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Review Article about the Role of Bacteria in Cadmium Bioremediation

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Annotation: Elevated levels of cadmium in soils and irrigation water pose a risk to food safety, human and animal health, and the environment. Because microorganisms, particularly bacteria, have a proven capacity to retain and convert heavy metals, microbial bioremediation has emerged as a promising approach to lower the concentration of toxic chemicals in the environment. Understanding the role of bacteria in cadmium bioremediation is crucial for developing effective strategies to remediate cadmium-contaminated environments.

This paper aims to explore the intricate relationship between bacteria and cadmium, focusing on the various mechanisms employed by bacteria to resist and tolerate cadmium, and provide insights into how bacteria can be harnessed for efficient cadmium removal.

Introduction

Microorganisms are ubiquitous in the environment, some of them are crucial to both the biogeochemical cycle of metals and the cleanup of heavy metal-contaminated habitats. Even though heavy metal are hazardous, microbes can endure in their presence because of a variety of coping mechanisms that either lessen or accept their toxicity. It is economical, practical, and efficient to use microbial remediation techniques. Bacteria exhibit resistance to heavy metals through five primary mechanisms: 1) Extracellular barriers: metal ions can be kept out of a cell by the cell wall, plasma membrane, or capsule; 2) Active transport of metal ions, or efflux, is a method that involves proteins from three families—P-type ATPases, CDF (Cation Diffusion Facilitator), and RND (Resistance, Nodulation, Cell Division)—that export hazardous metals from the cytoplasm; 3) Extracellular sequestration: this process involves the complexation of metal ions as insoluble compounds or the accumulation of metal ions by cellular components in the periplasm or the outer membrane; 4) Intracellular sequestration: this strategy involves building up metals in the cytoplasm in non-bioavailable forms to shield vital cell components from exposure (González and Ghneim-Herrera , 2021; Ma et al., 2023).

Cadmium-tolerant bacteria are a diverse population that can be found in soils, water, and the atmosphere. Cadmium-tolerant bacteria proliferate in an environment that is either heavily metal-polluted or enriched. Cd tolerant bacteria can take advantage of seven primary mechanisms that lead to the contribution of geostable chemical species of Cd as pathways for Cd detoxification. These mechanisms including biosorption, bioleaching biotransformation, Enzymatic Transformation, bio weathering, chemosorption and bioaacumulation (Bravo and Braissant , 2022)

The bioprocessing mechanism for cadmium involves the transformation of cadmium ions into less harmful forms through biological processes. One approach is consolidated bioprocessing, where microorganisms like Clostridium thermocellum facilitate the biotransformation of cadmium ions into cadmium sulfide (CdS). This conversion reduces the toxicity of cadmium by forming a less soluble and less bioavailable compound. Additionally, certain bacteria, such as Escherichia coli P4, exhibit resistance mechanisms against cadmium and other heavy metal ions, highlighting their potential in bioremediation efforts. Understanding the bioprocessing mechanisms for cadmium is essential for developing sustainable and effective strategies to mitigate cadmium pollution and its environmental impact (Uraguchi et al., 2011; Dhaliwal et al., 2020; Huang et al., 2020; Krämer et al., 2007).

1. Cadmium

Cadmium (Cd) is hazardous, bioaccumulates, highly migratory, persistent, non-degradable, and poses a concern to both human health and the environment. Because of its high toxicity and water solubility, cadmium (Cd) is a non-essential metal that is considered a significant pollutant. According to Kuber et al. (2019), the metal has a propensity to form stable dissolved complexes with both organic and inorganic ligands, which prevents it from solubilizing and precipitating. Moreover, cadmium can impede DNA-mediated transformation in microbes and disrupt enzyme activity; the main human sources of cadmium in soils are direct inputs of waste from mine, industry, and agricultural use (González and Ghneim- Herrera , 2021).

2. Harmful Effects of Cadmium

Exposure to cadmium can have detrimental effects on human health, affecting various systems and organs. Respiratory issues, kidney damage, circulatory problems, skeletal disorders, reproductive complications, and neurological impairments are among the health issues associated with cadmium exposure. The accumulation of cadmium in the body can lead to carcinogenic effects and long-term health consequences, emphasizing the need for preventive measures and monitoring strategies to mitigate its impact on individuals and ecosystems (Satarug et al., 2010; Tchounwou et al., 2012).

1. Permissible Limits for Exposure to Cadmium

Permissible exposure limits for cadmium are crucial in safeguarding the health of individuals occupationally exposed to this toxic heavy metal. Various regulatory bodies have established standards to mitigate the risks associated with cadmium exposure, considering its detrimental effects on human health.

