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A Comprehensive Review of Heavy Metals and Decontamination Efforts in Nigeria

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Abstract The objective of this review article was to provide a comprehensive summary and up-to-date overview of the current state of knowledge in heavy metals and decontamination efforts in Nigeria. The sources of heavy metals, both natural and anthropogenic, the toxicity effects, and water contamination in Nigeria have been examined in detail, as well as treatment technologies, primarily through biosorption. The literature has been reviewed, focusing on the removal of heavy metal ions using biological-based biosorbents. Key parameters, such as temperature, pH, and contact time, as well as biosorbent characteristics, have been investigated. Potential future research directions have been proposed.

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Heavy metals are naturally occurring elements known for their high atomic weight and density, which exceed those of water. Although these elements have inherent roles in various natural processes, their toxicological implications emerge when they accumulate in the environment at elevated concentrations (Oliomogbe and Emegha, 2024; Omonona *et al.*, 2020). This accumulation is frequently exacerbated by anthropogenic activities such as industrial manufacturing, mining, urbanization, and agricultural intensification, which mobilize these metals from geological matrices into ecosystems (Ukhurebor *et al.*, 2023a; Ukhurebor *et al.*, 203b). Consequently, heavy metals have become a pervasive environmental challenge, threatening ecosystems and human health on a global scale. The persistence of heavy metals in the environment and their tendency to bioaccumulate and biomagnify along food chains amplify their toxicity. Prolonged exposure to metals such as lead, mercury, cadmium, and arsenic has been linked to a spectrum of health disorders, ranging from neurological and developmental impairments to renal dysfunction, immunosuppression, and cancer (Oliomogbe *et al.*, 2024; Kurucz *et al.*, 2018). These health implications are not only a concern for direct exposure but also arise through secondary exposure routes, such as contaminated water, soil, and agricultural produce. From an ecological perspective, the impact of heavy metal contamination is equally severe. These metals disrupt the chemical balance of aquatic systems, reduce soil productivity, and alter the composition of

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microbial communities essential for nutrient cycling (Weissmannová *et al*., 2019). Biodiversity suffers as plant and animal species are unable to adapt to the toxicity levels in their habitats, leading to ecosystem imbalances and a decline in species populations. The damage is compounded by the difficulty of removing heavy metals once they have entered the environment, as they do not degrade and persist in various forms for decades.

In Nigeria, the issue of heavy metal contamination is particularly pronounced due to the country's economic reliance on resource extraction industries such as oil and gas production and mining (Ushie *et al.*, 2023). The Niger Delta region, home to Nigeria's vast petroleum reserves, highlights the intersection of economic progress and environmental degradation. Activities such as oil spills, the use of poorly regulated drilling techniques, and routine gas flaring introduce significant quantities of heavy metals like lead, chromium, and vanadium into the soil and water bodies of the region. These pollutants not only threaten the livelihoods of communities' dependent on agriculture and fishing but also have long-term implications for public health and ecosystem resilience (Idowu, 2022). The interplay between economic development and environmental sustainability in Nigeria exemplifies the broader global dilemma of balancing industrial growth with environmental preservation. Addressing this challenge requires a multi-faceted approach, including stringent regulatory frameworks, innovative remediation technologies, and community-based initiatives aimed at reducing heavy metal contamination and mitigating its impacts (Oliomogbe *et al.*, 2023). This review article starts with a general introduction section covering heavy metals, including their sources, toxicity, consequences, and biosorption characteristics. The use of biosorbents for the biosorption of aqueous heavy metal ions and other contaminants under different process conditions is also highlighted. The review establishes the knowledge gap between future perspectives and directions.

