JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Heavy Metal Pollution in Water, Detection and Remediations Strategies

[1]Odongo Irene Akinyi, [2]Sylvia Opiyo, [3]Peter W. Njoroge and [4]Elly T. Osewe
[1]Miss, [2]Professor, [3]Doctor, [4]Doctor
Department of Physical and Biological Sciences
Murang'a university of Technology, Murang'a, Kenya

Abstract: Heavy metal pollution poses a significant threat to both human health and the environment, stemming from industrial processes, agricultural methods and urbanization. This study examined the presence of heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), manganese (Mn), copper (Cu), zinc (Zn) and cobalt (Co) in water bodies. It investigated bioaccumulation processes and contamination pathways, highlighting the toxicological impacts these metal contaminants have on human populations and ecosystems, including acute and chronic health effects. The study further assesses various remediation techniques, emphasizing environmentally friendly and sustainable strategies. Techniques such as electrokinetic remediation, phytoremediation, adsorption remediation and chemical precipitation are evaluated for their effectiveness in mitigating heavy metal contamination. Advantages and limitations of analytical methods such as Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), Atomic Absorption Spectroscopy (AAS) and MP-AES were also examined.

Keywords: Pollution; heavy metals; detection; remediations

I. INTRODUCTION

Humans, plants, animals and microorganisms all live in the environment which consists of the land, the water and the atmosphere. The biosphere, atmosphere, lithosphere and the hydrosphere are the four spheres that make up the Earth's system and all function in unison to support life on Earth (Briffa *et al*., 2020). Among these, the hydrosphere is very important as it encompasses all water bodies, including oceans, rivers, lakes and groundwater. The hydrosphere refers to all the water on Earth's surface which include the oceans, seas, lakes, rivers, groundwater and spring (Ekinci, 2012).

II. World water resources

Salt water accounts for 97.5% of the world's water potential in seas and oceans (Ekinci, 2012). The remaining 2.5%, of 69.5%, of fresh water is trapped in glaciers, known as the "cryosphere"(Ekinci, 2012). Groundwater accounts for 30.1% of total fresh water, while surface water from rivers and lakes makes up 0.4%. Groundwater is mostly made up of fossil water, hygroscopic water and underground water stored at depths that are inaccessible (Ekinci, 2012). Oceans encompass around 71% of the Earth's surface, or nearly three-quarters and contain 321,003,271 cubic miles of water, accounting for 97% of all water on the planet (Fava, 2022). Seas are often smaller than the ocean and are found where the ocean meets land. Also, seas are frequently surrounded by land. The ocean, therefore, indicates a far greater body of open water than the sea (Fava, 2022). Lakes, which make up 0.3% of fresh water and marshes and wetlands, which make up 0.03%, are the sources of most fresh water after glaciers and underground water (Ekinci, 2012). However, the increasing industrial and economic growth has led to the production of various compounds and chemicals, resulting in undesirable pollutants (Espinoza-Quiñones *et al*., 2005). Water resources, especially surface waters like rivers, are vital in meeting the needs of people animals and industries, showing the urgent necessity to protect them from contamination. When such waste enters water systems, biological and chemical pollutants, including heavy metals, are also introduced into these critical resources (Shanbehzadeh *et al.*, 2014). Even if traces are transferred to bodies of water, they may still be very harmful to humans and other ecosystems (Dippong *et al.,* 2022). Heavy metal toxicity is determined by a variety of factors, including the type of metal present, the nature of the metal, the biological role of the metal, the organism exposed and the time period during which the organism is exposed. If one creature is harmed, the whole food chain suffers (Briffa e*t al*., 2020). The bioaccumulation and biomagnification of heavy metals up the food chain can lead to elevated levels in organisms, ultimately reaching humans through the consumption of contaminated water, fish and other aquatic resources (Dippong *et al.,* 2022). The weathering of rocks and soil, as well as natural occurrences like earthquakes and floods, are the primary natural resources of water pollution (Espinoza-Quiñones *et al*., 2005).

