American Journal of Innovative Research and Applied Sciences. ISSN 2429-5396 I www.american-jiras.com

REVIEW ARTICLE

BIOREMEDIATION OF HEAVY METALS BY ACTINOBACTERIA: REVIEW

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| Received | 06 October 2017 | | Accepted | 26 October 2017 | | Published 08 November 2017 |

Abstract

Background: Because heavy metals are increasingly found in microbial habitats due to natural and industrial processes, microbes have evolved several mechanisms to tolerate the presence of heavy metals. The extensive application of heavy metals in industrial processes lead to highly contaminated areas worldwide. Several studies focused in the use of actinobacteria for cleaning up the environment were performed in the last 15 years. New processes based on microorganism technology have provided an alternative or complementary way to conventional metal deposition/recovery techniques. Thus, the application of these new processes could be more economical. **Method:** In this review, we compiled and discussed works focused in the study of different bioremediation strategies using actinobacteria and how they contributed to the improvement of the already existing strategies. **conclusion**: From our analysis, it appears that the capacities of actinobacteria to remove heavy metals from contaminated areas can play very significant role in the bioremediation.
***Keywords**: Actinobacteria, Bioremediation, Heavy metals, Environmental pollution.*

1. INTRODUCTION

The accumulation of all wastes into the environment has become a major concern for several decades. It has given rise to a high level of awareness in developed countries, which are primarily responsible. Human industry has only complicated matters by introducing molecules that did not previously exist in nature. The major consequences of pollution, such as chemicals products have now become a worrying danger that affects the hydrosphere and causing growing concern.

At the same time, all international scientific organizations (UNEP / WHO / IAEA / FAO / IOC / SPC / UNESCO) carefully monitor the evolution of chemical pollution, the harmful consequences of which continue to appear. Pollution by heavy metals, like all other pollutants (organochlorine, organophosphorus pesticides, fungicides, herbicides, petroleum hydrocarbons, nuclear waste, etc.), is currently an important toxicological factor affecting marine organisms. Marine life, from primary producers; the danger of contamination increases gradually as through the links of the trophic chains [1]. Among the techniques currently used for the removal of heavy metals including physico-chemical methods (soil washing, excavation, ion exchange columns, treatment with alkaline solutions, precipitation, ion exchange, reverse osmosis, etc.) [2], have a high cost and are not applicable to large areas of contaminated soil. These techniques also have other methodological disadvantages, such as the incomplete removal of the metal, requires the supply of energy and the production of hazardous waste, which require extreme care to handle. In general, in situ remediation processes should not be applied because it is impossible to treat a particular metal due to competition in the presence of other metals. These disadvantages are accentuated even more when the concentrations of the metals to be removed are very low [3, 4].

Heavy metals are the main pollutants at sea, in land, at industrial discharges and even in wastewater treated in particular in developing countries [5]. Anthropogenic sources of metal contamination can be divided into five main groups: (i) metal mining, (ii) industry, (iii) atmospheric deposition, (iv) agriculture, and (v) waste disposal [6, 7]. These inorganic micropollutants can be accumulated in the human body through the food chain, thus promoting chronic and acute disorder and the obvious creation of serious health problems in human society [8, 9]. The introduction of heavy metals in various forms into the environment can produce considerable changes in microbial communities and their activities [10, 11]. Conventional technologies such as precipitation, oxidation / reduction, ion exchange, membrane filtration and evaporation, which are capable of eliminating these toxic metals in the environment, are often inefficient and very expensive [12]. For these reasons, it is necessary to introduce, through new biotechnology proposals, the development of low-cost disposal techniques, which should reduce the concentration of pollutants to regulatory levels in order to protect human health and provide a permanent solution, either to extract the metals or stabilize them in non-toxic or less toxic chemical species. However, new methods for remedying the polluted environment have been studied on the basis of organisms, which include bioremediation [13, 14] and / or phytoremediation [15, 16].

This review focuses on the general ways in which microbes interact with metals. Some bacteria have evolved mechanisms to detoxify heavy metals, and some even use them for respiration. Microbial interactions with metals may have several implications for the environment. Actinobacteria may play a large role in the biogeochemical cycling of toxic heavy metals also in cleaning up or remediating metal-contaminated environments.

2. Contamination of environment by heavy metals

2.1. Generality of heavy metals

The term "heavy metal", because it is often used with connotations of pollution and toxicity, is probably the least satisfactory of all the terms known as (trace elements, toxic metal, etc) it leads to the greatest confusion. "Heavy" in conventional usage implies high density. "Metal" in conventional usage refers to the pure element or an alloy of metallic elements [17].