The Occupational Safety and Health Administration (OSHA) in the United States has set a Permissible Exposure Limit (PEL) for cadmium at 5 micrograms per cubic meter (µg/m³) for fumes. Additionally, the National Institute of Occupational Safety and Health (NIOSH) has defined an Immediately Dangerous to Life and Health level (IDLH) for cadmium at 9 milligrams per cubic meter (mg/m³) (OSHA, NIOSH).

Moreover, health agencies have implemented exposure standards to protect the general public from excessive cadmium exposure from various sources. For instance, the Food and Drug Administration (FDA) has established a maximum limit of 0.005 milligrams per liter (mg/L) for cadmium in bottled water. The Agency for Toxic Substances and Disease Registry (ATSDR) has defined a Chronic durational oral minimal risk level (MRL) of 0.1 micrograms per kilogram per day (µg/kg/day) for cadmium based on its renal effects (FDA, ATSDR).

Internationally, the World Health Organization (WHO) has set a Tolerable Weekly Intake for cadmium at 7 micrograms per kilogram of body weight per week. Furthermore, the EPA classifies cadmium as a probable human carcinogen, aligning with classifications by other internation

3. Locations of Cadmium

Cadmium is widely distributed in the environment due to natural sources and human activities. It is found in ores alongside other metals and is released into the environment through industrial processes like battery production and fossil fuel combustion. Soil contamination from phosphate fertilizers and anthropogenic activities like smelting contribute

to cadmium pollution. Monitoring the locations of cadmium contamination is essential for assessing environmental risks and implementing remediation strategies to protect human health and ecosystems (Alloway, 2013; Kabata-Pendias & Mukherjee, 2007).

1. Sources of Cadmium Pollution

Cadmium pollution arises from various anthropogenic activities and natural processes, contributing to environmental contamination and posing significant health risks to ecosystems and human populations. The primary sources of cadmium pollution include:

Industrial Activities: Mining, smelting, and refining operations associated with metals like copper and nickel are significant contributors to cadmium pollution. These activities release cadmium into the environment, contaminating soil, water, and air (UNEP, 2022; Zhao et al., 2015).

Agricultural Practices: The use of phosphate fertilizers in agriculture can introduce cadmium into the soil, leading to contamination of crops and potential human exposure through the food chain. Sewage irrigation and waste recycling processes also contribute to cadmium pollution in agricultural settings (Zhao et al., 2015).

Combustion of Fossil Fuels: The burning of fossil fuels, such as coal and oil, releases cadmium into the atmosphere, contributing to air pollution. This source of cadmium contamination poses risks to both environmental and human health (UNEP, 2022).

Household Products: Cadmium is used in various consumer products like batteries, paints, plastics, and electroplating. Improper disposal of these products can lead to cadmium leaching into the environment, further exacerbating pollution levels (UNEP, 2022).

Waste Recycling: The recycling of electronic waste, which often contains cadmium in components like batteries, can result in the release of cadmium into the environment if not managed properly. This source of pollution highlights the importance of responsible e-waste recycling practices (Zhao et al., 2015).

Natural Processes: Natural occurrences like volcanic activity, erosion of rocks and soil, and forest fires can also contribute to cadmium pollution. These processes release cadmium into the environment, adding to the overall contamination levels (Zhao et al., 2015).

4. Distribution of Cadmium in the Environment

Cadmium (Cd) is a non-essential trace element that is widely distributed in the environment through various pathways. Both geogenic and anthropogenic sources contribute to the elevated levels of cadmium in different environmental compartments. Natural sources of cadmium include soil particles, forest and bush fires, sea salt, volcanoes, and meteoric dust. On the other hand, anthropogenic sources, such as non- ferrous metal production, iron and steel production, stationary fossil fuel combustion, cement production, and waste disposal, significantly contribute to cadmium emissions. The distribution of cadmium in the environment can be influenced by factors like wildfires, industrial activities, and atmospheric deposition, leading to varying concentrations in different regions (Zwonitzer et al., 2003; Bigalke et al., 2017; Merkel and Sperling, 1998; UNEP, 2010).