III. Sources of water pollution

Industrial operations, particularly those involving mining, smelting, manufacturing and electroplating, are primarily to blame for heavy metal contamination (Alloway, 2012). Fossil fuel combustion and waste incineration are other industrial processes that contribute to the atmospheric release of heavy metals (Nriagu & Pacyna, 1988). These processes regularly generate wastewater that contains high levels of metals that could be harmful to aquatic life (Alloway, 2012). These metals can enter aquatic habitats through precipitation or dry deposition (Nriagu & Pacyna, 1988). Pesticides, herbicides and fertilizers are among the agricultural practices that discharge heavy metals into nearby rivers, lakes and streams. These metals can accumulate in soils and eventually make their way into groundwater and surface water (Nagajyoti *et al*., 2010). Runoff from urban areas carries heavy metals from construction materials, road surfaces and other sources into aquatic environments (Makepeace *et al*., 1995). Metals like lead, zinc and copper are frequently found in urban runoff (Makepeace *et al.*, 1995).

In contrast to other pollutants such as petroleum hydrocarbons and domestic or municipal litter which may visibly build up in the environment, heavy metals in the environment often accumulate unnoticed to toxic levels. They tend to settle on river beds or persist in streams or land for long periods of time, providing a long-term source of contamination to the surrounding inhabitants. These heavy metals have the potential to harm the environment and human health as they continue causing long time damage after mining has ceased (Motswaiso *et al.*, 2019). The presence of heavy metals in water can have significant consequences for aquatic ecosystems and human health, making it a critical environmental concern. Heavy metals are metallic chemical elements that have relatively high density and are toxic at low concentration (Duffus, 2002). They are found in agrochemicals, factories and urban runoff and are detrimental to both human and aquatic life (Duffus, 2002). Examples include zinc, cobalt, manganese, cadmium, copper, lead and mercury.

Zinc ore, commonly known as sphalerite (ZnS), is a mineral that occurs in sedimentary, igneous and metamorphic rocks. It is the principal ore of zinc, a widely utilized metal with many industrial applications (Mat, 2023). Zinc is vital for galvanizing metals, alloying with copper for brass and bronze, producing batteries, chemicals, dietary supplements, anti-corrosion coatings, pharmaceuticals, die casting and in making of agricultural fertilizers (Mat, 2023). Some fertilizers include zinc, which can seep into groundwater (Ullah *et al.*, 2022).

Examples of cobalt ore minerals are akutterudite ($CoAs_3$–$NiAs_3$) and cobaltite (CoAsS–FeAsS). In addition to these deposits, it is most prevalent in ferromagnesium minerals that are relatively unstable, with basic igneous rocks containing olivine, pyroxenes, amphibole and biotite (Aubert & Pinta, 1980). The introduction of cobalt into surface waters is mostly the result of the metals and ceramics industries. Because of the extensive use of this metal, especially in the petrochemical, aviation and power sectors (Abd-Alla *et al*., 2014). The quantity of wastewater that is introduced that contains significant amounts of cobalt has an adverse effect on both the surface water and groundwater conditions (Abd-Alla *et al*., 2014).

With a relatively high-density ore manganese metal is heavy and has a high mass per unit volume. It is usually encountered in block or ingot form. Compared to diamond and certain other minerals, it is not as hard, but it is harder than most other metals. Even though it isn't naturally magnetic, exposure to powerful magnetic fields can make it magnetic (Naoum, 2024).