Sources of Heavy Metals: Natural and Anthropogenic

Natural Sources: Heavy metals are intrinsic components of the Earth's crust, entering the environment through natural geological and geochemical processes. One primary source is lithogenesis, where sedimentary rocks are formed from pre-existing materials. Over time, these rocks undergo weathering, breaking down into smaller particles that release metals such as radium and arsenic into soils, sediments, and groundwater systems (Lyu *et al*., 2019; Okonkwo and Okunlola, 2022). This natural leaching process contributes to the baseline levels of heavy metals within ecosystems, creating a geological footprint of their presence. Beyond lithogenesis, volcanic eruptions act as significant natural emitters of heavy metals. During eruptions, molten magma releases gases and particulates rich in metals such as mercury and lead, dispersing them over large distances and depositing them in terrestrial and aquatic environments. Other geochemical processes, such as soil erosion and sediment resuspension, further mobilize heavy metals from their geological reservoirs. Atmospheric deposition, where particles laden with heavy metals settle onto surfaces from the air, also contributes to their environmental presence (Ukhurebor *et al.*, 2021). While natural sources generally contribute to background concentrations of heavy metals, their ecological impact can still be significant, particularly in areas with high geological activity or unique mineral compositions. However, these natural inputs are often overshadowed by the far more pervasive effects of anthropogenic activities, which introduce metals at concentrations that far exceed natural baselines (Saha *et al*., 2022).

Anthropogenic Sources: Human activities have exponentially increased the levels and distribution of heavy metals in the environment, driven by industrialization, urbanization, and modern agricultural practices (Emegha *et al.,* 2024a; Egboduku *et al.*, 2023). Key contributors include industrial discharges, mining, vehicular emissions, and improper waste disposal. Industries such as metal smelting, petrochemical refining, and textile manufacturing release significant quantities of metals into nearby soils, air, and water bodies (Stepanova *et al*., 2021; Shimod *et al*., 2022). Similarly, the extraction and processing of minerals mobilize heavy metals from ore bodies, introducing them into the surrounding environment through tailings and leachates. In agriculture, the widespread use of chemical fertilizers, pesticides, and biosolids enriches soils with heavy metals such as cadmium, arsenic, and lead. This contamination often extends to surface water and groundwater through agricultural runoff, threatening aquatic ecosystems and water supplies (Perumal *et al*., 2021; Ukhurebor *et al.*, 2020). The application of animal manure and sewage sludge further compounds soil contamination, as these materials often contain trace metals accumulated from livestock feed or industrial wastewater. Urban environments contribute heavily to heavy metal pollution through vehicular emissions, construction activities, and runoff from paved surfaces. Lead, zinc, and copper, for instance, are commonly deposited near roadways and urban centers due to the wear and tear of tires, brake pads, and vehicle engines (Akinnifesi *et al*., 2021). Additionally, atmospheric deposition from industrial emissions introduces heavy metals to areas far removed from their point of origin. In Nigeria, the oil and gas sector is a particularly significant source of heavy metal pollution. Frequent oil spills, a recurring issue in the Niger Delta, release hazardous metals such as mercury, vanadium, and chromium into soils and waterways, contaminating ecosystems and posing severe health risks to local communities. Gas flaring, a routine practice in oil extraction, introduces airborne pollutants, including heavy metals, into the atmosphere, which subsequently settle in nearby environments (Egbon and Mgbame, 2020). Small-scale industries and informal economic activities further exacerbate heavy metal contamination. For instance, artisanal mining, which is prevalent in several Nigerian states, uses rudimentary methods that release significant amounts of heavy metals into the environment. Additionally, urban mechanics and small workshops often improperly dispose of used motor oil, batteries, and electronic waste, contributing to localized contamination hotspots (Kaur *et al*., 2023).

Environmental and Ecological Implications of Heavy Metals: The release of heavy metals into the environment has far-reaching consequences, both for ecological systems and human health. In aquatic ecosystems, heavy metals accumulate in sediments, plants, and animals, disrupting food chains and reducing biodiversity. Fish and other aquatic organisms, such as catfish in Nigerian water bodies, often bioaccumulate toxic metals, posing risks to human consumers (Wu *et al*., 2018). Similarly, contaminated agricultural soils reduce crop productivity and transfer metals into the food chain, affecting food security and safety. The Niger Delta region exemplifies the intersection of industrial activity and environmental degradation, where oil spills and gas flaring have extensively polluted wetlands and water resources. The resulting contamination has rendered soils infertile, decimated fish populations, and increased health risks for communities' dependent on natural resources for their livelihoods (Ebuete *et al*., 2019).