5. Natural and Industrial Sources of Cadmium

Cadmium is introduced into the environment through a combination of natural processes and human activities. Natural sources of cadmium include volcanic activity, forest fires, and meteoric dust, contributing to the presence of cadmium in soil and water. Industrial activities, such as non-ferrous metal production, iron and steel manufacturing, and fossil fuel combustion, are significant anthropogenic sources of cadmium emissions. Other sources of cadmium pollution include waste disposal, cement production, and the use of nickel-cadmium batteries. The widespread use of phosphate fertilizers also plays a role in elevating cadmium levels in soil and groundwater. Understanding the interplay between natural and industrial sources of cadmium is essential for effective environmental management and pollution control efforts (ATSDR, 2012; WHO, 2019; Bigalke et al., 2017; Khan et al., 2017).

1. The Role of Bacteria in Bioremediation

Bacteria play a crucial role in bioremediation, a process that utilizes living organisms to remove contaminants, pollutants, and toxins from soil and water. These microorganisms are essential agents in the decomposition, elimination, immobilization, or detoxification of various chemical wastes and hazardous substances present in the environment. Through their enzymatic pathways, bacteria facilitate biochemical reactions that lead to the reduction of pollution levels. Bacteria act as biochemists, breaking down pollutants like hydrocarbons, heavy metals, pesticides, and dyes into non-toxic forms through metabolization. This enzymatic activity contributes significantly to solving environmental challenges and addressing pollution issues effectively (Abatenh et al., 2017; Colleran, 1997).

Bacteria, along with archaea and fungi, are key bioremediators that are widely used in biotechnological processes to address and eliminate environmental hazards. Their metabolic versatility and ability to thrive in diverse environmental conditions make them valuable tools in bioremediation efforts. By converting, modifying, and utilizing toxic pollutants to generate energy and biomass, bacteria contribute to the breakdown and transformation of contaminants, promoting the restoration of natural environments and preventing further pollution. The application of bioremediation techniques involving bacteria is crucial for managing and restoring polluted environments, offering an eco-friendly and sustainable approach to waste treatment and pollution control (Abatenh et al., 2017; Colleran, 1997).

1. Mechanism of Bacterial Resistance to Cadmium

Bacterial resistance to cadmium is a fascinating area of study that sheds light on the adaptive strategies employed by microorganisms to survive in environments contaminated with this toxic metal. Understanding the mechanisms behind bacterial resistance to cadmium is crucial for developing strategies to mitigate its impact on ecosystems and human health.

2. Efflux Pumps in Bacterial Resistance to Cadmium

Efflux pumps play a pivotal role in bacterial resistance to cadmium, enabling microorganisms to expel toxic cadmium ions from their cells and maintain cellular homeostasis. Understanding the mechanisms by which efflux pumps contribute to bacterial cadmium resistance is essential for elucidating microbial adaptation strategies in contaminated environments.

Role of Efflux Pumps: Efflux pumps are integral membrane proteins that actively transport cadmium ions out of bacterial cells, reducing intracellular cadmium concentrations and preventing toxicity. These pumps serve as a defense mechanism against cadmium stress, allowing bacteria to survive and thrive in environments with elevated cadmium levels (Abbas et al., 2018; Abbas et al., 2018).

Efflux Pump Systems: Bacteria utilize various efflux pump systems, such as P-type ATPases and Cation Diffusion Facilitators (CDFs), to facilitate the efflux of cadmium ions. These systems encode specific proteins that interact with cadmium ions and pump them out of the cell, contributing to bacterial cadmium resistance. The cadA and cadB gene systems, for instance, encode efflux pump proteins that play a crucial role in expelling cadmium from bacterial cells (Abbas et al., 2018; Abbas et al., 2018).

Mechanisms of Action: Efflux pumps function by actively transporting cadmium ions across the bacterial membrane, maintaining low intracellular cadmium concentrations. By preventing the accumulation of cadmium within the cell, efflux pumps protect essential cellular components from cadmium-induced damage and ensure bacterial survival in cadmium-contaminated environments. Additionally, efflux pumps contribute to the detoxification of cadmium and play a key role in bacterial adaptation to heavy metal stress (Abbas et al., 2018; Abbas et al., 2018).

Industrial Applications: Efflux pump systems in cadmium-resistant bacteria have significant industrial applications, particularly in bioremediation processes aimed at removing cadmium from contaminated environments. Understanding the genetic and functional aspects of efflux pumps provides valuable insights for developing biotechnological solutions for cadmium pollution and environmental sustainability (Abbas et al., 2018; Abbas et al., 2018).

3. Metallothioneins and Chaperone Proteins in Bacterial Resistance to Cadmium

Metallothioneins and chaperone proteins play crucial roles in bacterial resistance to cadmium, contributing to the detoxification and sequestration of this toxic metal within bacterial cells. Understanding the functions of these proteins provides insights into the mechanisms by which bacteria adapt to cadmium stress and survive in contaminated environments.