At first glance, it seems to be a fairly simple matter to define a "heavy metal" as a metal that is "heavy" based on its high density. Unfortunately, a thorough review reveals problems with this simple definition. Since this physical property is completely meaningless in the context of plants and other living organisms. We do not know the existence of a correlation between the density of a metal and its physiological and toxicological effects, or the chemical properties of its compounds. Duffus (2002) concluded that "any idea of defining" heavy metals "on the basis of density should be abandoned" [17].Thus, a "heavy metal" remains an obscure term in the life sciences. Parameters such as specific weight, atomic weight, atomic number, specific chemical properties and toxicity were all mentioned as a possible basis for the classification of heavy metals but are then discarded. Definitions that are widely accepted are those of Phipps (1981) and Weast (1984) defining heavy metals as elements with a density greater than 6 gcm^{-3} and 5 gcm^{-3}, respectively. Metals are often characterized and distinguished from non-metals by their physical properties, ability to drive heat, and an electrical resistance [18, 19, 20, 21]. Heavy metals are present in all compartments of the environment, but generally in very small amounts "in trace amounts". The classification of heavy metals is often discussed because some toxic metals are not particularly "heavy" (zinc), while some toxic elements are not all metals (arsenic, for example).

2.2. Roles of heavy metals

Metals can be subdivided in essential micronutrients (e.g., iron, copper, zinc, cobalt, and nickel) that are critical for normal development and growth of organisms [22, 23] and other elements (e.g., such as cadmium, lead, and mercury) that are generally considered nonessential. Whereas deficiencies of micronutrients can seriously disturb normal development, excess of metals in general adversely affects biochemical reactions and physiological processes in organisms, causing a major risk for the environment and human health.

Some elements (essential metals) are actually needed for organisms in low concentrations [24]. Among the heavy metals and trace elements that are needed to quantify the tiny for living organisms and for their normal metabolic function. However, at high concentrations in the environment, they have a toxic effect. Several heavy metals such as copper, zinc and iron are essential for the physiological functioning of living organisms, but they have all become toxic at high concentrations. Some metals such as V, Mn, Fe, Co, Ni, Cu, Zn, Mo and W are required for cellular functions acting as cofactors, for structural and catalytic roles in enzymes and proteins, and stabilization of molecules organic. They are also used in electron transfer, the use of dioxygen, osmotic equilibrium [25], and as components of metallo-enzymes, which account for about 30% of all cell enzymes [26]. For example, zinc (Zn) is a component found in a variety of enzymes (proteinases and peptidases), but it is also involved in the metabolism of carbohydrates, proteins, phosphates and ribosome formation in plants [27, 28]. Copper (Cu) contributes to several physiological processes of plants (photosynthesis, respiration, carbohydrate, nitrogen distribution and cell wall metabolism), including disease resistance [27].The correct functioning of human metabolisms and bacteria is also dependent on these two metals [24, 29, 30].

2.3. Origin of environmental contamination by heavy metals

The contamination of soil can derive from distinct activities such as (1) industrial operations, (2) agricultural activities, and (3) agricultural domestic and urban activities. As a consequence of the adverse effects of the technical civilization of the world, soil as a component of the biosphere has been viewed as a natural buffer system that controls the fate of chemical elements in the environment. The presence of heavy metals at the soil level may be natural or anthropogenic (figure.1).
Trace elements accumulate locally in soils due to weathering of rock minerals. Because trace elements are essential for plants, animals, and human beings, it is necessary to ensure their adequate levels in agricultural products. Apart from trace elements originating in parent materials and entering the soil through chemical weathering processes, soil toxic trace elements have many anthropogenic sources [31]. Campbell et al. (1983) compared natural and anthropogenic quantities of trace metals emitted to the atmosphere and showed that around 15 times more Cd; 100 times more Pb; 13 times more Cu; and 21 times more Zn are emitted by man's activities than by natural processes [32].

