RESEARCH PAPER

Bioremediation Studies on the Response of Different Bacteria in Cadmium-Contaminated Soil: A Review

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Abstract
Cadmium (Cd) is one of the most hazardous heavy metals in soil because it is highly mobile, readily taken up by plants, persistent, and toxic even at relatively low concentrations. