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Assessment of Heavy Metal Pollution in Groundwater Sources in Onitsha Area, Southeastern Nigeria.

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ABSTRACT
The study assesses the extent and implications of heavy metal pollution in groundwater sources in Onitsha, Southeastern Nigeria, highlighting the environmental and public health risks posed by industrial activities, improper waste disposal, and urban runoff. Lead (Pb), cadmium (Cd), and nickel (Ni) were identified as the most prevalent contaminants, with concentrations exceeding the World Health Organization (WHO) permissible limits in 91.67% of groundwater samples for lead, posing significant risks, especially to vulnerable populations like children and pregnant women. Industrial effluents, e-waste dumping, and leachate from poorly managed waste disposal sites are major contributors to the contamination. The research emphasizes the bioaccumulative nature of these heavy metals, which contaminate the food chain through agricultural crops irrigated with polluted water and livestock exposed to contaminated sources, amplifying health risks. Long-term exposure to these contaminants has been linked to cognitive impairments, kidney damage, cancer, and other chronic conditions. The study calls for urgent intervention, including enhanced waste management practices, cost-effective remediation techniques, and public health initiatives to minimize the detrimental consequences of groundwater contamination locally.
Keywords: Heavy metals, groundwater, Onitsha, bioaccumulation, lead, cadmium, remediation

I. INTRODUCTION

1.1. Background

Water is a vital resource that sustains human life and is essential for socio-economic development. Groundwater, in particular, plays a significant role in meeting domestic, agricultural, and industrial water needs globally, especially in areas where surface water is scarce or contaminated [1,2]. In urban areas like Onitsha, Southeastern Nigeria, groundwater serves as a crucial source of potable water for millions of residents [3]. However, the rapid pace of industrialization and urbanization in Onitsha has significantly degraded the quality of groundwater, making heavy metal contamination a pressing environmental and public health concern [3,4].

Heavy metals, including lead (Pb), cadmium (Cd), nickel (Ni), chromium (Cr), and mercury (Hg), are of particular concern because of their toxic nature even at low concentrations [5]. These metals do not degrade easily in the environment and can bioaccumulate in living organisms, causing severe health effects such as cancer, organ damage, and neurological disorders [5,6]. In areas like Onitsha, where groundwater is the primary source of drinking water, the presence of heavy metals poses a significant threat to the health and well-being of the population. The situation is exacerbated by extensive industrial activities, including the manufacturing sector, automobile repairs, and the disposal of electronic waste (e-waste), which all contribute to the heavy metal burden in groundwater sources [3,7].

Recently, increasing attention has been drawn to the rising heavy metal levels in Onitsha's groundwater, attributed to improper waste management, unregulated discharges from industries, and the use of crude methods to handle e-waste. These activities lead to the release of heavy metals into the soil, which subsequently leaches into the groundwater, contaminating the water supply and posing a risk to public health [8-10]. Investigating the sources, trends, and effects of heavy metal pollution in the groundwater within Onitsha is crucial for developing solutions that protect both public health and the environment.

1.2. Study Area: Onitsha

Onitsha is a densely populated urban center and a major commercial hub located along the eastern bank of the Niger River in Anambra State, Southeastern Nigeria (Figure 1). It ranks among the biggest cities in Nigeria and is renowned for its extensive trade, industrial activities, and vibrant commercial markets. The city's industrial landscape includes a range of activities such as automobile repair workshops, chemical processing, textile manufacturing, and various small-scale industries [11]. These industries are significant contributors to environmental pollution, particularly in terms of waste generation and improper disposal [12].

Geologically, Onitsha sits on the Eocene Nanka Formation, characterized by sandy soils and alluvial deposits. The porous and permeable nature of this formation makes the local groundwater aquifers highly vulnerable to contamination from surface pollutants [13,14]. The city's rapid urban expansion, combined with the lack of proper waste management systems, has exacerbated the contamination of both surface water and groundwater sources. The shallow aquifer system in Onitsha allows pollutants from industrial waste, e-waste, and municipal refuse to easily infiltrate the groundwater, making water quality a major concern for the city's residents [15].