Pure manganese is silvery-gray in appearance, similar to steel or aluminum, but depending on the mineral it is found in, it can have a variety of unique colours. Pyrolusite (black or dark grey), braunite (black or dark brown), hausmannite (generally dark brown or black, occasionally reddish-brown) and manganite (usually black or dark brown, occasionally with a reddish tint) are some of these. It can also be found in rhodonite, commonly used as a gemstone or decorative stone, which is pinkish red (Naoum, 2024). Electrical storage batteries and engineering steels are two examples of goods that use manganese. Additionally, it is vital to living things. In soils lacking in the element Mn, MnSO4 and MnO are added in amounts ranging from 10 to 100 kg of Mn per hectare this is because higher plants have Mn as a micronutrient (Masagni & Cox, 1985). Through human activities including burning fossil fuels, using inorganic fertilizers for farming and industrial processes, manganese can enter the environment (Modaihsh *et al*., 2004).

Cadmium (Cd), which is mostly produced as a byproduct of zinc mining, is utilized in solar photovoltaic cells, battery storage, alloys, pigments, plating and nuclear reactors (Werner *et al.*, 2024). The non-essential transition metal cadmium (Cd) is hazardous to human and animal health. It is a naturally occurring contaminant in the environment that comes from both industrial and agricultural sources (Khan *et al*., 2022). Mining, the metallurgy sector, pigments and plastic stabilizers and the production of nickel-cadmium batteries are the main sources of cadmium pollution in the environment (Khan *et al*., 2022). The disposal of wastes containing Cd, such as burning batteries and plastic containers, the application of sewage sludge to the land and the burning of fossil fuels are the sources of Cd contamination (Bowen, 1979). Approximately 28% of the Cd mobilised annually by mining comes from places with seasonal or permanent surface water cover (Werner *et al.*, 2024).

The crystalline structure of copper is face-centered and it is a reddish metal. Red and orange light are reflected by it, whereas other visible spectrum frequencies are absorbed. It is incredibly effective at conducting heat and electricity and is ductile and flexible. There are two different oxidation states for copper, with +2 being the most prevalent. The main types of ores include halides, sulphides and oxides. There are cuprous and cupric oxides. The two most significant examples of the many copper sulphides are Cu_2S and CuS. Both cupric and cuprous halides including iodine, bromine and chlorine are well known (Selwyn, 2004). In its free form, copper is found in nature in large quantities as carbonates, sulphides, arsenides and chlorides. Electrical wires are made from it and its alloys find employment in a variety of industrial settings. Through soil erosion and mineral deposits, copper finds its way into aquatic environments. Copper and copper alloy tubes are used extensively and more frequently in industries, air conditioning, heating systems, refrigerators and home plumbing. Fertilisers, fungicides, insecticides and nutritional supplements for animal feed all contain copper sulphate (Wekesa, 2015).

Compared to most conventional materials, lead heavy metal has a higher density. Lead has a comparatively low melting point and is pliable and soft. Lead is silvery with a trace of blue when it is first cut; when it is exposed to air, it tarnishes to a dull grey color. Lead completes the three main decay chains of heavier elements and has the highest atomic number of any stable element. Lead exists naturally in the earth's crust at an average concentration of 13 mg/kg. Its components can be found throughout the environment. All isotopes of lead except for ^{204}Pb can be found in the end products of radioactive decay (Boldyrev, 2018). There are various potential sources of lead in water. Possible sources of lead pollution include ground water and municipal water piping (Duffus, 2002). Lead enters the environment through several uses, including storage batteries, solders, ammunition, shielding systems for X-rays and radiation and tank lining (Duffus, 2002). There are three types of mercury (Hg) that can be found in water elemental or metallic mercury (Hg0), inorganic mercury (Hg^+, $Hg2^+$) and organic mercury (usually methyl or ethyl mercury) (Li et al., 2017). At room temperature, elemental mercury is a liquid that easily evaporates to form vapor. The liquid form of mercury is less dangerous than the vapor. When a container breaks, mercury leaks out and breathing in a lot of mercury vapor can be lethal. Methyl mercury (Me-Hg) and ethyl mercury (Et-Hg) are examples of organic mercury compounds that are more hazardous than their inorganic counterparts. $Hg^0 < Hg^{2+,}$ $Hg^+ <$ CH3-Hg is the order of increasing toxicity associated with various forms of mercury (Kungolos *et al.*, 1999). Mercury compounds are used in a variety of industrial processes and mining operations, such as the extraction of gold. Fluorescent light bulbs are made with mercury in lamp manufacturing plants. To prevent plant diseases, fungicides such as Me-Hg and Et-Hg have been employed. Additionally, mercury has been used medicinally in the past, but safer pharmaceutical medications have taken its place (Balali-Mood *et al.*, 2021).

IV. Effect of heavy metal contamination on human

Exposure to heavy metals has been linked to serious health consequences, such as cancer, kidney and cardiovascular problems, skin irritation and liver damage, according to studies (Balali-Mood *et al.*, 2021). Table 1 outlines the hazardous effects of various heavy metals on human health.

Table 1: Hazardous Effects of Heavy Metals on Health

Heavy metal	Related hazardous effects	References
Zn	Overdosing will result in dizziness and exhaustion.	(Hess & Schmid, 2002)
Co	Causes allergic dermatitis, rhinitis and asthma	(Lauwerys & Lison, 1994)
Mn	Neurotoxicity is the most obvious effect of Mn, as it affects the metabolism of neurotransmitters, particularly dopamine.	(Röllin, 2011)
Cd	Chronic anemia, mutagenic, renal failure and carcinogenic	(Degraeve, 1981); (Salem *et al.*, 2000)
Cu	Brain and kidney injury, liver cirrhosis, stomach and intestinal inflammation have all been linked to elevated levels.	(Wuana & Okieimen, 2011)
pb	Exposure to very high levels of lead can severely damage the brain and central nervous system causing coma, convulsions and even death. Children who survive severe lead poisoning may be left with permanent intellectual disability and behavioral disorders.	(WHO, 2024)
Hg	Tremors, Emotional changes (such as mood swings, irritability, nervousness, excessive shyness), insomnia, neuromuscular changes (such as weakness, muscle atrophy, twitching); Headaches, disturbances in sensations, changes in nerve responses; Poor performance on tests of mental function. Higher exposures may also cause kidney effects, respiratory failure and death.	(US EPA, 2024)

Moreover, children are particularly vulnerable to the negative impacts of heavy metal pollution, as their developing bodies and brains are more susceptible to the toxic effects (Al-Saleh *et al.*, 2017). For communities that depend on surface and groundwater for drinking water, heavy metals can contaminate natural resources. Polychlorinated biphenyls (PCBs), particularly the so-called "dioxin-like" PCBs and heavy metals like lead, cadmium and mercury deserved special attention among these pollutants because they are a class of extremely toxic compounds that build up in the tissues of marine organisms and are passed on to humans through the food chain (Storelli, 2008).

V. Effects of heavy metals on aquatic ecosystems

Heavy metals can disrupt aquatic ecosystems by affecting the growth, reproduction and behavior of aquatic organisms (Yusoff *et al.*, 2020). Other impacts include acute and chronic toxicity, immunological system suppression, physiological stress, behavioral changes, bioaccumulation and biomagnification are some of the possible outcomes (World health organization, 2024). Once in the environment, bacteria have the ability to convert mercury to methylmercury. Then, methylmercury bioaccumulates in fish and shellfish (bioaccumulation is when an organism has higher amounts of the material than the environment). For instance, eating a lot of lesser fish increases the likelihood that large predatory fish will have elevated mercury levels (World health organization, 2024). Ecosystems also experience changes in the food web, habitat degradation, water quality degradation, biodiversity loss and disturbances in ecosystem functioning. Toxic effects can cause sensitive species to diminish or vanish, upsetting the equilibrium and functionality of ecosystems (Abubakar *et al.*, 2024). Some of the analytical tools for measuring these heavy metals include inductively coupled plasma atomic emission spectroscopy (ICP-AES), Atomic absorption spectroscopy (AAS), and Microwave Plasma Atomic Emission Spectroscopy (MP-AES).