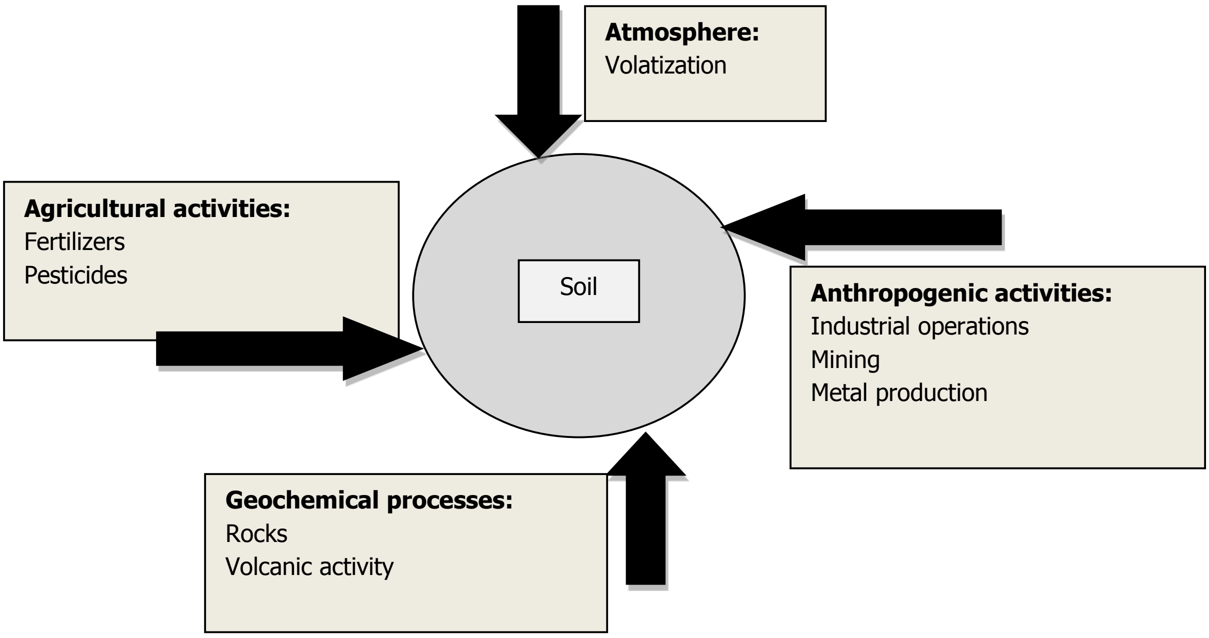

Figure 1: Schematic illustration of the origin of environmental contamination by heavy metals

2.3.1. Natural origin: Heavy metals are common sources of soil contaminants; they are also present in natural waters because of natural processes or man's activities. In this aqueous phase they do not stay under the soluble form for a long time; they are rather present as suspended colloids or they are fixed by organic material and mineral substances [33]. Heavy metals are naturally present in rocks; they are released when altered to form the geochemical background. The natural concentration of these heavy metals in soils varies according to the nature of the rock, its location and age. They represent less than 1% of the Earth's crustal composition due to alteration of the rocks, natural incidents (volcanic eruptions, leaching of the earth, atmospheric deposition, etc.).

3.3.2. Anthropogenic origin: The main types of anthropogenic pollution responsible for the increase in metal fluxes are atmospheric pollution (urban and industrial discharges), pollution from agricultural activities and industrial pollution. Some anthropogenic contributions of trace elements are little or not controllable because they are linked to many human activities (table.1).

The anthropogenic sources of trace elements in waters are associated with mining of coal and mineral ores, and manufacturing and municipal wastewater operations [34]. Most of the regional contamination of the soil originates from industrial regions and urban areas where factories, motor vehicles, and municipal waste are the common sources of heavy metals. Furthermore, fertilizers, pesticides, and sewage sludge constitute other important sources of heavy metals in the soil. Effects of sewage sludge application on soil composition are of great environmental concern because of their heavy cumulative load, which tends to increase the soils' levels of Ni, Cr, Pb, Zn, Cu, and Hg because of long-term use [35, 36].

Table 1: Anthropogenic entry of trace elements into soil that is friendly or close to past or present human activities

Transportation Infrastructure	Routes	Pb, Cd, Cu, Zn
	Car park	Pb, Cd, Zn
	Air traffic	Pb, Cd, Cu, Zn
	Railway	Cu, Cd, Zn
Energy	Fossil fuel heating	Pb, Cd, Zn, V, Cu, Cr, Ni, Hg, Se, As
	Gas plants	Pb, Cd, Zn, As
	Coal Warehouse	Pb, Cd, Zn, Hg
	Tanks	Pb, Cd, Zn, Cr
Waste disposal and sanitation	Incineration of household waste	Pb, Cd, Zn
	Batteries and accumulators	Cd, Cu, Cr, Pb, Ni, Zn, Hg, Se, As
	Temporary storage of incineration slag	Pb, Cd, Zn
	Treatment plants	Cr, Cu, Ni, Zn
	Composting plant	Pd, Cd, Zn

Industry, crafts	Textile industry	Cu, Cr
	Wood treatment, furniture manufacturing	Cu, Cr, Zn, Hg, As
	Printing	Pb, Cd, Zn
	Paintings	Pb, Cd, Zn
	Leather processing, footwear, manufacturing	Cr
	Plastic processing	Cd, Cr, Pb, Zn, Se
	Construction of machinery and vehicles	Pb, Cd, Zn
	Electrical	Cu, Cd
	Glass processing	Cd, Cu, Cr, Pb, Ni, Zn, Se, As
	Cement	Tl, F, Cr, Pb, Zn
	Production of iron and steel	Cd, Cu, Cr, Pb, Ni, Zn, As, Hg
Nutrients	Mineral fertilizers, fertilizers from rocks	Cd
	Mineral fertilizers, slag	V, Cr
	Sludge	Cd, Cu, Mo
	Compost	Pb, Cd, Zn
	Fertilizers (slurry, etc.)	Cu, Zn