One of the major environmental challenges facing Onitsha is the indiscriminate dumping of waste, particularly e-waste, which includes old electronics and appliances [8]. E-waste contains harmful heavy metals such as lead, cadmium, and copper, which leach into the soil and groundwater, contaminating water sources. Studies have shown that the levels of these heavy metals in groundwater in Onitsha often exceed permissible limits, leading to significant health risks for the population [16]. The city's dependence on groundwater for drinking and daily activities, coupled with the high levels of industrial pollution, underscores the importance of addressing groundwater contamination in Onitsha.

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Figure 1: Densely populated Onitsha Metropolis, Anambra State, Nigeria.

1.3. Objective of the Review

The primary objective of this review is to assess the extent, sources, and impacts of heavy metal pollution in Onitsha's groundwater. Specifically, the review seeks to Identify the common heavy metals found in groundwater in Onitsha and their concentrations relative to safe limits; Examine the sources of heavy metal contamination in the area, including industrial activities, waste disposal practices, and other anthropogenic factors; Evaluate the spatial distribution of contamination, identifying areas most affected by heavy metal pollution; Analyze the ecological and health threats from groundwater contamination by heavy metals, emphasizing vulnerable groups such as pregnant women and children; and highlight gaps in the existing research and propose future research directions to improve groundwater quality and mitigate the effects of heavy metal pollution in Onitsha.By providing a comprehensive assessment of the state of groundwater contamination in Onitsha, this review aims to inform policy development, environmental management strategies, and public health interventions to reduce the threats linked to pollution by heavy metals.

II. GROUNDWATER POLLUTION BY HEAVY METALS: GENERAL OVERVIEW

2.1. Common Heavy Metals Found in Groundwater

Heavy metals are elements that occur naturally in the Earth's crust, but their concentrations have been significantly increased in many environments due to human activities. In groundwater, the most commonly detected heavy metals include nickel (Ni), cadmium (Cd), lead (Pb), copper (Cu), chromium (Cr), manganese (Mn), and iron (Fe) [17-19]. These metals enter groundwater systems primarily through industrial discharges, improper waste disposal, leachate from dumpsites, and runoff from agricultural fields [20,21].

In the context of Onitsha, several studies have documented high concentrations of lead, cadmium, nickel, and chromium in groundwater sources [22-24]. Lead, in particular, has been identified as the most prevalent contaminant, largely due to its use in automobile repair shops, battery manufacturing, and e-waste [23]. Cadmium and chromium, both of which are highly toxic, have also been detected in significant concentrations in groundwater samples from industrial areas. These metals are harmful to human health, even at low concentrations, and pose serious risks due to their tendency to bioaccumulate in the body over time [23].

2.2. Mechanisms of Groundwater Contamination

Groundwater contamination by heavy metals occurs through several pathways. This section explores the primary mechanisms of contamination in Onitsha.

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2.2.1 Leaching from Waste Dumps: Waste dumps, particularly those containing e-waste, are major sources of heavy metal pollution (Figure 2). When rainwater percolates through these dumpsites, it dissolves heavy metals from the waste materials, which then leach into the soil and contaminate the underlying groundwater. This process is accelerated by the porous nature of the local geology, which allows pollutants to move easily into the aquifers [22,25].