VI. Detection Methods

Inductively coupled plasma atomic emission spectroscopy (ICP-AES), also known as inductively coupled plasma optical emission spectrometry (ICP-OES), can accurately identify trace components (Ghanati *et al.*, 2019). Inductively linked plasma is a gaseous mixture of argon, argon ions and electrons that conducts electricity. Plasma is created by combining argon gas and a strong radio frequency field. This results in highly atomized and ionized argon, with an excitation temperature of 7000-10,000 K that is used to excite the analyte present in the sample (Bulska & Ruszczyńska, 2017). Collisions between neutral argon atoms and charged particles create a stable plasma. When the sample is introduced into the plasma, it is immediately broken down into charged ions by collisions with electrons and charged ions. Different molecules disintegrate into atoms, which lose electrons and interact in the plasma. Excited atoms emit electromagnetic radiation with characteristic wavelengths for its element. The intensity of emission, detected by a photomultiplier or semiconductor detector, indicates the element's concentration in the sample (El Hosry *et al.*, 2023).

ICP-AES's key strengths include the capacity to determine the types and ratios of elements in complex samples (Levine, 2023). ICP-AES other advantages include, the ability to determine multiple elements quickly and simultaneously, to determine concentrations at the trace level and to trace small concentration changes. In addition, ICP-AES offers outstanding repeatability and a wide dynamic linear range (Faraji *et al.*, 2021). One of the most notable drawbacks of ICP-AES is the requirement for aerosolized samples. Despite major breakthroughs in aerosolization processes solid and liquid samples cannot be analyzed while they are still solid or liquid. Furthermore, ICP-AES is a destructive analytical process, which means that the sample cannot be retrieved following analysis. As a result, highly valuable or unusual samples cannot be analyzed using this method (Levine, 2023). Finally, ICP-AES necessitates expensive instrumentation for plasma generation, sample aerosolization and signal analysis, albeit at a lower cost than other comparable methods such as ICP-MS, therefore access to this approach is naturally limited (Lee *et al.*, 2016).

Atomic absorption spectroscopy (AAS) is a widely used and acknowledged technology that can detect trace and ultra-trace levels of elements or metals in a wide range of samples, including biological, clinical, environmental, food and geological materials, with high accuracy and precision. It is undoubtedly the most popular approach in elemental analysis. AAS entails the impingement of light with a specified wavelength upon previously created ground state atoms. The atoms absorb the light, causing a shift to a higher energy level. The intensity of this transition is related to the initial concentration of ground state atoms (Miiro & Ntale, 2024). AAS method offers advantages such as low cost per analysis, ease of operation, high sensitivity (up to ppb detection), high accuracy, freedom from inter-element interference and wide applications across industries. However, it has limitations, including the inability to detect non-metals, high cost of new equipment, being more suited for liquid analysis and sample destruction (Visser, 2024).

Microwave Plasma Atomic Emission Spectroscopy (MP-AES) is another analytical technique for detecting elements. This analytical technique analyses many elements with cheap operating costs, high detection power and quick detection (Balaram, 2020). Many research has employed MP-AES to detect metals or elements in various materials, including ground water, soil, sediment, liqueurs, henna, fertilizer and honey (Kamala *et al.*, 2014). The microwave generator produces microwaves that ionize the plasma gas, typically nitrogen, to create the plasma needed for excitation. Within the plasma torch, the sample aerosol is introduced and mixed with the plasma gas, sustaining the plasma and exciting the atoms in the sample. The nebulizer and spray chamber convert the liquid sample into a fine aerosol for efficient introduction into the plasma, ensuring uniform sample delivery for accurate measurements. Light emitted from the excited atoms is then separated by wavelength using the optics and monochromator, allowing for the detection of specific emission lines corresponding to various elements. Finally, the detector, typically a photomultiplier tube (PMT) or a charge-coupled device (CCD), quantifies the emitted photons, correlating their intensity with the concentration of elements in the sample (Courtenay, 2023).