The global demand for gold has driven millions into artisanal gold mining, especially in developing countries where economic opportunities are limited. However, this practice, often characterized by unregulated operations and rudimentary techniques, has profound consequences for environmental sustainability and human health. Artisanal gold mining, though a significant livelihood source for many, is a primary contributor to environmental degradation, particularly through heavy metal pollution. In regions where regulatory oversight is weak, these impacts are further exacerbated, posing severe risks to ecosystems and local communities (Yahaya *et al*., 2023).

During the mining process, significant quantities of heavy metals, including mercury, lead, cadmium, and arsenic, are released into nearby rivers and streams. These contaminants persist in aquatic systems, bioaccumulating in fish and other aquatic organisms, thereby jeopardizing entire food webs. Communities relying on these water sources for drinking, fishing, and agriculture face acute risks from degraded water quality and toxic exposures (Orosun *et al*., 2023). The land degradation caused by artisanal gold mining is equally troubling. Mining operations frequently disturb vast areas of soil, leaving behind contamination that can persist for decades. These soils often contain elevated levels of heavy metals, impairing their fertility and making them unsuitable for agriculture. The resulting sedimentation and soil erosion further exacerbate environmental harm, leading to the degradation of surrounding landscapes and threatening biodiversity (Ukhurebor *et al.*, 2022; Fagbenro *et al*., 2021). An often-overlooked aspect of artisanal gold mining is the hazardous disposal of mine tailings waste generated during the gold extraction process. These tailings frequently contain high concentrations of toxic metals and other chemicals, which leach into the environment, polluting both surface and groundwater systems. Moreover, the tailings contribute to greenhouse gas emissions, amplifying their negative impact on global climate systems. This dual threat of localized pollution and global climate implications underscores the extensive footprint of artisanal mining (Munganyinka *et al*., 2022).

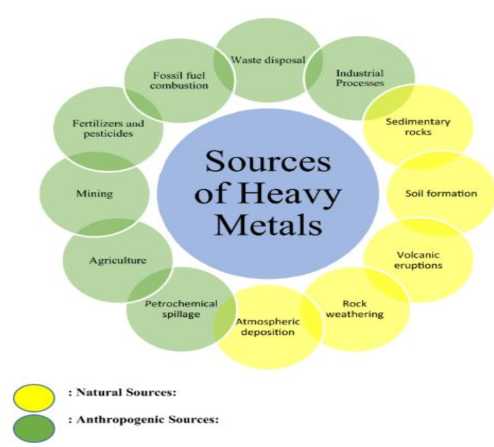

Fig. 1: Sources of Heavy metals pollution **(**Nnaji *et al*., 2023)

The health risks associated with heavy metal are significant. Mercury, widely used in gold extraction, is particularly dangerous. Its release into the environment can lead to widespread contamination, affecting miners and local populations. Direct inhalation of mercury vapor during gold processing is a common exposure pathway, leading to neurological disorders and other chronic health conditions. Additionally, mercury can transform into methylmercury in aquatic environments, where it enters the food chain, posing long-term health risks to consumers of contaminated fish (Munganyinka *et al*., 2022). Contaminated soil and water also pose indirect health risks by infiltrating local food systems. Crops grown in heavy-metal-laden soils can absorb toxic elements, resulting in unsafe food that endangers consumer health. This contamination not only threatens human health but also disrupts local economies dependent on agriculture. Declining soil fertility and polluted water sources diminish agricultural productivity, compounding the socioeconomic hardships faced by affected communities (Timsina *et al*., 2022).