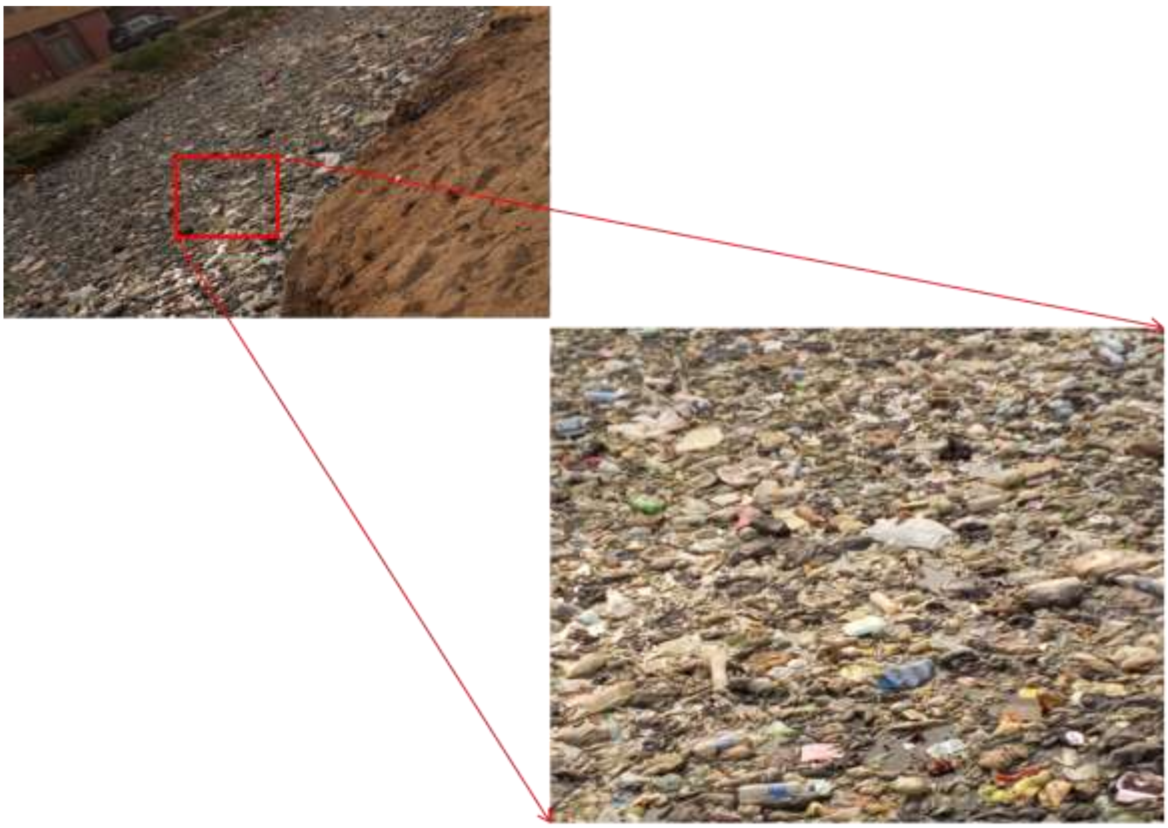

Figure 2: A very large open dump close to residential buildings in Onitsha Metropolis.

2.2.2 Industrial Effluents: Industrial activities in Onitsha, such as chemical processing, manufacturing, and automotive repairs, generate effluents that contain high concentrations of heavy metals [26,27]. These wastewaters are frequently released into the environment without adequate treatment, leading to the contamination of nearby water bodies and soil. Over time, the heavy metals in these effluents seep into the groundwater, further degrading water quality [28].

2.2.3 Urban Runoff: Urban runoff, particularly from areas with high vehicular activity, carries pollutants such as lead from fuel combustion and other heavy metals from industrial sites. This runoff flows into drainage systems and eventually infiltrates groundwater sources, contributing to contamination [21,29].Onitsha's topography and aquifer system play a significant role in facilitating groundwater contamination [30,31]. The Nanka Formation, with its sandy and permeable structure, allows pollutants from surface activities to easily infiltrate the groundwater system. Consequently, the groundwater in Onitsha is highly susceptible to being contaminated by municipal and industrial waste [32].

2.3. Health Implications of Groundwater Contamination byHeavy Metal

Groundwater contaminated with heavy metals endangers the health of Onitsha's populace. Each heavy metal has specific toxic effects on the human body [25]. In children, being exposed to lead (Pb) can lead to difficulties in cognition, delays in

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development, and behavioral problems; for adults, it results in kidney damage, high blood pressure, and reproductive problems [33-35]. Cadmium (Cd) is a known carcinogen linked to kidney damage, bone disorders, and respiratory problems. Prolonged exposure to cadmium can cause the accumulation of the metal in the kidneys, leading to kidney dysfunction and an increased risk of fractures [36,37]. Nickel (Ni) and chromium (Cr) are both classified as carcinogenic, with chronic exposure potentially resulting in skin irritation, respiratory issues, and lung cancer. Additionally, nickel exposure is connected to cardiovascular diseases and allergic reactions [38,39]. Manganese (Mn) exposure, especially at high levels, can lead to neurological symptoms similar to those of Parkinson's disease, such as muscle rigidity, tremors and walking difficulties [40].

