



## Bioremediation of heavy metal ions from contaminated soil and water by microbes: A review

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### Abstract

Scientists all over the world are working tirelessly on the management of environmental toxicants and their control over the past two decades due to their injurious effects on plants, animals, and humans. These calcitrants released to the environment from both anthropogenic industries and natural sources can enter the food chain. The removal of such xenobiotic materials such as heavy metals from the soil and water around industrial areas has received great attention nowadays globally. It is, therefore; against this backdrop that this review research was conducted solely to establish the potentials of microorganisms (algae, fungi, bacteria, and plants) in the bio-removal of heavy metals contaminated soils and water. The study revealed that the use of these microbes in the decontamination of the environment cannot be overemphasized hence cost-effective, eco-friendly, and available almost everywhere on planet earth.

**Keywords:** *Bioremediation, Heavy metals, Xenobiotics, Wastewater sludge, Phytoremediation*

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### 1. Introduction

Much research had been focused on the management of environmental toxicants and their control over the past two decades due to their injurious effects on plants, animals, and humans as well. These hazardous materials released to the environment from both anthropogenic and natural activities had the potential to enter the food chain. The removal of such xenobiotic materials such as heavy metals from the soil and water around industrial areas has been a major challenge. The major focus on remediation of toxic heavy metals was but not limited to the following; mercury, lead, and chromium due to their devastating impact on the environment. Some of the deleterious effects of cadmium on lives include both acute and chronic malfunctions, such as *itai-itai* disease, renal damage, emphysema, hypertension, and atrophy (Nanganuru et al., 2012). Although there are various definitions of what heavy metal is, density has been a yardstick in establishing what heavy metal is. Heavy metals are best defined as those metals with a specific density exceeding 5 g/cm<sup>3</sup> and having atomic weights between 63.5 and 200.6. With the rapid infrastructural and industrial developments

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such as metal plating facilities, mining operations, fertilizer industries, tanneries, batteries, paper industries, and pesticides, etc., heavy metals' sludge is continually discharged indiscriminately into the environment (Fu and Wang, 2011). Some of the risks posed to human health from these xenobiotic materials are associated with exposure to cadmium, lead, mercury and arsenic (although arsenic is a metalloid, it is normally categorized as heavy metal). The use of heavy metals in different industries over the past centuries across the globe cannot be overemphasized. Lead which has been used for over 5000 years had its initial applications including building materials, pigments for glazing ceramics, and pipes for transporting water. Cadmium pigments were used largely in the artists' material works in the mid-1800s but their scarcity hindered the progress of the industry in the early 1900s (Zeitoun and Mehana, 2014). Despite the threats to human health emanating from exposure to heavy metals, their indiscriminate disposal to the environment is still on the rise in many parts of the world. A clear indication of some of these pollutants in the environment is the use of mercury in gold mining in many parts of Latin America. Arsenic is still widely used in wood preservatives and tetraethyl lead is one of the main additives to petrol even though some countries have drastically reduced its usage to mitigate the concomitant emissions to the environment and human health implications involved (Zeitoun and Mehana, 2014).