2.4. Toxicity of heavy metals

The term "heavy metal" is related in the minds of many people for metals (and their compounds) that are toxic. However, it is a feeling rather than a conclusion based on scientific evidence. Then it is necessary to recall two well-known facts. (1) First, a heavy metal is not toxic by itself, it is toxic only when its concentration exceeds a certain threshold ("it is the dose that makes the effect"). Thus, there are no substances that are always toxic. (2) Several metal ions are essential for cell metabolism at low concentrations, but are toxic at high concentrations, resulting in a bell-shaped dose-response relationship [37].

The known toxic metals are Al, Au, Ag, Bi, Cd, Cr, Hg, Pb, Sn and Tl. There are several metalloids which are also known to be toxic: As, Sb et Te [38]. In addition, there are other metals that have no known biological role and can be toxic to bacteria such as Be, Cs, Li and Sr [25, 26-38-39]. The toxicity of a metal depends on the metal itself, its total concentration, the availability of metal to the body, and the body itself. In addition to directly causing non-infectious diseases in humans, heavy metals can also have a significant impact when released into the environment. They are a serious and persistent pollutant of terrestrial and aquatic ecosystems [40]. These compounds unlike various organic refractories, there is no possibility of destruction of these elements in the biosphere. Contamination of soils by heavy metals is a long-term problem. Estimates of the half-lives of some elements of the 15 to 1100-year soil range for cadmium, 310 to 1500 years for copper and 740-5900 years for lead, with the wide range of values due to different soil conditions [41].

At relatively high concentrations of heavy metals, they act as a protoplasmic poison, inducing the denaturation of proteins and nucleic acids [42]. Cobalt, copper, chromium, nickel, vanadium and zinc are as toxic as trace elements. Arsenic, cadmium, lead, mercury, silver and uranium are highly toxic with limited biological function [43].

A long-term exposure to heavy metals can be carcinogenic, affecting central and peripheral nervous system and circulatory effects. High concentrations of heavy metals can cause adverse health effect to human being, only several of them are important to human in low concentration. Heavy metal is biodegradable and has ability to accumulate in living tissues according to Wan Ngah and Hanafiah (2007) [44]. The disasters that hit some countries after heavy metal poisoning remain unforgettable. Examples of the toxicity of certain heavy metals include:

Mercury : Mercury poisoning on account of consumption of agricultural crops reported in Iraq was due to the consumption of seeds treated with mercury fungicides and not trophic transfer [45]. Methyl mercury affects the formation of microtubules and thus neuronal migration and cell division [46-48]. The Minamata catastrophe in Japan in the 1950s was caused by methyl mercury poisoning from fish contaminated by mercury discharges to the surrounding sea. In the early 1970s, more than 10,000 persons in Iraq were poisoned by eating bread baked from mercury-polluted grain [49]. Sakamoto et al. (2001) found that a declining male birth ratio was associated with increased male fetal death due to Me Hg exposure in Minamata, Japan [50].

Lead: Numerous human health problems are associated with exposure to Pb. The effects of Pb poisoning occur when Pb is present in the bloodstream. This is typically the result of ingestion and/or inhalation of Pb-containing dust, particulates, fluids, or fumes. In 1979, the effect on neurologic development and IQ was found [51]. Other health effects can occur at lower levels [52]. The Centers for Disease Control [53] recommended that the blood lead level of concern from the standpoint of protecting the health of sensitive populations was to 10µg/dl whole blood.

Cadmium: has been established to be a very toxic heavy metal. Cadmium can inhibit the growth of shoots and roots, affect the absorption of nutrients and homeostasis, and are frequently accumulated under the influence of agriculture.

Thus, diseases are caused. Vegetable products enriched with Cd are consumed by animals and humans. It is known to disrupt enzymatic activities, to intervene in the symbiosis between microbes and plants, and to increase the predisposition of plants to fungal invasion [27]. In humans, it can promote several problems in the metabolism of calcium and vitamin D, leading to degeneration of beings and renal lesions (itai-itai) [24]. Aquatic food species (fish, crab, oysters, etc.) bioconcentrate Cd and therefore can have high Cd concentrations [54]. Typical Cd concentration reported in fish muscle is about 0.02 mg/kg, although higher levels may also be found in some fish species. Certain other sea foods may also accumulate Cd from contaminated waters. Cadmium can cause irreversible renal tubular injury, nonhypertrophic emphysema, osteoporosis, anemia, eosinophelia, anosmia, and chronic rhinitis [54-56].