Sensitive species are particularly vulnerable, and their population declines can disrupt the ecological balance, affecting ecosystem services and overall resilience. Moreover, contaminated sediments in river systems act as reservoirs of pollutants. These sediments can be resuspended during floods or human activity, reintroducing toxins into the water column and perpetuating ecological damage over time (Orosun *et al*., 2023). The structural instability of artisanal mining sites adds another layer of environmental and safety concerns. Open pits and abandoned mine shafts left behind by miners increase the risk of land subsidence and accidents, creating long-term hazards for nearby communities. These features also alter natural landscapes, leading to habitat destruction and further endangering wildlife.

Heavy Metals and water Contamination in Nigeria: Wastewater is a major environmental concern in Nigeria, serving as a significant source of heavy metals, chemical contaminants, and biological hazards. The improper treatment and disposal of wastewater have led to the contamination of water bodies, soil, and agricultural land, posing serious risks to both human health and the environment. Numerous studies have documented the presence of various contaminants, including heavy metals, pharmaceutical residues, and antibiotic-resistant bacteria, in wastewater discharges across Nigeria, highlighting the urgent need for effective treatment and management systems (Badejo *et al*., 2021). The discharge of untreated or inadequately treated wastewater into Nigeria's water bodies is a growing issue that continues to impact public health. It is common for wastewater from hospitals, industries, and agricultural runoff to be released into the environment without appropriate treatment processes (Osunmakinde *et al*., 2021). This practice not only leads to the contamination of aquatic ecosystems but also affects the surrounding soil, contributing to the buildup of harmful substances such as heavy metals and pharmaceutical residues. These pollutants pose significant health risks, as they can enter the human food chain through contaminated drinking water, seafood, and crops. The presence of heavy metals in wastewater has been a particular focus of research due to its toxic nature and persistence in the environment. Heavy metals such as lead, mercury, cadmium, and arsenic are frequently found in wastewater, originating from industrial discharges, mining operations, and the use of chemicals in agriculture. These metals do not biodegrade and can accumulate in water bodies and agricultural soils over time. In Nigeria, the contamination of agricultural soils with heavy metals has raised concerns about food safety, particularly regarding the accumulation of these metals in crops and vegetables (Okafor *et al*., 2023). This contamination poses a threat not only to human health through direct consumption but also to the broader ecosystem, as heavy metals can affect soil fertility and biodiversity.

One of the key areas of concern is the use of wastewater in irrigation, which has become a common practice in many parts of Nigeria. Wastewater is often used to irrigate crops, especially in areas where fresh water is scarce or where access to proper irrigation systems is limited. While this may offer short-term economic benefits, it carries significant long-term environmental and health risks. Studies have shown that the use of wastewater in agriculture can lead to the contamination of both soil and crops with heavy metals, antibiotics, and other toxic substances (Xie, 2024**;** Samuel *et al*., 2022). The resulting contamination can reduce the quality of agricultural produce, affecting both the safety and nutritional value of the food. For instance, research on the impact of wastewater on fruit quality attributes has highlighted the negative effects on mango cultivars, with wastewater containing high levels of heavy metals leading to reduced fruit quality (Anjum *et al*., 2021). This has raised concerns regarding the safety of consuming fruits and vegetables irrigated with contaminated water. The presence of pharmaceutical residues in wastewater is another critical concern. Hospitals and pharmaceutical industries contribute to wastewater contamination through the discharge of expired or unused medications, along with other pharmaceutical byproducts. These compounds, including antibiotics, hormones, and other chemical residues, can persist in water systems and contribute to the emergence of antibiotic-resistant bacteria (Badejo *et al*., 2021). The proliferation of antibiotic-resistant microorganisms in wastewater poses a serious challenge to public health, as these resistant bacteria can spread through water systems, making infections harder to treat. Given the widespread impact of wastewater contamination, it is essential to develop and implement comprehensive treatment strategies to remove harmful contaminants, including heavy metals, pharmaceuticals, and pathogens. Current treatment systems in Nigeria are often inadequate due to insufficient infrastructure, lack of maintenance, and limited technical expertise. As a result, untreated wastewater continues to pose a significant environmental hazard. The development of more efficient and sustainable wastewater treatment technologies is critical to reducing the levels of contaminants in water and improving the overall quality of water resources in the country (Ahmad *et al*., 2021). To address the environmental and public health challenges posed by wastewater, several steps can be taken. These include the establishment of stricter regulations on wastewater disposal, the promotion of sustainable agricultural practices, and the expansion of wastewater treatment facilities. Additionally, there is a need for greater public awareness about the risks associated with wastewater contamination and the importance of proper waste management practices. Ultimately, addressing the issue of wastewater contamination requires a multi-faceted approach that combines technological advancements, regulatory frameworks, and public participation in water quality management.