Metallothioneins: Metallothioneins are small, cysteine-rich proteins that have a high affinity for binding heavy metals like cadmium. In bacterial cells, metallothioneins sequester cadmium ions, preventing their interaction with essential cellular components and reducing their toxic effects. By binding to cadmium, metallothioneins help to maintain metal homeostasis and protect bacterial cells from cadmium-induced damage (Tchounwou et al., 2012; Satarug et al., 2010).

Chaperone Proteins: Chaperone proteins are essential for the proper folding and function of metal-binding proteins, including metallothioneins, involved in cadmium detoxification. These proteins assist in the correct assembly of metallothioneins and other metal- binding proteins, ensuring their stability and functionality in the presence of cadmium stress. By facilitating the correct folding of metal-binding proteins, chaperone proteins enhance bacterial tolerance to cadmium and promote the efficient sequestration and detoxification of cadmium ions (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Functional Interplay: Metallothioneins and chaperone proteins work synergistically to protect bacterial cells from cadmium toxicity. Metallothioneins bind cadmium ions, while chaperone proteins ensure the proper folding and function of metallothioneins, enhancing their ability to sequester and detoxify cadmium. This functional interplay between metallothioneins and chaperone proteins is essential for bacterial resistance to cadmium and highlights the intricate molecular mechanisms that bacteria employ to survive in cadmium-contaminated environments (Agency for Toxic Substances and Disease Registry, 2012; Järup, 2003).

4. Enzymatic Detoxification

Enzymatic detoxification is a vital process employed by organisms, including bacteria, to neutralize and eliminate toxic substances like cadmium. Enzymes play a crucial role in catalyzing reactions that convert harmful compounds into less toxic or more easily excretable forms. Understanding the mechanisms of enzymatic detoxification provides insights into how organisms combat the deleterious effects of cadmium exposure and adapt to polluted environments.

Metallothioneins and Glutathione S-Transferases: Metallothioneins and glutathione S-transferases are key enzymes involved in enzymatic detoxification of cadmium. Metallothioneins bind to cadmium ions, sequestering them and preventing their interaction with cellular components. Glutathione S-transferases catalyze the conjugation of glutathione to cadmium, facilitating its excretion from the cell and reducing its toxicity. These enzymes play a critical role in protecting cells from cadmium-induced damage (Tchounwou et al., 2012; Satarug et al., 2010).

Oxidoreductases and Hydrolases: Oxidoreductases and hydrolases are enzymes that participate in the detoxification of cadmium by catalyzing redox reactions and hydrolysis processes. Oxidoreductases facilitate the conversion of cadmium ions to less toxic forms through reduction-oxidation reactions. Hydrolases break down cadmium complexes into simpler compounds that are easier to eliminate from the cell, reducing the overall burden of cadmium toxicity (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Cytochrome P450 Enzymes: Cytochrome P450 enzymes are involved in the metabolism of xenobiotics, including cadmium, by catalyzing the oxidation of organic compounds. These enzymes play a role in the biotransformation of cadmium into metabolites that are more readily excreted from the body. By enhancing the breakdown and elimination of cadmium, cytochrome P450 enzymes contribute to the detoxification process and protect cells from metal-induced damage (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Enzymatic Pathways and Regulation: Enzymatic detoxification of cadmium involves complex pathways and regulatory mechanisms that coordinate the expression and activity of detoxifying enzymes. Cells regulate the production of detoxification enzymes in response to cadmium exposure, ensuring a rapid and effective response to metal stress. Understanding the enzymatic pathways and regulatory networks involved in cadmium detoxification is essential for developing strategies to enhance metal tolerance and mitigate the toxic effects of cadmium contamination (Alloway, 2013; Agency for Toxic Substances and Disease Registry, 2012).

5. Biofilm Formation

Biofilm formation is a crucial adaptive strategy employed by bacteria to survive in environments contaminated with cadmium. This protective mechanism involves the aggregation of bacterial cells within a matrix of extracellular polymeric substances, creating a structured community that adheres to surfaces and provides resistance to environmental stresses, including cadmium exposure.

Extracellular Polymeric Substances (EPS): Biofilms consist of EPS, which are composed of polysaccharides, proteins, nucleic acids, and lipids. These substances form a protective matrix that shields bacterial cells from cadmium ions, preventing their penetration and reducing the toxic effects on the microbial community. EPS also facilitate nutrient exchange and communication among bacteria within the biofilm, enhancing their survival in cadmium-contaminated environments (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Adhesion and Colonization: Bacteria in biofilms adhere to surfaces through specific adhesion molecules and structures, allowing them to colonize and form multicellular communities. The adhesion of bacterial cells to surfaces promotes biofilm formation and provides a physical barrier that limits cadmium diffusion into the cells. This adhesion- mediated protection enhances bacterial resistance to cadmium stress and promotes the stability of the biofilm structure (Tchounwou et al., 2012; Satarug et al., 2010).