Treating soil and wastewater sludge laden with heavy metal ions (HMs) is a daunting task as it greatly depends on techno-economic, environmental, and social considerations. Therefore, the challenges require the development of a single technology that can treat a large number of wastewater effluents and at the same time able to curtail soil, water, and atmospheric pollution. Examples of the previously commonly used HM removal (HMR) technologies include chemical precipitation, coagulants/flocculants, membrane filtration, ion exchange, photocatalysis, and adsorption to inorganic materials. Merits that are derived from the use of these conventional methods include rapid processing time, controllability, resilience to the high concentration of HMs, ease of operation, and well understood molecular basis. While most of these conventional methods can remediate HMs extremely well, their side effects would result to the production of waste by-products that are difficult to dispose. Further, they require a large amount of energy which may be cost-prohibitive, and more importantly, most of them may be unsustainable as they require the use of materials that are derived from non-renewable resources like coal and oil (Diep et al., 2018). Therefore, research has been shifted nowadays towards the use of microorganisms due to their eco-friendly, their availability, and the ease with which they can grow in a wide range of environmental conditions (Abatenh, 2018). Microbial activities are of great importance in establishing the extent to which metals move in the environment and can be harnessed for their potential application in bioremediation. Processes such as autotrophic and heterotrophic leaching mechanisms, reductive precipitation, sulfate reduction, and metal sulfide precipitation are vital in the bioremediation of metal pollution (Umrana, 2006). Bioleaching of heavy metal toxicants, bio-oxidation of gold ores, desulfurization of coal and oil, tertiary recovery of oil, and biosorption of metal ions are examples of many varieties of potential and actual applications of microbes in mining and other related industries (Nanganuru et al., 2012). Bioremediation involves the use of microorganisms to clean up contaminated water or soil, whereby the microbes utilize the pollutant as a source of energy or as nutrients. For the successful implementation of bioremediation technology, there is a great need to incorporate the following three main components. The three main components are; the microorganisms, a food source, and nutrients (Kumar et al., 2011). Further work was carried out on the use of microorganisms for removal of contaminants and was analyzed by Nies and three prospective uses were identified: (1) Biotechnological processes can be enhanced by the addition of metal resistance microorganisms. (2) Expensive metals could be recovered from environmental sources through bioleaching with metal resistant bacteria. (3) Bioremediation of metal-contaminated environments could be possible through metal tolerant microorganisms. Although many bacterial strains have been very useful in bioremoval processes, some of them can only function well in laboratory conditions. Some of the factors that militate against the use of bacteria as biosorbents for heavy metals include pH, soil structure, nutrient availability, temperature, and the presence of other toxins and contaminants. In laboratory conditions, these factors are provided in the right amount and are easily controlled for the effective functioning of bacteria during the bioremediation process. However, in the environmental setting, these factors are difficult or no longer controlled thereby affecting the performance of microbes for their tolerance and use in bioremediation of hazardous metals (Kumar et al., 2011; and Johnson and Johnson, 2016). Different materials that are of biological origin are good biosorbents. Some of them are low-cost and high-cost biosorbents. For the low-cost biosorbents, biomaterials are by-products or waste products emanating from industrial activities such as yeast from brewery plants, wastes from agriculture and food industries, seaweeds, and crab shells. In some instances, biosorption properties of sorbents from this group of biomaterials are rather weak, ca. 20 mg metal/g d.w. biomass. High-cost biosorbents include biomass which

is designed specifically for biosorption with some special characteristics such as having very high biosorption capacity (200 mg/g). They should also have high potential to attract sorbate so that even at very low concentrations of metal cations, biosorption efficiency would be high. One example of such biosorbents is the microalgae *Spirulina specie*. Another very important process of metal ions recovery is bioaccumulation. Extracted metal ions are attached exteriorly on the cell in the first, passive stage, which resembles biosorption, and then are carried (transported by active transport system, which requires extracellular energy) to the interior of the cell (Chojnacka, 2007). Thus, part of the metal cation is bound extracellularly while the other part remains in the interior of the cell thereby making elution processes effective in removing only the part of metal bound to the surface of the cell. In such cases, destructive methods such as combustion of the biomass and reuse of metal-laden ash would be best for complete metal ions recovery. Although bioaccumulation enhances the remediation of metal cations to very low levels as compared to biosorption, it is more complex as it involves the use of living organisms (Amin Al Sulami, 2015). The manufacturing of energy from nuclear power plants, uranium mining, nuclear weapons production, and accidents release large amounts of radionuclides into the environment (Amin Al Sulami, 2015). The microbial technologies involved in the bioremediation of hazardous metals and radionuclides from waste streams employ living cells, non-living biomass, or biopolymers as biosorbents. Extensive research had been carried out on the use of fungi, algae, bacteria and plants as the most suitable biosorbents for heavy metals' remediation (Umrana, 2006; and Johnson and Johnson, 2016). The aim of this study is to show the potentials of microorganisms (algae, fungi, bacteria and plants) in bioremoval of heavy metals contaminated soils and water.