The bioaccumulative nature of these metals means that even small amounts, when consumed over time, can lead to serious health problems. In Onitsha, where drinking water predominantly comes from groundwater, the risks associated with heavy metal contamination are especially serious. Groups such as pregnant women, the elderly, and children are particularly susceptible to chronic health issues due to extended exposure to this contaminated water [41,42].

III. HEAVY METAL POLLUTION IN ONITSHA GROUNDWATER

The primary sources of heavy metal pollution in Onitsha's groundwater are predominantly linked to the city's rapid industrialization, urbanization, and anthropogenic activities [41]. Onitsha, being one of the largest commercial hubs in Southeastern Nigeria, is home to numerous industrial operations, mechanic workshops, and informal waste management practices that have significantly contributed to the contamination of the local groundwater sources with heavy metals [41,43].

The release of**industrial effluent discharge**is one of the primary contributors to heavy metal pollution in Onitsha[44]. Onitsha's industrial sector includes factories involved in chemical processing, textile production, brewing, and automotive repairs, all of which generate significant amounts of hazardous waste [29,45]. These factories frequently release effluents containing toxic metals such as cadmium (Cd), lead (Pb), nickel (Ni), copper (Cu), and chromium (Cr) into the environment. Without adequate waste treatment facilities, these effluents are often discharged directly into nearby water bodies or onto the ground, where they infiltrate the soil and eventually leach into the groundwater system [46]. According to the analysis, approximately 91.67% of groundwater samples from Onitsha exceed the acceptable limits established by the World Health Organization (WHO) for lead, reflecting the significant impact of industrial activities on water quality in the area [47].

E-waste dumping represents another significant contributor to pollution by heavy metals in Onitsha [48]. The improper disposal of electronic waste, such as computers, discarded mobile phones batteries, and other electronic equipment, has been identified as a significant environmental hazard [48,49]. In sites like the Ochanja market dumpsite, crude methods are used to dismantle and burn e-waste, releasing high levels of heavy metals like copper, cadmium, and lead into the surrounding soil. This leads to the contamination of both the soil and the groundwater. E-waste contains toxic substances, and when it is incinerated or allowed to degrade in open dumps, heavy metals are released into the environment. Over time, these metals percolate through the soil layers and contaminate the shallow aquifers, which are a primary source of drinking water for the local population [50].

Another significant source of heavy metal pollution is **urban runoff and leachate from dumpsites**(Figure 3). Onitsha is characterized by poorly managed waste disposal systems and unregulated landfills. During the rainy season, runoff from the streets and industrial areas, which contains oils, heavy metals, and other pollutants, washes into the city's drainage systems [51-53]. Additionally, the leachate from solid waste dumpsites, which often contains a combination of organic and inorganic contaminants, further exacerbates the pollution of groundwater. This leachate, rich in toxic metals likecadmium and lead, migrates through the soil and contaminates the groundwater system [4]. Studies have shown that about 66.67% of the sampled groundwater collected near such dumpsites show elevated levels of cadmium, a known carcinogen that poses significant risks to human health [8,22,25].

Figure 3: Indiscriminate refuse disposal close to a major drainage near Onitsha main market.

Furthermore, **mechanic workshops** scattered across Onitsha are significant contributors to heavy metal pollution [8,25,53]. These workshops handle large volumes of spent oils, batteries, paints, and metal scraps, all of which contain hazardous metals. Indiscriminate disposal of these materials leads to the seepage of pollutants into the soil [25]. For instance, lead-acid batteries, which are commonly disposed of inappropriately in Onitsha, are a major source of lead contamination [25,53]. The groundwater samples analyzed from areas around mechanic workshops revealed concentrations of lead as high as 1.21 mg/L, far surpassing the WHO safe limit of 0.01 mg/L for drinking water [25].

Lastly, **vehicular emissions and fuel combustion** also contribute to the heavy metal burden in Onitsha. The large volume of traffic within the city leads to the deposition of heavy metals such as copper, zinc, and lead from vehicle exhausts, brake linings, and tires onto the ground. Over time, these metals accumulate in the soil and are eventually washed into groundwater sources during rainfall events. The extent of pollution from vehicular emissions is particularly pronounced in densely populated and high-traffic areas, where groundwater samples have shown significant concentrations of heavy metals [25,26,29].

Several studies have shown alarming trends in the concentration of heavy metals in groundwater in Onitsha [8,22,25,26,29,53]. The concentrations of chromium, cadmium, nickel, and lead in several areas have consistently exceeded the permissible limits set by the World Health Organization (WHO) and Nigerian standards. For instance:

- Lead levels in some groundwater samples have reached concentrations as high as 1.21 mg/L, far exceeding the WHO limit of 0.01 mg/L for drinking water [25,53].
- Nickel concentrations have been recorded at up to 1.82 mg/L, significantly higher than the WHO limit of 0.05 mg/L [22,25].
- Cadmium levels in several areas also exceed the permissible limits, posing a serious risk to public health [22,53].

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Seasonal variations have been observed in heavy metal concentrations, with higher levels typically recorded during the dry season. This is likely due to reduced water volumes, which increase the level of metals in groundwater, and the increased dissolution of metals from soil and industrial waste during periods of low rainfall [22, 25,53].

Spatial Distribution of Contamination

The spatial distribution of heavy metal contamination in Onitsha demonstrates considerable variation, with significantly higher concentrations found in areas close to industrial zones and waste disposal sites [Tables 1 & 2]. Groundwater samples collected from key industrial zones, such as the Obosi automobile junk market and residential areas like Fegge, consistently show elevated levels of heavy metals, including lead, nickel, and cadmium [22]. These regions are characterized by the presence of numerous small-scale industries and a high density of automobile repair workshops, which are the primary source of the contamination. Their accumulation in groundwater is indicative of long-term industrial activity and insufficient waste management practices in these areas [8,29,53].

Odoh et al., [8] reported that areas near e-waste dumpsites, such as the Ochanja area, where electronic waste is poorly managed, exhibit some of the highest levels of heavy metal pollution. The improper handling and disposal of e-waste allow toxic substances to leach into the surrounding environment, significantly contaminating the groundwater. While the concentration of pollutants decreases progressively with distance from the dumpsites, traces of heavy metals can still be detected in groundwater sources far from the contamination origin. This indicates that the impact of pollution extends well beyond the immediate vicinity of the dumpsites, highlighting the widespread influence of improper waste disposal on groundwater quality across the region [8,25,53].

The spatial analysis of contamination patterns thus emphasizes the localized impact of industrial operations and inadequate waste disposal practices, particularly in proximity to these pollution sources. However, the pervasive nature of this contamination suggests that it is not confined to specific hotspots or areas near industrial activities. Instead, the entire groundwater system in Onitsha is affected, with pollutants spreading over broader areas, contributing to a regional water quality crisis that presents serious risks to the environment and public health [29,44,48,53].