Copper: is an essential element used in the process of blood formation and the use of iron. Symptoms of acute toxicity are gastric ulcers, haemolysis, jaundice, hepatic necrosis, and kidney damage. In addition, copper has been found to be carcinogenic to animals but not conclusively to humans [27].

Zinc: Zinc tends to be less toxic than other heavy metals. However, some symptoms of zinc toxicity include vomiting, dehydration, electrolyte imbalance, stomach pain, nausea, lethargy, dizziness and muscle incoordination [27].

Chromium: In the trace state, chromium is an essential trace element for humans and animals. It is associated with glucose metabolism by its action on insulin and is also implicated in the metabolism of fats. Chromium is biologically inert [57, 58]. The hexavalent form is not the nutritional source because it is very toxic and mutagenic. The toxicity of Cr^{6+} comes from its great ease in crossing biological membranes. Humans can absorb chrome compounds by inhalation, through skin contact and through ingestion. These very frequent occupational exposures result in severe ulcerations and perforations of the nasal septum, but can also result in respiratory tract cancers and skin allergies.

3. Remediation as an alternative to conventional treatment

Bioremediation is a technology that uses microorganisms to reduce, eliminate, contain or transform contaminants in soil, sediment, water and air into benign products. Bioremediation has been used for more than 100 years, with the opening of the first biological wastewater treatment plant in Sussex, UK, in 1891. However, the word "bioremediation" is relatively new; its first appearance in a review by the scientific literature was in 1987 [59].

Bioremediation involves the biological restoration of historically contaminated sites and the recent clean-up of contaminated areas either accidentally or incidentally as a result of the production, storage, transport and use of organic and inorganic chemicals [60, 61].

3.1. Bioremediation treatment technologies

Bioremediation treatment technologies have been broadly divided into two categories: *in situ* or *ex situ* [62]. *In situ* bioremediation involves treating contaminated material at the site, while *ex situ* involves removing the contaminated material to be treated elsewhere. Some examples of bioremediation technologies are bioventing, spreading, bioreactor, composting, bioaugmentation, rhizofiltration and bio-stimulation [63].

3.1.1. In situ bioremediation techniques: *In situ* bioremediation is the ability to convert contaminants to less toxic compounds, making it a promising clean-up technique (National Research Council, 1993). *In situ* techniques are concerned with improving the rate of biodegradation of organic contaminants in affected soils, sediments, surface waters or in groundwater environments. Although *in situ* bioremediation, by definition, involves the treatment of contaminated materials in place, "pump and treat" technologies are generally included in this category, despite the fact that they involve the removal, treatment, and return of water associated with contaminated soil areas [62].

3.1.2. Ex situ bioremediation techniques: *Ex situ* techniques require physical removal of contaminated materials (usually soils or sediments) followed by treatment under bioreactors, bio-piles, compost piles, ponds or lagoons [61, 62].

3.2. Interaction between heavy metals and microorganisms

3.2.1. Impact of heavy metals on microorganisms

The undesirable effects of heavy metals on microbial processes have been examined in detail by several researchers Among the typical effects of heavy metal contamination are the decrease in the number of microbes (microflora), microbial biomass [7], or the increase in the frequency of bacteria resistant to metallic elements [64, 65]. However, measuring these parameters is not an appropriate approach for determining changes in the entire structures of soil communities exposed to pollutants. Sensitive microorganisms are negatively affected by heavy metals, but it should also be noted that heavy metals favor the development of tolerant species that can survive and adapt due to their genetic characteristics [66, 67] and can also degrade and detoxify a wide variety of hazardous compounds [68].

Some studies indicate that not all species have the ability to develop resistance or tolerance mechanisms for metals. Many sensitive species will be eliminated by pollutants and their place is taken by resistant species that have a different ecological role.

The high concentration of heavy metals can directly affect the microbiotope by modifying the population size, diversity and activity [43-69]. These modifications are expressed by the blocking of the main functional groups, the displacement of the essential metal ions, or by the modification of the active aspect of the biological molecules [70, 71]. Haferburg and Kothe (2007) reported that there was a clear mutual influence in the mining areas from which microbes in the soil are not only directly and indirectly affected by their environment, but they control in particular the soil parameters [6]. Haferburg and Kothe (2007) also suggest that growth and metabolism can lead to changes in pH and ionic strength of the soil [6].