## 2. Use of algae in bioremediation

Conventional technologies, such as ion exchange or lime precipitation, are often ineffective and/or expensive, mainly for the removal of heavy metal ions at low concentrations (below 50 mg/L) (Dwivedi, 2012). Most of the biological treatment knowhow involves the use of bacteria, but microalgae have already been applied for effluent treatment, either as single species, as is the case of *Chlorella*, *Scenedesmus* or *Arthrospira*, *Spirulina sp.*, *Chlorella*, *Scenedesmus*, *Cladophora*, *Oscillatoria*, *Anabaena*, *Phaeodactylum tricornutum* (Lee and Lee, 2001; Mulbry, 2001; and Bwapwa et al., 2017) or as mixed cultures/consortia (Mulbry, 2001; Ogbonna, 2000; and Tarlan, 2002) to treat and remove nitrogen, phosphorus, and chemical oxygen demand, from diverse types of effluents. These organisms are also capable of removing and incorporate heavy metals, such as lead (Aksu and Kustal, 1991). Amongst the numerous microalgae used to treat effluents, *Chlorella* is found to grow in a mixotrophic environment (Karlander and Krauss, 1996). The industrialization has led to a surge in the discharging of pollutants into ecosystems. Metal pollutants can enter the food chain if heavy metal-contaminated soils are used for the production of food crops (Gosavi et al., 2004). The buildup of toxic metals such as Mercury, Copper, Cadmium, Ni, Chromium, Zinc others in humans has several health consequences such as growth and developmental abnormalities, carcinogenesis, neuromuscular control defects, mental retardation, renal malfunction, embryotoxic, teratogenic and wide range of other illnesses. Higher levels of such metallic ions are mostly toxic and cause major damage to cells and the general well-being of that individual (Dwivedi, 2012). Cadmium (Cd) is carcinogenic, embryotoxic, teratogenic, and mutagenic and may cause hyperglycemia, reduced immune-potency, and anemia, due to its interference with iron metabolism. The toxicity of Cd has also been well documented in other eukaryotes (Rainbow, 1995; and Dwivedi, 2012). Nickel contamination may come from desorption and uptake of the metal to natural waters from the earth's crust after the global climatic change or from growing electroplating/steel industries. It can cause contact dermatitis, predominantly in young women using nickel-containing earrings. Acute inhalation contact to nickel can cause metal fume fever and acute exposure to nickel carbonyl can cause pneumonitis, nephrotoxic, hepatotoxic, immune-toxic, and teratogenic (Ross, 1995; and Dwivedi, 2012). Algae especially those species of *Chlorella*, *Anabaena inaequalis*, *Westiellopsis prolifica*, *Stigeoclonium tenue*, *Synechococcus sp.* accumulate heavy metals. However, several species of *Chlorella*, *Anabaena*, marine algae have been employed for the removal of heavy metals. But the operating condition limits the practical application of these organisms (Rai et al., 1998; and Dwivedi, 2012). They have a great ability for the removal of excess nitrogen and phosphorus from wastewater including the farm runoff. They can capture carbon dioxide as well in the flue gas from coal-fired power plants thereby sinking greenhouse gas and also producing algal biomass, which can be changed into biofuel *Chlorella*, *Scenedesmus* and *Spirulina* are the most widely used algae for nutrient removal (Dwivedi, 2012). Metals are taken up by these algae through their adsorption process. At first, the metal ions are adsorbed over their cell surface very quickly just in a few seconds or minutes; this process is called physical adsorption. Then, these ions are then transported

slowly into their cytoplasm through a process called chemisorption. Polyphosphate bodies of algae enable freshwater unicellular algae to store other nutrients. Some researchers have established that metals such as Ti, Pb, Mg, Zn, Cd, Sr, Co, Hg, Ni, and Cu are sequestered in polyphosphate bodies in green algae. *Scenedesmus obliquus* is a typical example of green algae that is capable of accumulating increased Cd and Zn. These bodies complete two different functions in algae; first of all, they provide a "storage pool" for metals, and secondly, they act as a detoxification mechanism (Dwivedi, 2012). They act as hyper-accumulators and hyper-adsorbents with high discrimination for diverse elements. Besides, they produce high alkalinity which is essential for the precipitation of heavy metals during the treatment of acid mine drainage (Bwapwa et al., 2017).