Heavy Metal	Concentration Range (mg/L)	WHO Limit (mg/L)	NSDWQ Limit (mg/L)	Health Impacts
Lead (Pb)	0 – 1.21	0.01	0.01	Lead exposure can cause cognitive impairment, kidney damage, developmental delays, and high blood pressure. Chronic exposure is particularly harmful to children, causing irreversible neurological damage.
Nickel (Ni)	0 – 1.82	0.05	0.02	Nickel is carcinogenic and causes lung cancer, cardiovascular diseases, and skin irritation. Long-term exposure can also lead to respiratory issues.
Cadmium (Cd)	0 – 0.68	0.003	0.003	Cadmium is linked to kidney damage, bone disorders, and an increased risk of fractures. It is a known carcinogen and can lead to chronic conditions like kidney dysfunction.
Manganese (Mn)	0 – 0.195	0.05	0.2	High levels of manganese can result in neurological symptoms similar to Parkinson's disease, such as tremors and muscle stiffness.
Copper (Cu)	0 – 0.325	0.05	0.1	Although essential in small amounts, high copper intake leads to gastrointestinal distress, liver and kidney damage. Chronic exposure can cause anemia and immune dysfunction.
Chromium (Cr)	0 – 0.19	0.05	0.05	Chromium, particularly in its hexavalent form, is highly carcinogenic and can cause lung cancer, skin ulcers, and respiratory issues.
Iron (Fe)	0 – 0.68	Not specified	0.3	Although not highly toxic, excess iron in water can lead to gastrointestinal problems and contribute to conditions like hemochromatosis.
Zinc (Zn)	0 – 0.09	5.00	3.00	While essential, excess zinc intake can cause nausea, vomiting, loss of appetite, and long-term consumption may lead to immune dysfunction.

Table 1: Heavy Metal Concentration around Obosi Area, Onitsha. Modified from Igwe & Chukwura [22]

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Heavy Metal	Concentration (Rainy Season)	Concentration (Dry Season)	Permissible Limit (WHO/NDWQ)	Negative Impacts
Lead (Pb)	Not Detected	Not Detected	0.01 ppm	Neurotoxicity, developmental delays in children, cardiovascular issues.
Copper (Cu)	Not Detected	0.144 - 0.250 ppm	1.0 ppm	Stomach and intestinal distress, liver or kidney damage in high concentrations.
Nickel (Ni)	Not Detected	0 - 0.022 ppm	0.02 ppm	Skin irritation, lung, nose, throat cancers with prolonged exposure.
Mercury (Hg)	0 - 0.190 ppm	0.027 - 0.218 ppm	0.001 ppm	Neurological damage, developmental defects in fetuses, kidney damage.
Cadmium (Cd)	0.004 - 0.027 ppm	0.002 - 0.015 ppm	0.003 ppm	Kidney damage, skeletal damage, cancer, and potential for bioaccumulation.
Silver (Ag)	0 - 0.018 ppm	0.01 - 0.148 ppm	0.02 ppm	Skin and eye irritation; high levels can cause argyria (skin discoloration).

Table 2: Heavy Metal Concentration in Onitsha Metropolis. Modified from Okolo et al., [53]

IV. ENVIRONMENTAL AND HEALTH IMPACTS

4.1. Environmental Degradation

Heavy metal contamination in Onitsha's groundwater has profound environmental consequences, exacerbating soil degradation, aquatic ecosystem disruption, and increasing bioavailability of toxic metals [22,25]. The presence of heavy metals like chromium, lead, and cadmium, which often surpassacceptable limits, fundamentally alters the chemical properties of the environment, with cascading effects on agricultural productivity, biodiversity, and public health [54,55].

Soil degradation is a key consequence of heavy metal pollution in Onitsha. The absorption of metals like cadmium and lead into the soil alters its natural composition, reducing its fertility and thereby affecting agricultural yields [26,295,6]. Chromium, a known carcinogen, inhibits essential biological processes in plants, resulting in stunted growth and lower crop yields, posing a serious risk to food security in the region. Lead contamination, particularly prevalent due to widespread industrial and vehicular activities, further reduces soil productivity, impacting the livelihood of farmers who depend on the fertility of the land for sustenance. The reduction in soil quality also diminishes its ability to support diverse plant species, contributing to a decline in local biodiversity [57-59].