Heavy Metal Biosorption: Biosorption is a complex, multi-step process in which various biological materials, including plant biomass, algae, and microorganisms, adsorb and accumulate pollutants from aqueous solutions. This technique, widely applied for the removal of heavy metals and organic contaminants, functions through various physical and chemical interactions between the contaminants and functional groups on the biosorbent surface. The mechanism of biosorption can be considered a dynamic process that involves several phases, including adsorption, reduction, and the possibility of desorption. The biosorption of heavy metals, such as hexavalent chromium (Cr (VI), involves intricate interactions between the contaminant ions and the surface of the biosorbent, which significantly influence the efficiency and effectiveness of the treatment process. The first phase of the biosorption mechanism involves the adsorption of metal ions onto the surface of the biosorbent. For example, hexavalent chromium, which commonly exists as anionic Cr(VI) in aqueous environments, interacts with the positively charged functional groups present on the surface of biosorbents, such as hydroxyl (-OH), carboxyl (-COOH), or amino (-NH_2) groups. These functional groups on the biosorbent surface are capable of attracting and binding the metal ions through electrostatic forces, van der Waals forces, and hydrogen bonding (Emegha *et al.*, 2023). This initial attraction between the biosorbent and the metal ion is a key step in the uptake process, where the contaminant is held on the surface of the biosorbent, forming a complex structure (Ren *et al*., 2022). Following the adsorption phase, the process of reduction plays a critical role in the transformation of Cr (VI) into its less toxic, more stable trivalent form, Cr (III). Cr (VI) is a potent carcinogen and highly mobile in water, while Cr (III) is less soluble and significantly less toxic. During the reduction phase, electron transfer occurs from the biosorbent surface or associated microbial agents to the Cr (VI) ions, reducing them to Cr (III). This transformation is typically facilitated by electron-rich sites on the biosorbent or through microbial activity that provides the necessary electron donors. The reduction of Cr (VI) to Cr (III) is essential for rendering the treated water safer, as Cr (III) is less likely to cause environmental or health hazards (Ren *et al*., 2022). The final stage of the biosorption mechanism involves either the stabilization of the adsorbed Cr (III) ions on the biosorbent surface or their potential desorption into the surrounding solution. The binding of Cr (III) to the biosorbent may occur through ion-exchange reactions, coordination with negatively charged sites, or complexation with functional groups on the biosorbent. This interaction creates a stable bond, preventing the release of the metal ion back into the solution. However, under certain conditions, such as changes in pH or ionic strength, desorption can occur, releasing the adsorbed Cr (III) ions back into the solution. Factors such as the concentration of competing ions, temperature, and pH levels can influence this desorption process, making it crucial to carefully control the operating conditions to maximize the efficiency of biosorption (Qasem *et al*., 2021). One of the distinctive features of biosorption is its reversibility, which offers the potential for regenerating biosorbents. This is particularly advantageous in large-scale industrial applications where biosorbents can be used cyclically for the removal of heavy metals. Regeneration typically involves altering the environmental conditions, such as adjusting the pH, ionic strength, or temperature, to disrupt the interactions between the metal ions and the biosorbent, allowing for the release of the metal ions and the reuse of the biosorbent. This process of desorption and regeneration ensures that biosorbents can be efficiently reused, reducing the cost and increasing the sustainability of the treatment process. Biosorption occurs naturally in certain types of biomass, such as algae, fungi, and bacterial species, which have evolved the ability to accumulate heavy metals from their surroundings (Emegha *et al.*, 2024b) these biomasses possess a range of chemical and physical properties, such as high surface area and functional groups, that enable them to bind heavy metals effectively. In addition to these natural biosorbents, researchers have explored the use of modified biosorbents, which are chemically or physically altered to enhance their capacity to adsorb pollutants. This modification increases the surface area, introduces additional functional groups, and can improve the selectivity of biosorbents towards specific contaminants, thereby enhancing their performance in wastewater treatment (Wang *et al*., 2017). Although biosorption offers numerous advantages, such as low cost, environmental sustainability, and high specificity for heavy metals, it also has certain limitations. The adsorption capacity of biosorbents is often lower than that of synthetic adsorbents, which may reduce the overall efficiency of the process, especially when dealing with high concentrations of contaminants. Additionally, the biosorption process can be slow, requiring extended contact times between the contaminant and the biosorbent to achieve optimal removal rates. The efficiency of biosorption is also highly dependent on environmental factors such as pH, temperature, and the presence of competing ions, which can interfere with the biosorption process. As such, it is essential to optimize these conditions for each specific application to ensure the most effective and efficient removal of pollutants (Ordóñez *et al*., 2023).