3.2.2. Mechanisms of resistance adopted by microorganisms with respect to heavy metals: The relationship between microorganisms and the toxicity of heavy metals is well documented [72]. Studies have explained the tolerance of certain microorganisms to heavy metals by their ability to adsorb, bioaccumulate and / or transform metals [73-75]. This is achieved by the virtue of covalent interaction of metal on the cell surface or inside the cell by different methods [76].

Bacteria have developed several strategies to combat metal poisoning: (1) metal resistance is achieved via intra- and extracellular mechanisms; (2) metals can be excreted via efflux transport systems; (3) cytosol sequestration compounds can bind and detoxify metals in the cell; (4) The release of chelators in the extracellular medium capable of binding and fixing metals; (5) the structure of the cell envelope which is capable of binding large quantities of metals by sorption thus preventing impulses [6]. Figure 2 illustrates these main interactions between metals and microorganisms. As for bioprocesses of metal accumulation, they generally fall into one of two categories: (1) bisorption (passive) using non-living cells, (2) bioaccumulation using living cells [77]. In these two cases, either live or dead, microorganisms are used to remove metal ions which are toxic [78].

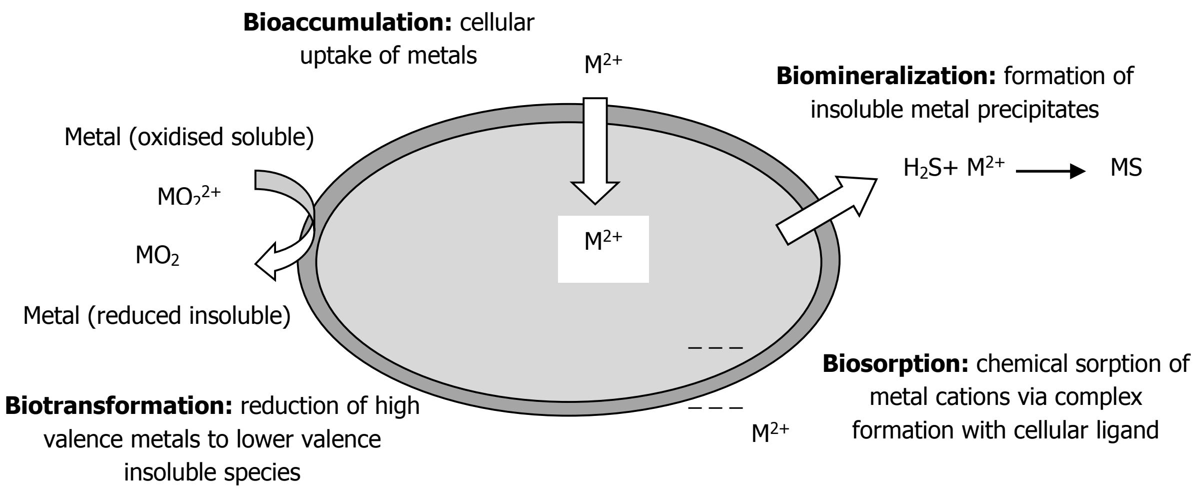

Figure. 2: Schematic illustration of the main mechanisms of interaction of metal (M) on the cell surface or inside the cell by different methods

3.2.2.1. Biosorption: Sorption conditions and adsorption are used when the natural affinity of biological compounds is exploited for metallic elements, a process also known as passive bioaccumulation. Can be involved with dead or living cells. This approach relies on components on the cell surface and the spatial structure of the cell wall on one side and on the other, the physico-chemical conditions of the environment where the cell develops [79, 80]. It is recognized that pH, ionic strength, temperature, and the presence of other metals and organic compounds play an important role in this process [77-81, 82].

3.2.2.2. Absorption or active bioaccumulation : The term "absorption" is used when intracellular transport-dependent metabolism is involved during accumulation and many living cell characteristics, such as intracellular sequestration followed by localization within cellular components, binding metallothioneins, and the formation of a complex [63-83]. Bioaccumulation or biotransformation is a metabolism-dependent process, so that the pollutant or cation is accumulated intracellularly or through the cell membrane, or removed through the metabolic cycle of the cell [63]. Envelopes of the cell surface of bacteria can adsorb various heavy metals, by virtue of ionic bonds to their intrinsic chemical groups [84]. Anionic groups such as carboxylate groups and peptidoglycan phosphate and teichoic acid groups are considered the primary metal binding sites [84, 85]. The cell surface of the microorganisms is negatively charged due to the presence of various anionic structures, such as glucan and chitin [86].

3.2.2.3. Biotransformation: As mentioned earlier, the mobility and toxicity of heavy metal forms are different. Microorganisms exhibit a number of enzymatic activities that transform certain species of metal by oxidation, reduction, methylation and alkylation [87].