### 3. Use of fungi for bioremediation

White-rot fungi breakdown lignin by the secretion of enzymes and give a decolorized appearance to the wood, from undissolved cellulose, therefore their name. In divergence, brown-rot fungi degrade cellulose, leaving lignin as a characteristically brownish deposit. These fungi also cause chequered, cubical cracking, and shrinking in wood, which is regularly apparent on felled conifer trees (Stamets, 2005; and Fayyad et al., 2020). It has been estimated that some 30% of the literature on fungal bioremediation is concerned with white-rot fungi (Singh, 2006). There are several prospects of using fungi, essentially white-rot fungi, for cleaning contaminated land are surveyed. White rot fungi are so effective in degrading a wide range of organic molecules is due to their release of extracellular lignin changing enzymes, with a low substrate-specificity, so they can act upon various molecules that are broadly similar to lignin. Such enzymes present in the system employed for degrading lignin include lignin-peroxidase (LiP), manganese peroxidase (MnP), various H<sub>2</sub>O<sub>2</sub> producing enzymes, and laccase. The degradation can be increased by adding carbon sources such as sawdust, straw, and corn cob at polluted sites (Rhodes, 2014). The use of white-rot fungi in bioremediation is anticipated to be comparatively economical because the fungi can be grown on several low-cost agricultural or forest wastes such as rice straw, corn cobs, and sawdust (Adenipekun and Lawal, 2012). *Aspergillus niger* is a typical example of *white rot*, they are the most deeply examined as decolorizing fungal group to uptake or assimilate the dye by their mycelia without true degradation. Numerous physical factors affect the decolorization rate such as temperature, pH concentration of dye, and agitators (Ramachandran and Gnanadoss, 2013; and Fayyad et al., 2020). Soils may also be cleansed from been polluted with crude oil, with the requirement that lignocellulosic substrates (e.g., sawdust straw and corn cob) must also be provided, to support the growth of fungal species in the soil (Rhodes, 2014). Many toxic materials have been successfully degraded using white-rot fungi are polychlorinated biphenyls and dioxins, pesticides, phenols and chlorophenols, effluents from pulp and paper mills, dyestuffs, and heavy metals (Singh, 2006). Besides, a very massive range of organic molecules are susceptible to the actions of various strains of white-rot fungi, to changing degrees, and even normally highly intractable and persistent substances, including polyaromatic hydrocarbons (PAH), may be broken down by them (Singh, 2006; and Fayyad et al., 2020). The white-rot fungus *Phanerochaete chrysosporium* is an ideal model for bioremediation by fungi since it is more competent than other fungi or microorganisms in degrading toxic or insoluble materials. It presents concurrent oxidative and reductive mechanisms which permit its use in many different situations, both regarding the type of contamination, its degree, and the nature of the site itself. Some other white-rot fungi also can degrade persistent xenobiotic compounds, e.g., *Pleurotus ostreatus*, *Trametes versicolor*, *Bjerkandera adusta*, *Lentinula edodes*, *Irpex lacteus*, *Agaricus bisporus*, *Pleurotus tuberregium*, *Pleurotus pulmonarius*. (Singh, 2006; Adenipekun and Lawal, 2012; and Rhodes 2014). *Lentinusedodes* mushroom has been appropriately to remove up to 60% of pentachlorophenol from polluted soil. *Penicillium steckii* has also been used to isolated from samples of soil where the Simazine herbicide had been spread (Fayyad et al., 2020). Pesticides treatment on surface water and groundwater may be contaminated with pesticides when there is excessive concentration of a pesticide or its metabolic wastes or by-products in this case remediation is needed to prevent migration to more sensitive locations of the ecosystem *Phanerochaete Chrysosporium* was the first fungal strain to be apprehensive with organo pollutants degradation and it has been extensively studied as a model organism for lignin degradation mechanism (Fayyad et al., 2020).

#### 3.1. Bioremediation using bacteria

The use of bacteria either whole and or their extract to deal with pollutants has become a promising technology because of its low cost and environmentally friendly nature (Guerra et al., 2018). The remediation of contaminated soils which relies on the abilities of bacteria to degrade hydrocarbons component has been established to be



efficient (Folwell et al., 2016). Therefore, heavily polluted sites do not need to be diluted to enhance the activities their indigenous biodegrading bacteria, as a result, high oil concentration selectively enriches such sites with bacteria strains capable of tolerating and degrading of hydrocarbon (Ali et al., 2020). The various mechanism could be used to clean-up the environment, among which techniques like biostimulation and bioaugmentation are greatly employed. The technique can be performed as natural attenuation or as assisted microorganism clean-up, the addition of nutrient to fortify and stimulate the growth and metabolism of indigenous bacteria (biostimulation) and the introduction of suitable exogenous bacteria to enhance the clean-up of targeted contaminant (Kure, et al., 2018). Adaptation is the first criterion of the selection of appropriate bacteria strain used for bioremediation. Thus, successful environmental decontamination using biological approaches requires bacteria strains that can degrade targeted pollutants (Katarina et al., 2018).