Types of Biosorbent Materials: Biosorbents are naturally occurring or engineered materials derived from biological sources that are utilized for the removal of contaminants, particularly heavy metals, from wastewater. The types of biomass used as biosorbents are highly varied and include plant residues, agricultural byproducts, fungal biomass, algae, and microbial materials, as well as more recently, nanomaterials synthesized through environmentally friendly methods (Buhani *et al*., 2023). The versatile properties of biosorbents make them an attractive alternative to traditional chemical methods for pollution control, offering an eco-friendly, cost-effective, and sustainable solution for treating wastewater contaminated with toxic metals. The efficiency of biosorbents in removing heavy metals largely stems from the specific characteristics of the biomass, which possess various functional groups such as hydroxyl, carboxyl, and amino groups. These groups facilitate interactions with metal ions through processes like adsorption, ion exchange, and complexation (Blaga *et al*., 2021). Over the years, researchers have demonstrated that a wide variety of microorganisms, algae, fungi, and even plant-based materials can serve as effective biosorbents, depending on the type of contaminants present in the wastewater (Oyewole *et al*., 2019). Biosorption operates through two major mechanisms: metabolism-dependent and metabolism-independent. The metabolism-dependent mechanism involves the active processes of living organisms, such as microorganisms or plant roots, to uptake and accumulates metals. This process often requires energy and is regulated by the biochemical activities of the organism. On the other hand, metabolism-independent biosorption refers to the passive interaction of non-living biomass with metal ions, where uptake occurs through physical interactions such as electrostatic forces, surface complexation, or adsorption (Blaga *et al*., 2021; Abdelhamid *et al*., 2021). These two mechanisms work synergistically to enhance the overall efficiency of biosorption, making it a versatile and adaptive process for metal removal. One of the key factors influencing the effectiveness of biosorbents is the surface chemistry of the material. Biomass materials, such as plant residues or microbial cells, contain functional groups like carboxyl, hydroxyl, and amine groups, which readily interact with metal ions. These functional groups play a crucial role in the biosorption process, as they serve as binding sites for metal ions, facilitating their removal from the wastewater. Characterizing the surface functionality of biosorbents is essential for understanding how they interact with pollutants. Techniques such as Fourier-transform infrared spectroscopy (FTIR) are commonly employed to identify these functional groups and to assess their role in the biosorption process (Blaga *et al*., 2021). Biosorbent materials can be broadly classified into several categories based on their origin and chemical structure. Among the most widely used biosorbents are those derived from cellulose-based materials. Cellulose is a naturally abundant biopolymer found in plant cell walls and is an excellent candidate for biosorption due to its high availability, low cost, and biodegradability. Various plant-derived cellulose materials, such as cotton fibers, banana peels, wheat husks, and coconut shells, have shown promising results in removing heavy metals from wastewater. These materials are often preferred for their eco-friendly nature and their ability to function as a low-cost alternative to synthetic adsorbents (Abdelhamid *et al*., 2021). In addition to cellulose materials, activated carbon is another widely used biosorbent. Derived from carbon-rich materials such as wood, coal, or coconut shells, activated carbon has a highly porous structure that provides an extensive surface area for the adsorption of contaminants. It is especially effective in removing organic pollutants and heavy metals from wastewater. However, despite its efficiency, activated carbon is often expensive, which limits its use in large-scale applications where cost-effectiveness is a major concern. A newer class of biosorbents that has gained significant attention in recent years is green-synthesized nanomaterials. These nanomaterials are typically synthesized using biological methods, such as plant extracts or microorganisms, which makes them environmentally benign and sustainable. Due to their high surface area and reactive properties, these materials offer superior adsorption capabilities compared to traditional biosorbents. Green-synthesized nanomaterials have shown great potential for removing a wide range of contaminants, including both metals and organic pollutants, from wastewater (Yaashikaa *et al*., 2021). Additionally, their small size and high reactivity allow them to interact with contaminants at a molecular level, enhancing their adsorption efficiency. Zeolites, a naturally occurring class of aluminosilicate minerals, are also used as biosorbents due to their unique structure and high ion-exchange capacity. Zeolites have a three-dimensional, crystalline framework that provides numerous micropores, which enable them to adsorb metal cations effectively. They are especially effective for removing ions such as lead (Pb), copper (Cu), and cadmium (Cd) from contaminated water. Moreover, modified zeolites, which have been treated or functionalized to enhance their biosorption capacity, have demonstrated increased efficiency in the removal of both cations and anions, as well as organic pollutants (Huang *et al*., 2020). The natural availability of zeolites, along with their high reusability and ability to treat large volumes of wastewater, makes them an attractive option for both small-scale and industrial wastewater treatment systems.