Other strategies are also possible. Resistance properties generally accompany the acquisition of additional genes encoding new proteins. Microorganisms often use at the same time several defense systems which are practically always regulated by induction and repression. In addition, cells enhance their ability to resist by exacerbating repair mechanisms related to stress. In addition, it is important to mention that microorganisms participate in the carbon cycle and thus influence the amount and nature of organic matter. This phenomenon can be of considerable importance for the mobility of metals because organic compounds can bind metals. Microbial degradation of the organometallic complex can change the speciation of the metal. However, metal bonding in various organic materials may decrease the microbial degradation of the organic compound [88]. In addition, microorganisms can produce or release organic compounds such as pigments, biosurfactants or siderophores in the presence of heavy metals which can indirectly reduce or increase the mobility of heavy metals. Iron metabolism has also been studied because of the potential role of microbial siderophores in coping with stress factors, including metallic toxicity, by facilitating heavy metal uptake and mobilization [89-91]. Other studies have shown that ferroxamines can chelate nickel, cadmium, gallium, aluminum, vanadium and plutonium [92, 93], whereas the coelichelin can chelate nickel and cadmium [94]. The pyoverdine and pyohelin are capable of chelating Ag^{+}, Al^{3+}, Cd^{2+}, Co^{2+}, Cr^{2+}, Cu^{2+}, Eu^{3+}, Ga^{3+}, Hg^{2+}, Mn^{2+}, Ni^{2+}, Pb^{2+}, Sn^{2+}, Tb^{3+}, Tl^{+} et Zn^{2+} [94, 95]. Two different possibilities have been proposed to explain the stimulating effect of siderophore production in the presence of heavy metals: (1) that the metal can be directly involved in the pathways of siderophore biosynthesis or its regulation [96], (2) or the concentration of free siderophors in the medium could be reduced by the formation of complexes with metal ions (fig.3). The production of these low molecular weight compounds was also detected in basidiomycetes [97, 98]. Therefore, it is conceivable that these isolates with its secondary metabolites (siderophores) can withstand heavy metals.

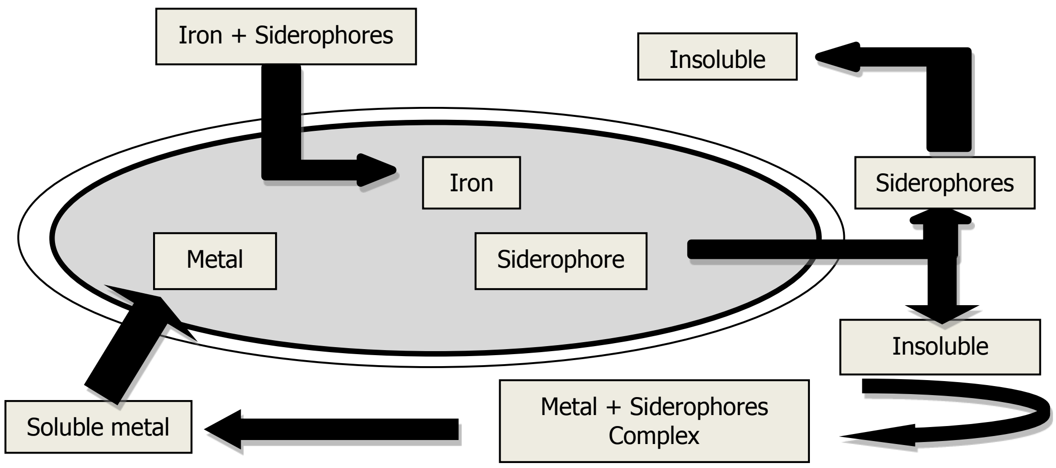

Figure. 3: Schematic illustration of interaction of metal on the cell surface or inside the cell by siderophores

3.2.2.4. Biomineralization: On the other hand, microorganisms can also produce inorganic compounds such as sulfur which reduces the mobility of many metals and even precipitates them. In addition to these processes, microorganisms can influence the mobility of metals since they affect pH, redox potential (Eh), and so on. All these parameters should be kept in mind while studying the influence of microbial metal accumulation on the mobility of metal [79].

3.3. Use of actinobacteria in bioremediation

3.3.1. General features of the phylum: The phylum Actinobacteria constitutes one of the main and most diverse phyla within the domain Bacteria, on the basis of its branching position in 16S rRNA gene tree. The group encompasses six classes, 19 orders, 50 families, and 221 genera, although new taxa continue to be discovered [99]. The filamentous bacteria (Actinomycetes), belonging to Gram positive bacteria, live mainly as a significant component of soil and sometimes in marine and aquatic sediments and have many roles in removal of different heavy metals and pollutions [100]. Actinobacteria are a group of bacteria present in high concentrations in soils. They play an important role in recycling substances, since they are able to metabolize complex organic matter [101]. Actinobacteria are used for the production of antibiotics, improvement of soil quality, degradation of toxic products and waste, protection of plants against phytopathogenic and other diseases. Actinobacteria are an important group of microorganisms that are secondary metabolite producers, many of which are bioactive compounds. 75% of the secondary metabolites are produced by the genus *Streptomyces* [102].