The technology showed great potential for everyday analytical applications, with various benefits including a reduced size, multi-element capabilities, low maintenance cost, good detection power and speed. Several workers were drawn to the use of microwave plasma powered by readily available nitrogen from a generator rather than bottles or liquid storage devices. Thus, MP-AES has become a cost-effective analytical method compared to ICP-AES or ICP-MS and offers more possibilities than AA (Balaram, 2020). MP-AES limitations include spectral interferences, low sensitivity and inability to analyze samples with high Total Dissolved Solids (TDS), as compared to techniques such as quadrupole ICP-MS (Balaram, 2020).

Table 2 provides an overview of heavy metal concentrations detected in various rivers using different analytical instruments, along with the corresponding World Health Organization (WHO) guidelines for acceptable levels of these metals.

Table 2: Heavy Metal Concentrations in River Water Samples measured using different Analytical tools

Source	Instrument	Metals Detected	Level (ppm)	WHO	**Reference**
River Riana	ICP-AES	Zn	0.084- 0.370	3	(Mong'are *et al.*, 2023)
		Mn	0.014-0.277	0.4	(Mong'are *et al.*, 2023)
		Cu	0.073- 0.370	2	(Mong'are *et al.*, 2023)
		Pb	0.018-0.195	0.01	(Mong'are *et al.*, 2023)
		Hg	ND	0.001	
		Cr	0.001-0.008	0.05	(Mong'are *et al.*, 2023)
		Ni	0.014-0.254	0.07	(Mong'are *et al.*, 2023)
Rivers Naka	AAS	Pb	0.0537 ± 0.103	0.01	(Mutembei *et al.*, 2014)
		Cd	0.003	0.005	(Mutembei *et al.*, 2014)
River Irigu	AAS	Pb	0.765 ± 0.782	0.01	(Mutembei *et al.*, 2014)
		Cd	0.005	0.005	(Mutembei *et al.*, 2014)
Lake in Pusat Marin	MP AES	Mg	0.62-1.47	-	(Jamari & Firdaus, 2024); (WHO, 2011)
		Al	0.02	0.90	(Jamari & Firdaus, 2024) ;(WHO, 2011)

In River Riana, metals such as zinc (Zn), manganese (Mn), copper (Cu), lead (Pb), chromium (Cr) and nickel (Ni) were measured using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). Notably, the concentration of Pb at 0.018-0.195ppm is significantly above the WHO limit of 0.01 ppm, indicating a potential health risk. Other metals, such as Mn and Ni, also exceeded the WHO standards. The presence of Pb in the river water was linked to surface runoff from garages and motor washing points, application of agrochemicals including herbicides, insecticides and fertilizers, sewage contamination, urban and industrial waste (Awofolu *et al.*, 2005). Higher Pb concentrations than the current study in water have been reported with mean Pb concentration range (0.57±0.09 - 3.36±1.15) for water from river Kuywa and the adjacent wells (Wasike *et al.*, 2019). Other authors observed lower Pb values from the Athi-Galana-Sabaki rivers, in the range of 0.004mg/l to 0.047mg/lm (Muiruri *et al.*, 2013). Lead paint is a major cause of exposure worldwide. The Global Alliance to Eliminate Lead Paint is led by WHO and the United Nations Environment Programme. It seeks to persuade all countries to enact legally enforceable policies governing the use of lead in paint. As of January 2024, 48% of countries had legally obligatory limitations on lead paint (WHO, 2024).