The aquatic ecosystems in Onitsha are similarly affected by heavy metal pollution. Groundwater contaminated with toxic metals often finds its way into nearby rivers, wetlands, and other surface water bodies, where it accumulates and disrupts aquatic life [28,60]. The ecological risk index (ERI) analysis conducted in the region by Egbueri et al [25] shows that 58.33% of groundwater samples introduce a significant threat to the ecosystem due to heavy metal pollution, with metals such ascadmium and lead being major contributors. These metals accumulate in the sediments and biota of aquatic systems, leading to a decrease in fish populations and other aquatic organisms sensitive to changes in water quality. The disruption of these ecosystems affects not only the biodiversity of the region but also the livelihoods of those who depend on fishing and other water-related activities [25,61-64].

Bioavailability of heavy metals is another critical concern, as the contaminated soil and water increase the uptake of these metals by plants and animals, ultimately introducing them into the food chain [65,66]. Heavy metal contamination of groundwater contributes to their accumulation in crops irrigated with polluted water. This bioaccumulation process results in the concentration of toxic metals in edible plant parts, which are then consumed by humans and animals. In Onitsha, where agricultural activities rely heavily on groundwater for irrigation, this poses a direct threat to food safety and public health [28,67,68]. According to Egbueri et al [25] the hazard index (HI) values for heavy metals such ascadmium and lead in Onitsha's groundwater indicate that 91.67% of the samples are associated with medium to high risk of chronic health issues for children and adults through ingestion, pointing to the severity of the issue.

4.2. Health Risks to the Onitsha Population

The health risks associated with heavy metal contamination in Onitsha's groundwater are substantial, particularly due to the significant exposure of the population to toxic metals [3,25,28]. These metals are known to have both acute and chronic health effects that can severely impact public health. In Onitsha, the hazard indices (HI) for lead, cadmium, and nickel consistently surpass acceptable limits, highlighting a serious concern for non-carcinogenic health risks [3,41]. For instance, report by Egbueri et al [25] show that the hazard indices for children ranged from 0.438 to 46.367, while for adults, the values ranged from 0.127 to 20.294. This indicates that 91.67% of groundwater samples pose medium to high chronic risk levels for both children and adults, as the HI values for these samples exceed 1, a threshold that signals unacceptable health risks [25].

Lead (Pb) contamination, which was found in 91.67% of the samples, poses a particularly grave threat, especially to children [25,69]. Lead exposure can cause developmental delays, cognitive impairments, and behavioral issues in children, while in adults it is associated with kidney damage, high blood pressure, and reproductive issues [70]. Being exposed to lead while pregnant can lead to a heightened risk of miscarriage, low birth weight in newborns, and early labor. The health hazard index (HQ) for lead in children ranged up to 23.714, far above the acceptable limit, indicating severe health risks [25].

Cadmium (Cd) was found in 66.67% of groundwater samples, with health risks manifesting as bone demineralization, kidney damage, and an increased risk of fractures due to long-term exposure [22,25,53]. The accumulation of cadmium in the kidneys can lead to chronic kidney disease, and the hazard index for cadmium in children reached as high as 46.000 in some samples. Similarly, adults consuming water contaminated with cadmium are at risk of renal dysfunction and osteoporosis, as their HI values also exceeded the acceptable threshold in several cases [25,71,72].

Nickel (Ni) and chromium (Cr) are known carcinogens, with chronic exposure leading to respiratory problems, skin irritation, and increased risk of cancers such as lung cancer [38,73]. In Onitsha, the hazard indices for nickel exceeded the acceptable limits in 50% of the groundwater samples, and chromium was found in 70.83% of the samples [8,25]. Prolonged exposure to chromium can also lead to gastrointestinal issues such as stomach cramps and ulcers. The cancer risk probability (PCR) for nickel and chromium ingestion was particularly high, with 62.5% and 66.67% of samples posing a significant cancer risk to children, respectively [25].