Factors Influencing the Biosorption of Heavy Metals: The efficiency of biosorption, a promising method for removing heavy metals from aqueous solutions, depends on a variety of factors. These include the pH of the solution, temperature, contact time, and the amount of biosorbent material used. Each of these factors interacts with the chemical nature of both the biosorbent and the metal ions, influencing their binding affinity and the overall effectiveness of the biosorption process (Ukhurebor *et al.*, 203b; Ukhurebor *et al.*, 2024).

pH of the Solution: One of the most crucial parameters affecting the biosorption of heavy metals is the pH of the solution. The pH determines the ionization state of both the biosorbent's functional groups and the metal ions in solution. The biosorption process typically improves as the pH decreases, primarily because many biosorbent materials contain acidic functional groups (such as carboxyl, hydroxyl, and phosphate) that become negatively charged in acidic environments. This negative charge enhances the attraction between the biosorbent and positively charged metal ions, thereby increasing the biosorption efficiency (Bamisaye *et al*., 2023).

However, the relationship between pH and biosorption is not linear and can become more complex at very low pH levels. Under highly acidic conditions, metal hydroxides may precipitate out of the solution, which reduces the concentration of free metal ions and consequently the availability of metal ions for biosorption (Gadd, 2008). On the other hand, at higher pH levels, certain functional groups on the biosorbent, such as amino groups, may become neutral, diminishing their ability to interact with the metal ions. This shift can reduce the biosorption capacity, especially when the metal species are less prone to bind with the functional groups of the biosorbent (Yu *et al*., 2021). Thus, optimizing the pH is essential for maximizing the biosorption capacity and ensuring the stability of the biosorbent throughout the process.