### **3.2. Bioremediation using plant (phytoremediation)**

Phytoremediation is a practice that uses selected plants (trees, shrubs, grasses, and aquatic plants) to clean up contaminants from the environment to improve and sustain environmental health. The term phytoremediation is made up of two words, a Greek prefix *phyton* meaning "plant" which is been attached to a Latin suffix *remedium* meaning "to correct" (Favas et al., 2014).

Phytoremediation works by using plants to stop or extract toxins from contaminated soil or water. In ideal cases, the selected plant converts toxins into less harmful forms or substances. It has been observed that some plants break down organic contaminants by releasing enzymes into the soil or by extracting the contaminants and breaking them down inside their tissue (Beans, 2017). Substances that may be subjected to phytoremediation include metals, metalloids, inorganic compounds, radioactive chemical elements, petroleum hydrocarbon, pesticides and herbicides, explosive, industrial organic waste, chlorinated solvent, and others (Ensley, 2000). Phytoremediation consist of six different strategies of which more than one can be used simultaneously by the plant (Favas et al., 2014).

#### **3.2.1. Phytodegradation (phyto-transformation)**

This involves the breakdown of organic substances taken up by plants through metabolic processes. The degradation occurs within the plant through the effect of specific enzymes and an example of plants that have this enzyme system is the *Populus* species (Rylott et al., 2008).

#### **3.2.2. Phytoextraction**

This involves the removal of the contaminated matrix (soil and water) by roots followed by translocation and accumulation in harvestable parts (Suman et al., 2018). It is mainly applied to metals (Cd, Ni, Cu, Zn, Pb) but can also be used for other elements and organic compounds (Favas et al., 2014). This method of clean-up uses plants that can store high concentrations of specific metals (0.01% to 1% dry weight, depending on the metal). Examples of these plants are *Alyssum bertolonii*, *Elsholtzia splendens*, *Thlaspi caerulescens*, and *Pteris vittata*, these are also known as hyper-accumulator (Van der Ent et al., 2013).

#### **3.2.3 Phyto-filtration**

Plants are normally used to absorb concentrate and/or precipitate contaminants from an aqueous medium through their root system or other submerged organs. The plants are kept in a hydroponic system, whereby the effluents pass and are filtered by via various part of the plant that absorbs and concentrate contaminants (Dhote and Dixit, 2009). Plants with high root high absorption surface, with more accumulation capacity and tolerance to contaminants are best for this type of clean-up process (Jabeen et al., 2009; and Muszynska and Hanus-Fajerska, 2015).

#### **3.2.4. Phyto-stabilization (Phyto-immobilization)**

Contaminants either organic or inorganic, are incorporated into the lignin of the cell wall of roots cells or humus. The mechanism underlying this process is the complexation of metal ions and exudes/mucilage or with the cell walls and also binding with metal-binding molecules like phytochelatins and metallothionein and finally sequestering them to the root vacuoles (Shackira and Puthur, 2019). Metals are precipitated as insoluble forms by the direct action of root exudates and subsequently trapped in the soil matrix.

### 3.2.5. Phytovolatilization

Plants interact with a variety of contaminants via their uptake and partitioning into the airspace within the plant and subsequent diffusion into the ambient air resulting in phytochemical decay in the atmosphere. Contaminants may be volatilized from the stem or leaves (direct volatilization) or soil due to plant root activities (indirect volatilization) (Limmer and Burken, 2016).

### 3.2.6. Rhizodegradation

Degradation of contaminants in the rhizosphere (area of the soil surrounding the plant roots) via microbial activities which is enhanced by the presence of plant roots (Alamin et al, 2020). Plant- microorganism interaction has great potential to boost the degradation of recalcitrant in the rhizosphere by symbiotic association via the release of chemicals that contain compounds like amino acids, carbohydrates and flavonoids (Weller and Thomashow, 2007). However, the community of these microorganisms in the rhizosphere is heterogeneous due to the spatial distribution of nutrients (Khan et al., 2009).

## 4. Conclusion

This review focuses on several aspects of detoxifying recalcitrant using different microorganisms. Bioremediation has been employed globally to achieve varying degrees of success when it comes to cleaning up the environment. The advantages are far greater than the disadvantages which are evident by the number of sites that were chosen for this technology. The effectiveness of this technology is highly dependent on the microbial growth and other environmental parameters of the site. However, satisfactory progress has been witnessed in the field of bioremediation among various contaminants with the role of certain metabolites applicable via synthetic and biological methods.

## Authors' Contributions

This work was carried out in collaboration with the authors; PAM, AK, and EME designed and wrote the manuscript.

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