Quorum Sensing: Biofilm formation is regulated by quorum sensing, a cell- to-cell communication system that coordinates bacterial behavior in response to population density. Quorum sensing enables bacteria to synchronize their gene expression and physiological activities, leading to the production of EPS, adhesion factors, and other biofilm components. This coordinated response enhances the resilience of biofilms to cadmium exposure by promoting structural integrity and protective mechanisms within the microbial community (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Biofilm Maturation and Resistance: As biofilms mature, they develop complex three-dimensional structures that provide physical protection and chemical resistance to cadmium. The layered architecture of biofilms creates microenvironments with varying nutrient availability and oxygen levels, allowing bacteria to adapt to changing conditions and survive in cadmium-contaminated habitats. The mature biofilm structure enhances bacterial persistence and resistance to cadmium toxicity, highlighting the importance of biofilm formation as a survival strategy in metal-polluted environments (Alloway, 2013; Agency for Toxic Substances and Disease Registry, 2012).

2.3 Bioprocessing Mechanism for Cadmium

Cd tolerant bacteria can take advantage of seven primary mechanisms that lead to the contribution of geostable chemical species of Cd as pathways for Cd detoxification bioaacumulation (Bravo and Braissant , 2022):

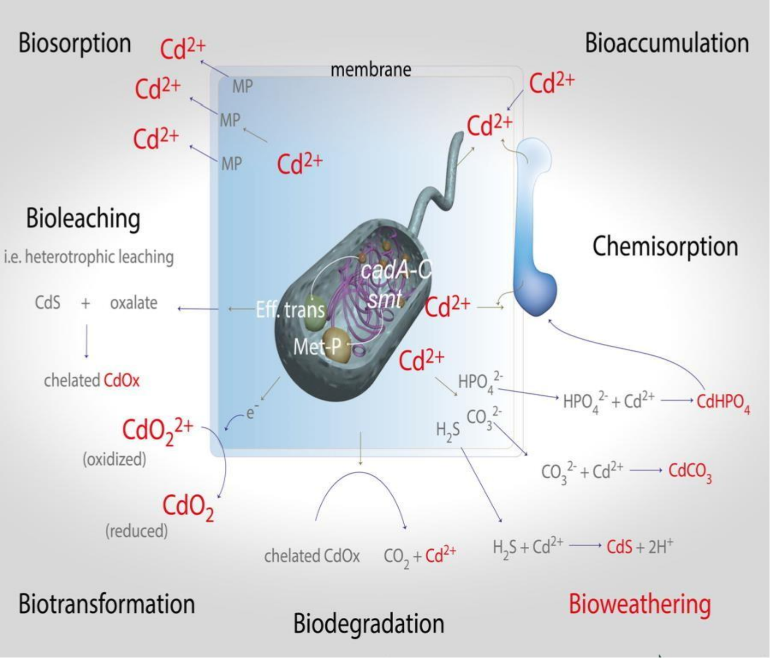

Figure (1): An overview of the Cd metabolic activity of CdtB in their environment

3. Biosorption

Bacteria have developed various mechanisms to process cadmium, a toxic heavy metal, and survive in contaminated environments. One of the most intriguing mechanisms is biosorption, a passive process by which bacteria bind and accumulate cadmium ions on their cell surfaces. Biosorption plays a critical role in bacterial cadmium detoxification and is a promising strategy for bioremediation.

Biosorption Mechanism: Biosorption involves the interaction of cadmium ions with functional groups on bacterial cell walls, such as carboxyl, phosphate, amino, and hydroxyl groups. These groups possess a negative charge, attracting positively charged cadmium ions through electrostatic interactions. Bacterial cell walls also contain extracellular polymeric substances (EPS), which can bind to cadmium ions, enhancing the biosorption process (Tchounwou et al., 2012; Satarug et al., 2010).