Cr concentration of River Riana ranged from <0.001-0.008 ppm, with monthly averages below the recommended limit of 0.05mg/l (Mong'are *et al.*, 2023). The ICP-AES was able to detect chromium (Cr) at low levels, it indicates the technique's high sensitivity and effectiveness in analyzing trace metal. River Riana contamination with Cr was linked to sewage pollution, contamination with fossil fuels, pesticides, fertilizers and discharges from untreated urban and industrial waste (Awofolu *et al.*, 2005). According to Mong'are et al (Mong'are *et al.*, 2023), the river's low Cr levels was attributed to less human activities, such as wood preservation and treatment, which cause Cr contamination (Mong'are *et al.*, 2023). The level of manganese (Mn) in the water sample was below the World Health Organization (WHO) standard of 0.4 mg/L (Mong'are *et al.*, 2023). This indicates that the manganese concentration was within acceptable limits for drinking water and does not pose a significant health risk. A study by Wekesa, (2015) also reported that the Mn levels in the analyzed water sample were low and ranged between 0.15±0.14 mg/L - 0.25±0.03 mg/L, which were within the acceptable limits of 0.4 mg/L set by the WHO. The concentrations of copper (Cu) and zinc (Zn) in the water samples ranged from 0.073–0.370 mg/L and 0.084–0.370 mg/L, respectively (Mong'are *et al.*, 2023). These levels are significantly lower than the WHO guideline limits of 2.0 mg/L for copper and 3.0 mg/L for zinc. This confirmed the safety of level of the water for human consumption and minimal contamination from anthropogenic sources. Mercury (Hg) was not detected in the water samples analyzed, indicating that its concentration is below the detection limit of the analytical method used and thus was within safe thresholds for human health as per WHO guidelines. The method used to analyze mercury may have had a detection limit higher than the actual mercury concentration in the water.

Rivers Naka and Irigu were analyzed using Atomic Absorption Spectroscopy (AAS), the concentrations of lead (Pb) in the water samples from River Irigu were measured at 0.765 ± 0.782 mg/L, significantly exceeding the WHO recommended standard of 0.01 mg/L for drinking water (Mutembei *et al.*, 2014). In contrast, River Naka showed Pb concentration of 0.0537 ± 0.103 mg/L, which is still above the standard but considerably lower than that of River Irigu. Both value above the WHO guideline of 0.01 ppm (Mutembei *et al.*, 2014). This indicated a serious potential health risk. The elevated lead concentration was linked to the effluents from Chuka Town that flow into the River Naka. These may contain lead from petrol stations, soldering, plumbing and car exhausts on the road. Corrosion from the metal linings of the pipes through which coffee berries move could be the source of excessive amounts of lead in River Irig (Mutembei *et al*., 2014).

Cadmium (Cd) levels were also raised a concern, with River Naka recording 0.003 ppm (exceeding the WHO limit of 0.005 ppm) and River Irigu at 0.005ppm (Mutembei *et al.*, 2014). The concentration of 0.1 ppm cadmium was reported by Favour & Obi, (2014) when they studied the levels of lead, iron and cadmium contamination in fish, water and sediment from Iwofe site on New Calabar River, Rivers State.

MP-AES was used to analyze water samples obtained from two lakes in Pusat Marin, Mg concentrations ranged from 0.62 to 1.47 mg/L (Jamari & Firdaus, 2024). Despite being the most abundant metal in all water samples, magnesium's content is not toxic to humans as long as dietary consumption does not exceed 400 mg (Jaishankar *et al.*, 2014).

Nickel (Ni) and copper (Cu) were not found in any of the samples obtained from the two lakes located in Pusat Marin (Jamari & Firdaus, 2024). The lack of detection of these metals could be attributed to the sensitivity and limitations of the MP-AES instrument used in the analysis. This method may have a detection threshold that is higher than the actual concentrations present in the samples, leading to non-detectable results. The concentration of aluminum (Al) in the water sample was measured at 0.02 mg/L, which is significantly lower than the World Health Organization (WHO) guideline limit of 0.90 mg/L for drinking water (Jamari & Firdaus, 2024). The low concentration suggests minimal contamination from anthropogenic sources, making the water source relatively safe in terms of aluminum exposure. To address the elevated levels of heavy metals detected in river water the following remediation strategies can be implemented;

VII. Remediation Strategies

Chemical precipitation

Adding chemicals like phosphate, charcoal, aluminum salts, silicocalcium materials, clay minerals and sulphides to stabilize and eliminate heavy metals from the environment is known as chemical remediation. These compounds' mechanisms of action include ion exchange, complexation, oxidation, reduction, adsorption and precipitation (Xu *et al.*, 2022). Chemical cleanup is a quick, easy and straightforward method, but the chemicals utilized can also pollute the environment (Xu *et al.*, 2022).

The most popular method for extracting dissolved (ionic) metals from solutions, like toxic metal-containing process wastewater, is chemical precipitation. The chemical reaction between the precipitating reagent and the soluble metal compounds transforms the ionic metals into an insoluble form (particle). By settling and/or filtering, the particles created by this reaction are extracted from the solution. Neutralization, precipitation, coagulation/flocculation, solids/liquid separation and dewatering are the unit operations usually needed in this technology (Dahman, 2017).

A number of variables affect how well a chemical precipitation process works, such as the kind and amount of ionic metals in the solution, the precipitant used, the reaction conditions (particularly the solution's pH) and the existence of additional substances that could prevent the precipitation reaction. The most popular chemical precipitation method is hydroxide precipitation, also known as precipitation by pH, in which calcium hydroxide (lime) or sodium hydroxide (caustic) is used as the precipitant to form metal hydroxides (Dahman, 2017).

Adsorption remediations

Activated carbon adsorption has unquestionably emerged as the preferred technique to counteract this issue. Adsorption is a more favoured option for heavy metal remediation than other physico-chemical methods because it is straightforward, affordable, easy to scale up and most importantly it can effectively remove substances with low concentrations, even at parts per million (Zain*i et al., 2010).*

Phytoremediation

In essence, phytoremediation is the process of using plants and related soil bacteria to lessen the levels of pollutants or their harmful effects in the environment (Ali *et al., 2013*). The uptake of heavy metals (HMs) through phytoremediation technology includes a number of processes, including phytoaccumulation, phytovolatilization, phytostabilization, rhizodegradation and phytoextraction (Tangahu *et al*., 2011). Certain plants used in phytoremediation have the capacity to absorb large amounts of heavy metals (HMs) into their roots, can withstand a variety of metals and have physiological traits that allow them to adapt to adjusting conditions (Prieto *et al.*, 2018). According to Eid *et al.*, (2020), certain aquatic hydrophytes, including *Eichhornia crassipes*, *Echinochloa stagnina*, *Ludwigia stolonifera* and *Phragmites australis*, have the capacity to accumulate Cd, Ni and Pb. These species can then be used to identify and phytoremediate wetlands that have been contaminated by heavy metals.

Electrokinetic Remediation

Electrokinetic is an innovative in situ method for decontaminating metals by applying a low-intensity direct current between suitably spaced electrode arrays through a porous solid medium and causes ions and water to migrate toward the electrodes, which is the basis of the electrokinetic remediation principle. Electromigration, or the movement of ions and electroosmosis, or the movement of liquid containing ions, are the two contributing processes that carry contaminants. The primary mechanism of the electro remediation process is electromigration. Additionally, the process is aided by additional electrolysis effects like complexation, adsorption, diffusion and precipitation reactions. Numerous techniques, including electroplating, precipitation or co-precipitation, water pumping close to the electrode and complexation with ion exchange resins, are used to remove contaminants at the electrode (Rodríguez *et al.*, 2014).

VIII. CONCLUSION

In conclusion, this study highlights the critical role of analytical tools in protecting public health and maintaining ecological integrity. The findings underscore the urgent need for effective strategies to combat heavy metal pollution, ensuring timely detection and remediation to mitigate the detrimental impacts on both human populations and the environment.

Declarations of conflict of interest

The authors report no financial or nonfinancial conflict of interest. The authors alone are responsible for the content and writing of the paper.

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