3.3.2. Promising actinobaceria for bioremediation of heavy metals: The versatility of actinobacteria is reflected in their biotechnological applications, which has seen their use in 1) the production of commercially important enzymes, 2) the bioremediation of industrial waste, and 3) the production of recombinant proteins (Humans) [102]. Actinomycetes are an important source of new bioactive compounds such as antibiotics and enzymes [103]. Secondary metabolites may form in nature as a response to the effects of the environment [104]. Other secondary metabolism products may allow bacteria to cope with stressors, including toxic levels of heavy metals [91-105], siderophores, for example, are secondary metabolic products which can reduce the bioavailability of metals and therefore its toxicity by forming bonds with metal ions which have a chemical composition similar to iron [106]. Recently, Dimkpa et al. (2008) observed production of siderophore hydroxamates by *Streptomyces* spp. in the presence of Al, Cd, Cu and Ni [94]. The siderophores produced by *Streptomyces tendae F4*, improve the bioavailability of Cd and their production is regulated by the metal in the absence or presence of iron [107].

Several groups of actinobacteria are capable of removing heavy metals from polluted environments. This can be very interesting by using these bacteria in bioremediation processes [108-110]. Amoroso et al. (1998) and El Baz et al. (2015) reported that metal resistance can be widespread among live actinobacteria in contaminated environments [111, 112]. Several bacteria have resistance mechanisms such as superoxide dismutases [113], efflux transporters [114, 115] and metallothioneins [116, 117]. *Streptomyces* are the most common among actinomycete isolates in polluted water habitats [118] and artificial swamps for the treatment of industrial effluents [119]. *Streptomyces* and *Amycolatopsis* can survive in environments contaminated by heavy metals [108-120], This is probably due to their remarkable resistance to extreme environmental conditions and various pollutants. Alvarez et al. (2013) reported that the presence of heavy-metal-resistant strains in different *Streptomyces* clades can have two different explanations: (i) resistance was already present in the most recent common ancestor (MRCA) and was then inherited by the different lineages; (ii) the different lines inherited from the MRCA have developed new mechanisms or have modified those already existing, in order to generate resistance to heavy metals [121]. Schütze and Kothe (2012) reported that several morphological, physiological and reproductive characteristics of *Streptomyces* (filamentous growth, hyphae formation and spore production) would allow its species to occupy extreme environments [122]. Since these properties are shared by all species of the genus, this can be interpreted as evidence that supports the transmission of heavy metal resistance from the MRCA. This is in agreement with the work of Zhou et al. (2012), the latter indicated that the impressive biosynthesis machinery that the current Streptomyces species inherited from their MRCA would be an adaptive trait to survive in an unfavorable environment [123]. Physiological and biochemical studies on different strains of *Streptomyces* have shown that resistance to heavy metals is caused by several mechanisms, acting alone or in conjunction: an increase in reductase activity, metal efflux pumps; intracellular sequestration and biomineralization [122]. Cadmium is a very toxic metal and has been found in the environment at increased concentrations producing different pathologies in humans and animals. The accelerated growing of industrial activities producing this contamination has increased the cadmium liberation at a higher rate than the one of the natural geochemical processes [124].

4. CONCLUSION

Heavy metals such as lead, cadmium, copper, zinc and chromium cannot be biodegraded and therefore persist in the environment for long periods. In addition, they are continuously added to the soil by various activities: in agriculture by the application of sewage sludge or in the metallurgical industry, etc. On the microscopic scale, heavy metals also have deleterious effects on bacterial populations, which is not without consequence on the functioning of the ecosystem. In addition to their adverse effects, there is a lack of sanitation and waste water treatment, which is one of the main causes of the degradation of the quality of surface and underground water. It is generally accepted that environmental pollution by heavy metals leads to the establishment of a tolerant or resistant microbial population. It should also be taken into account that contamination at polluted sites is not usually caused by a single metal and that selection is probably ensured for the most toxic element or for the different metals that act in synergy [125]. Gadd and Sayer (2000) have reported that isolates isolated from contaminated environments may co-exhibit resistance to more than one ion and therefore co-tolerance may be a common natural response [126].

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Cite this article: Soraia EL baz. BIOREMEDIATION OF HEAVY METALS BY ACTINOBACTERIA: REVIEW. *American Journal of Innovative Research and Applied Sciences. 2017; 5(5): 359*-369.