Bacterial Cell Wall Components: Bacterial cell walls consist of various components that contribute to cadmium biosorption. Peptidoglycan, a polymer of sugars and amino acids, contains carboxyl and amino groups that can bind cadmium ions. Teichoic acids, polymers of glycerol or ribitol, are present in Gram-positive bacteria and contain phosphate groups that can interact with cadmium ions. Lipopolysaccharides (LPS), a component of the outer membrane in Gram-negative bacteria, contain lipid A, core polysaccharides, and O-antigen polysaccharides, which provide numerous functional groups for cadmium binding (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Biosorption Kinetics: The kinetics of biosorption involve several stages, including the initial rapid adsorption phase, followed by a slower adsorption phase. The initial rapid phase is attributed to the interaction of cadmium ions with readily accessible functional groups on the bacterial cell surface. The slower phase involves the diffusion of cadmium ions into the bacterial cell wall, where they interact with additional functional groups. The biosorption process is influenced by factors such as pH, temperature, and the presence of other ions, which can affect the electrostatic interactions between cadmium ions and bacterial cell surfaces (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Biosorption Capacity: The biosorption capacity of bacteria varies depending on the species and strain. Some bacteria, such as Bacillus sp. and Pseudomonas sp., have been reported to have high biosorption capacities for cadmium ions. The biosorption capacity can be enhanced through genetic modifications or the addition of exopolymers, which provide additional functional groups for cadmium binding (Alloway, 2013; Agency for Toxic Substances and Disease Registry, 2012).

2. Bioleaching Mechanism

a process where microorganisms extract metals from ores or solid materials. Bioleaching involves the use of bacteria to solubilize and mobilize cadmium from minerals, ores, or contaminated sites, offering a sustainable and environmentally friendly approach to metal recovery and remediation.

Biooxidation: In bioleaching, bacteria oxidize sulfide minerals containing cadmium, releasing metal ions into solution. Bacteria like Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans are commonly used in bioleaching processes due to their ability to catalyze the oxidation of sulfide minerals, liberating cadmium ions in the process (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Acid Production: Bacteria involved in bioleaching produce organic acids and sulfuric acid as metabolic byproducts. These acids lower the pH of the environment, creating acidic conditions that enhance the solubility of cadmium and other metals present in the substrate. The increased solubility facilitates the leaching of cadmium ions from the solid matrix, making them available for recovery (Tchounwou et al., 2012; Satarug et al., 2010).

Metal Binding and Uptake: Some bacteria possess metal-binding proteins and transporters that facilitate the uptake and sequestration of cadmium ions. These proteins bind to cadmium, preventing its precipitation or re- adsorption onto solid surfaces. By sequestering cadmium within the bacterial cells, microorganisms can concentrate the metal for further processing or removal, aiding in the bioleaching efficiency (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Biofilm Formation: Bioleaching bacteria can form biofilms on mineral surfaces, creating a microenvironment that promotes metal dissolution and enhances bacterial attachment. Biofilms provide a protective barrier that concentrates bacterial activity on the mineral substrate, increasing the efficiency of cadmium extraction. Additionally, biofilms can trap cadmium ions, preventing their re-adsorption onto solid surfaces and facilitating their recovery (Alloway, 2013; Agency for Toxic Substances and Disease Registry, 2012

3. Enzymatic Transformation:

Bacteria utilize enzymes to catalyze the degradation of cadmium compounds. Enzymes like metallothioneins, metalloproteins, and metalloenzymes play crucial roles in binding, sequestering, and transforming cadmium ions into less toxic forms. These enzymes facilitate the breakdown of cadmium complexes, enhancing bacterial resistance to cadmium toxicity (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Metal-Resistant Bacteria: Certain bacterial species have evolved mechanisms to resist and biodegrade cadmium. Metal-resistant bacteria possess genetic adaptations that enable them to thrive in cadmium- contaminated environments. These bacteria can metabolize cadmium compounds, converting them into less harmful substances through enzymatic reactions and metabolic pathways specific to cadmium degradation (Tchounwou et al., 2012; Satarug et al., 2010).

Bioaccumulation and Bioconcentration: Bacteria can accumulate and concentrate cadmium within their cells as a means of detoxification. Through active transport mechanisms and sequestration processes, bacteria sequester cadmium ions, preventing their interaction with cellular components and reducing their toxic effects. Bioaccumulation and bioconcentration of cadmium by bacteria contribute to the biodegradation and detoxification of cadmium-contaminated environments (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Synergistic Interactions: Bacterial communities often exhibit synergistic interactions in the biodegradation of cadmium. Consortia of bacteria with complementary metabolic capabilities work together to degrade cadmium compounds efficiently. Synergistic interactions enhance the overall biodegradation potential of bacterial communities, leading to the effective removal and detoxification of cadmium from contaminated sites (Alloway, 2013; Agency for Toxic Substances and Disease Registry, 2012).

4. Biotransformation

Bacterial biotransformation of cadmium is a critical process that alters the chemical form of this toxic metal, influencing its bioavailability, toxicity, and mobility in the environment. Biotransformation involves the enzymatic conversion of cadmium ions into less toxic or more soluble forms, facilitating bacterial detoxification and the potential for bioremediation.

Reduction: Bacteria can reduce cadmium ions from their oxidized state (Cd^2+) to a lower oxidation state (Cd^0) through the action of enzymes like nitrate reductases, nitrite reductases, and hydrogenases. This reduction process can lead to the formation of cadmium nanoparticles, which are less toxic and more soluble than the original cadmium ions. The formation of cadmium nanoparticles by bacteria has been observed in various environmental settings, including soils, sediments, and wastewater (Satarug et al., 2010; Tchounwou et al., 2012).

Methylation: Bacteria can also methylate cadmium ions, converting them into methylcadmium (MeCd) compounds. Methylation is a biotransformation process that involves the addition of methyl groups (-CH3) to the cadmium ions, increasing their volatility and bioavailability. Although methylcadmium compounds are more toxic than cadmium ions, their increased volatility facilitates their removal from the environment through bacterial-mediated processes (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Complexation: Bacteria can produce complexing agents, such as organic acids and siderophores, to bind to cadmium ions, forming soluble complexes. Complexation reduces the toxicity of cadmium ions by preventing their interaction with essential cellular components. Additionally, the formation of soluble complexes enhances the mobility of cadmium ions, facilitating their removal from the environment through bacterial-mediated processes (Nordberg et al., 2014; McLaughlin & Singh, 1999).

5. Bioweathering

Bioweathering is a process where bacteria interact with cadmium- containing minerals, leading to mineral dissolution and the release of cadmium ions into the environment. Understanding the intricate details of bioweathering sheds light on how bacteria process cadmium and influence its mobility and bioavailability in ecosystems.

Biochemical Reactions: Bacteria produce organic acids, such as citric acid and oxalic acid, as well as chelating agents like siderophores, which facilitate the dissolution of cadmium-containing minerals. These compounds form complexes with cadmium ions, enhancing their solubility and promoting mineral breakdown. The release of cadmium into the environment through bioweathering contributes to its cycling and availability for uptake by other organisms (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Enzymatic Activities: Bacteria secrete enzymes, such as metalloproteases and oxidoreductases, that catalyze the breakdown of cadmium- containing minerals. These enzymes facilitate the cleavage of mineral bonds and the release of cadmium ions, accelerating the bioweathering process. Enzymatic activities play a crucial role in enhancing the efficiency of cadmium dissolution by bacteria and influencing the geochemical fate of cadmium in the environment (Tchounwou et al., 2012; Satarug et al., 2010).

Surface Interactions: Bacteria interact with mineral surfaces through adhesion and colonization, forming biofilms that promote mineral dissolution. The physical contact between bacteria and cadmium- containing minerals enhances the efficiency of bioweathering by providing a concentrated source of microbial activity at the mineral interface. Surface interactions play a significant role in the spatial distribution of bioweathering processes and the release of cadmium into the surrounding environment (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Significance of Bioweathering:

Bioweathering of cadmium by bacteria is a fundamental process that influences the cycling and bioavailability of this toxic metal in natural environments. By understanding the mechanisms of bioweathering, researchers can elucidate the role of bacteria in cadmium mobilization and transformation, with implications for bioremediation strategies,

ecosystem health, and metal cycling dynamics. Studying the intricate details of bioweathering enhances our knowledge of bacterial interactions with cadmium and their impact on environmental processes.

6. Bioaccumulation

Bacterial processing of cadmium involves various mechanisms, among which bioaccumulation is a significant and well-studied phenomenon. Bioaccumulation refers to the active or passive uptake and concentration of cadmium ions by bacteria, leading to a higher intracellular concentration than in the surrounding environment. This process plays a crucial role in the biogeochemical cycling of cadmium and has implications for bioremediation strategies and environmental management.

Bacterial Uptake of Cadmium: Bacteria can actively transport cadmium ions across their cell membranes using specific transport systems. These systems include transporters like Cation Diffusion Facilitators (CDFs) and P-type ATPases, which facilitate the uptake of cadmium ions into the bacterial cytoplasm. Once inside the cell, cadmium ions can interact with various proteins and ligands, leading to their sequestration and detoxification (Satarug et al., 2010; Tchounwou et al., 2012).