Temperature Effects: Temperature is another significant factor influencing the biosorption of heavy metals, as it directly impacts both the biosorbent’s surface activity and the diffusion rates of metal ions. The effect of temperature on biosorption can vary depending on whether the process is endothermic (heat-absorbing) or exothermic (heat-releasing). In endothermic biosorption processes, higher temperatures typically increase the rate and capacity of metal ion removal, as the added thermal energy facilitates the interaction between metal ions and the biosorbent (Oliomogbe *et al.*, 2024). In contrast, exothermic processes tend to show reduced efficiency as the temperature rises, as the process is more favorable at lower temperatures. For instance, research has shown that while moderate temperature fluctuations (between 20°C and 35°C) may not have a significant impact on biosorption, excessive heat can reduce the efficiency of some biosorbents. Studies by Bamisaye *et al*. (2023) and Olukanni *et al*.

(2014) on biosorbents such as peanut shells and *Pseudomonas aeruginosa* demonstrated that as the temperature increases, the biosorption of lead (Pb) and other heavy metals can decrease, especially when the process is exothermic. These findings underscore the importance of maintaining an optimal temperature range to maximize biosorption efficiency.

Contact Time: Contact time, the duration for which the biosorbent and metal ions are in contact, is another critical factor in determining the success of biosorption. While it does not directly affect the biosorbent's inherent capacity, longer contact times generally allow for more extensive interaction between the biosorbent and metal ions, leading to higher adsorption. This extended interaction provides more time for metal ions to diffuse into the pores of the biosorbent material and bind to its active sites. However, beyond a certain point, the process reaches equilibrium, where all available binding sites on the biosorbent become saturated. At this stage, extending the contact time will no longer increase the metal uptake and can be inefficient (Adewuyi, 2020). Kanu *et al*. (2015) observed that with Rooibos shoot powder (RSP), biosorption of lead ions (Pb (II)) showed rapid uptake within the first 60 minutes, after which the rate of adsorption slowed significantly, signaling that the maximum adsorption capacity had been reached. Thus, identifying the optimal contact time is essential to avoid wasteful prolongation and to ensure that the biosorption process is both effective and efficient.

Biosorbent Dosage: The amount of biosorbent used, also known as the biosorbent dosage, plays a significant role in the overall biosorption efficiency. As the dosage of biosorbent increases, the available surface area and number of binding sites also increase, leading to enhanced biosorption capacity. This is particularly important when dealing with multiple metal contaminants, as a higher dosage reduces competition for the biosorbent's active sites, allowing more metal ions to be absorbed (Mehrotra *et al.*, 2021; Ali Redha *et al*., 2020).

However, the relationship between biosorbent dosage and metal ion removal is not always linear. Beyond a certain point, increasing the dosage may lead to diminishing returns, as the biosorbent may become saturated, and additional biosorbent material may not significantly improve the removal efficiency. Moreover, in systems with complex contamination, an excessively high biosorbent dosage could lead to difficulties in separating the biosorbent from the treated solution, complicating the overall process. Singh *et al*. (2021) demonstrated that a biosorbent dose of 2 g/L was optimal for the removal of Cr (VI) using chitosan-coated MnO_2 nanoparticles, beyond which no significant improvement in the removal efficiency was observed. This highlights the importance of balancing biosorbent dosage to maximize both the biosorption efficiency and the practicality of the process.

C*onclusion:* Nigerian water contamination has gained international attention due to the presence of heavy metal ions from both natural and man-made sources. The binding of heavy metal contaminants to various biosorbents was examined in this review. Temperature, pH, and ionic strength all had a major impact on the adsorption process. To fully understand the components and effectiveness of heavy metal biosorbents in terms of adsorption or removal, more research is essential. It is expected that more selective adsorbents will be developed from further research, which will also help to clarify the underlying biosorption mechanisms.

Declaration of Conflict of Interest: The authors declare that there is no conflict of interest.

Data Availability: Data are available upon request from corresponding author.

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