCME (2007) agricultural soil guideline values for elements with applicable benchmarks.

The food crop results showed the occurrence of the analysed elements in the sampled rice and cassava tissues. However, the crop dataset consisted of only three composite samples, with no crop sample from the Mechanic Village dumpsite and no field replication. Therefore, the findings provide descriptive evidence of elemental occurrence but do not support definitive conclusions regarding food safety or human health risk.

The Pollution Index assessment provided parameter-specific comparisons with selected environmental benchmarks for elements with applicable criteria. The results indicated benchmark exceedances for several elements in surface water, whereas the soil samples showed comparatively lower index values for the elements with available guideline values. These results were also interpreted as evidence of individual parameter exceedance rather than as a basis for ranking the overall contamination status of soil, water, and crops.

Collectively, the findings indicate that the investigated dumpsites are environmentally relevant sources of potential concern, particularly in relation to the measured elemental concentrations in nearby surface water. However, the study did not directly measure leachate composition, contaminant flux, groundwater connectivity, upstream/downstream gradients, or other source-apportionment variables. Therefore, the observed elemental concentrations cannot be conclusively attributed to dumpsite-derived leachate or used to establish specific contaminant transport pathways.

The findings highlight the need for improved municipal solid-waste management in Abakaliki, including waste segregation, controlled disposal, appropriate landfill design, leachate management, and routine monitoring of soil, surface water, and agricultural areas. Further studies incorporating larger spatially replicated and seasonal datasets, environmental reference sites, direct leachate and groundwater investigations, and source-oriented analyses are recommended to better establish contaminant sources, transport pathways, temporal trends, and potential human-health implications.

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Acknowledgements

The authors would like to thank all individuals and institutions that supported the fieldwork and laboratory analyses carried out during this study.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sector.

Author's Contributions

Conceptualization: J.C.E.; J.I.N.; J.N.O. and I.E.M. **methodology:** J.C.E.; software, J.C.E.; **validation:** J.C.E.; J.I.N. and I.E.M., **formal analysis,** J.C.E.; **investigation,** J.C.E.; **resources,** J.C.E; **data curation,** J.C.E.; **writing—original draft preparation:** J.C.E.; **writing—review and editing:** J.I.N.; J.N.O. and I.E.M., **visualization:** J.C.E.; **supervision:** J.I.N.; J.N.O. and I.E.M., **project administration:** J.I.N.; J.N.O. and I.E.M. All authors have read and agreed to the published version of the manuscript.

Ethical Approval

This study did not involve human participants or animals. Therefore, ethical approval was not required.

Competing Interests

The author declares no competing interests.

Data Availability Statement

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

Supplementary Material

Table S1. Descriptive statistics of soil and surface water physicochemical properties and elemental concentrations

Soil Physicochemical		Surface Water Physicochemical		Soil Heavy Metals		Surface Water Heavy Metals	
Parameter	Mean $\pm$ SD	Parameter	Mean $\pm$ SD	Metal	Mean $\pm$ SD (mg/kg)	Metal	Mean $\pm$ SD (mg/L)
Electrical Conductivity (μ S/cm)	194.33 $\pm$ 3.79	Conductivity (μ S/cm)	52.50 $\pm$ 11.32	Fe	5.4136 $\pm$ 0.5601	Fe	1.1667 $\pm$ 1.5344
Temperature ($^{\circ}$ C)	36.33 $\pm$ 0.58	Temperature ($^{\circ}$ C)	28.00 $\pm$ 0.00	Na	0.0928 $\pm$ 0.0758	Na	0.0062 $\pm$ 0.0076
Salinity (psu)	0.083 $\pm$ 0.053	Salinity (psu)	0.01 $\pm$ 0.00	Zn	2.8324 $\pm$ 1.0110	Zn	0.5910 $\pm$ 0.4550
Ph	6.04 $\pm$ 0.06	Ph	6.58 $\pm$ 0.10	Hg	0.021 $\pm$ 0.012	Hg	0.016 $\pm$ 0.005
TDS (mg/L)	219.67 $\pm$ 24.03	TDS (mg/L)	21.19 $\pm$ 6.56	Cr	0.010 $\pm$ 0.002	Cr	0.032 $\pm$ 0.023
Sodium (mEq/kg)	0.1376 $\pm$ 0.0082	Parameter	Mean $\pm$ SD	As	0.007 $\pm$ 0.004	As	0.002 $\pm$ 0.002
Calcium (mEq/kg)	0.0926 $\pm$ 0.0081	Conductivity (μ S/cm)	52.50 $\pm$ 11.32	Pb	0.029 $\pm$ 0.010	Pb	0.019 $\pm$ 0.003
Magnesium (mEq/kg)	0.1163 $\pm$ 0.0107			Cd	0.035 $\pm$ 0.004	Cd	0.047 $\pm$ 0.034
CEC (cmol(+)/kg)	0.3464 $\pm$ 0.0212			Cu	0.046 $\pm$ 0.040	Cu	0.024 $\pm$ 0.009
SAR	0.1168 $\pm$ 0.0038			Ni	5.088 $\pm$ 1.620	Ni	4.330 $\pm$ 0.157
				Ba	0.063 $\pm$ 0.020	Ba	0.039 $\pm$ 0.015
				V	0.009 $\pm$ 0.004	V	0.013 $\pm$ 0.005

Table S2 (a). Single-Factor Pollution Index of Selected Elements in Soil Samples

Element	Mean (mg/kg)	CCME (2007) Guideline (mg/kg)	PI
Fe	5.4136	–	–
Zn	2.8324	200	0.014
Hg	0.0213	6.6	0.003
Cr	0.0103	64	0.0002
As	0.0067	12	0.0006
Pb	0.0293	70	0.0004
Cd	0.0353	1.4	0.025
Cu	0.0457	63	0.0007
Ni	5.0883	45	0.113
Ba	0.0630	–	–
V	0.0093	–	–

Note: PI = Pollution Index $PI_i = \frac{C_i}{S_i}$; – = Not calculated because no corresponding CCME (2007) agricultural soil quality guideline value is available.

Table S2 (b). Single-Factor Pollution Index of Selected Elements in Surface Water based on Nigerian Environmental Surface Water Criteria

Element	Mean (mg/L)	Nigerian criterion (mg/L)	PI
Fe	1.1667	0.05	23.334
Zn	0.5910	0.01	59.100
Hg	0.0163	0.001	16.333
Cr	0.032	0.001	32.00
As	0.0017	0.05	0.034
Pb	0.0190	0.01	1.900
Cd	0.0470	0.005	9.400
Cu	0.0240	0.001	24.000
Ni	4.3303	0.01	433.030

Note: $PI_i = \frac{C_i}{S_i}$, where C_i is the mean measured concentration and S_i is the selected Nigerian environmental surface-water criterion.