4.3. Bioaccumulation and Food Chain Impacts

Bioaccumulation is the process where heavy metals gradually build up in living organisms over time, often reaching toxic levels, particularly when these organisms are exposed to contaminated water or soil [74,75]. In Onitsha, industrial activities and waste handling processes have contributed to the significant contamination of groundwater, the potential for heavy metals to enter and magnify within the food chain is of critical concern [22,53]. This is particularly alarming given the agricultural reliance on groundwater for irrigation in the region. Crops absorb metals like lead, cadmium, and nickel from contaminated soil and water, with these metals becoming integrated into plant tissues. Once absorbed, these metals are not easily eliminated, leading to their accumulation in the edible parts of the plants [20,54,58].In addition to plant uptake, livestock that drink contaminated water or graze on plants irrigated with polluted water are also susceptible to heavy metal accumulation [75,76]. This results in the deposition of toxic metals in animal tissues, particularly in organs such as the liver and kidneys, which are then consumed by humans. The bioaccumulation of heavy metals through this pathway amplifies the health risks posed to local populations who rely on these crops and livestock for sustenance [22,25,76].

Scientific data from groundwater samples in Onitsha reveal high concentrations of heavy metals across various locations. Lead (Pb) concentrations were found to be as high as 1.21 mg/L, significantly exceeding the WHO permissible limit of 0.01 mg/L [25]. Nickel (Ni) was recorded at up to 1.82 mg/L, far surpassing the safe limit of 0.07 mg/L, while cadmium (Cd), known for its severe toxic effects, was detected at 0.69 mg/L, compared to the permissible limit of 0.003 mg/L [8,22,25,53]. These elevated concentrations pose long-term risks as they enter the food chain, affecting both plant and animal health before being passed on to humans.

The process of bioaccumulation results in the gradual concentration of these metals as they move up the food chain, leading to greater health risks in organisms at higher trophic levels, such as humans [74-76]. It intensifies the toxic effects of heavy metals, increasing the potential for chronic illnesses, including cancer, kidney failure, and neurological disorders. The hazard indices calculated for Onitsha's groundwater reveal alarming risks, especially in children, who are more susceptible to the impacts of heavy metal exposure. For example, the hazard index (HI) values for lead exposure range from 0.127 to 20.294 for adults and from 0.438 to 46.367 for children, indicating high levels of health risk due to bioaccumulation [25].

The magnitude of the bioaccumulation problem in Onitsha is exacerbated by the reliance on groundwater for both agriculture and drinking water. As heavy metals accumulate in crops and livestock, local populations are exposed to these toxins through their diet, leading to long-term health implications [25,76]. Without effective intervention, the continued use of contaminated groundwater in agriculture will only worsen the bioaccumulation problem, increasing the potential for severe health outcomes.

V. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite extensive research on heavy metal contamination in Onitsha's groundwater, several critical gaps still need further investigation. One key area is the lack of comprehensive studies on the extended health effects of chronic exposure to these metals, particularly among susceptible populations like pregnant women and children. Longitudinal health assessments are necessary to fully understand the risks [22,25]. Additionally, there is a need for more detailed spatial mapping of contamination sources and analysis of seasonal variations in heavy metal concentrations to identify high-risk areas and develop targeted intervention strategies.

Another area requiring attention is the limited data on the bioaccumulation of heavy metals in local food chains and its implications for human health. Studies should investigate the extent to which crops, livestock, and humans are affected by consuming contaminated water and food. Furthermore, research into cost-effective and sustainable groundwater remediation techniques is crucial to mitigating the effects of heavy metal pollution. Innovative approaches to water treatment and waste management should be explored to reduce Onitsha's heavy metal burden [77,78].

VI. CONCLUSION

Heavy metal pollution in Onitsha’s groundwater presents significant environmental and public health challenges. Industrial activities, improper waste disposal, and urbanization are the primary drivers of contamination, with lead, cadmium, and nickel posing the most significant health risks. The pervasive nature of contamination, coupled with the bioaccumulative properties of heavy metals, has led to widespread environmental degradation and severe health impacts for the population. Immediate action is required to monitor groundwater quality, enforce pollution control measures, and implement sustainable waste management practices. Public awareness campaigns are also essential to educate the population about the dangers of consuming contaminated water and to promote safer water use practices. Without effective intervention, the health and environmental consequences of heavy metal pollution in Onitsha will continue to worsen, putting the lives of millions at risk.

Declaration of competing interest

The authors declare that they have no known competing financial interests.

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