Intracellular Sequestration: After uptake, bacteria employ various strategies to sequester and detoxify cadmium ions. Metallothioneins, small cysteine-rich proteins, bind to cadmium ions, forming stable complexes that prevent the metal from interacting with essential cellular components. This sequestration process reduces the toxic effects of cadmium on bacterial cells and enhances their tolerance to the metal.

Additionally, bacteria can utilize other intracellular ligands, such as glutathione and phytochelatins, to bind and detoxify cadmium ions (Nordberg et al., 2014; McLaughlin & Singh, 1999).

Bioaccumulation Kinetics: The kinetics of bacterial bioaccumulation of cadmium are influenced by various factors, including the concentration of cadmium in the environment, the bacterial species and strain, and the physicochemical conditions of the system. Bacteria can exhibit different bioaccumulation patterns, such as biphasic or triphasic kinetics, depending on the intracellular concentration of cadmium and the availability of intracellular ligands. Understanding the kinetics of bacterial bioaccumulation is essential for developing effective bioremediation strategies and predicting the fate of cadmium in the environment (Järup, 2003; Kabata-Pendias & Mukherjee, 2007).

Bioaccumulation and Bioremediation: Bacterial bioaccumulation of cadmium has potential applications in bioremediation. By cultivating cadmium-accumulating bacteria in contaminated environments, it may be possible to reduce the concentration of cadmium in the soil, water, or air. However, the effectiveness of bioremediation strategies based on bacterial bioaccumulation depends on various factors, including the bioavailability of cadmium, the bacterial species and strain, and the physicochemical conditions of the system. Further research is needed to optimize bioremediation strategies and assess their long-term impacts on environmental and human health (Alloway, 2013; Agency for Toxic Substances and Disease Registry, 2012).

7. Chemisorption

This mechanism plays a significant role in the bioremediation of cadmium- contaminated environments and the detoxification of bacterial cells.

Chemisorption Process: Chemisorption is a chemical adsorption process where cadmium ions bind to bacterial surfaces through chemical reactions. This process involves the formation of covalent or ionic bonds between cadmium ions and functional groups on the bacterial surface, such as carboxyl, hydroxyl, amino, and phosphate groups. The binding of cadmium ions to these functional groups reduces their bioavailability and toxicity, facilitating the detoxification of bacterial cells (McLaughlin & Singh, 1999; Alloway, 2013).

Bacterial Surface Components: Bacterial surfaces are rich in extracellular polymeric substances (EPS) that contain functional groups capable of binding cadmium ions. EPS is a complex mixture of polysaccharides, proteins, lipids, and nucleic acids that provide a protective layer around bacterial cells. The functional groups present in EPS, such as carboxyl, hydroxyl, amino, and phosphate groups, readily interact with cadmium ions, facilitating the chemisorption process (Kabata-Pendias & Mukherjee, 2007; Tchounwou et al., 2012).

Bacterial Adaptation and Evolution: Bacteria have evolved to adapt to cadmium-contaminated environments by enhancing their chemisorption capabilities. Through genetic modifications, bacteria can increase the production of EPS and the expression of functional groups capable of binding cadmium ions. This adaptation enhances their survival in cadmium-contaminated environments and contributes to the bioremediation of contaminated sites (Järup, 2003; Nordberg et al., 2014).

Biofilm Formation: Bacteria can form biofilms as a protective mechanism against cadmium exposure. Biofilms are complex communities of bacteria embedded in a matrix of EPS. The EPS matrix provides a scaffold for cadmium binding, facilitating the chemisorption process and reducing the bioavailability of cadmium ions within the biofilm. This mechanism enhances bacterial survival in cadmium-contaminated environments and contributes to the bioremediation of contaminated sites (Agency for Toxic Substances and Disease Registry, 2012; Satarug et al., 2010).

Conclusion

The comprehensive exploration of cadmium, its harmful effects, distribution, bioprocessing mechanisms, bacterial resistance, permissible exposure limits, sources of pollution, and toxic effects on bacteria provides a holistic understanding of the challenges and implications associated with this toxic heavy metal.

From examining the detrimental impact of cadmium on human health to delving into the intricate mechanisms of bacterial resistance and bioremediation, this research paper underscores the urgency of addressing cadmium pollution and its repercussions on ecosystems and public health.

Regulatory bodies' establishment of permissible exposure limits and the identification of sources contributing to cadmium pollution highlight the importance of proactive measures to mitigate environmental contamination and safeguard human well-being.

Moreover, the interconnectedness between heavy metal toxicity, and bacterial responses, underscores the need for integrated approaches to address the complex challenges posed by cadmium pollution.

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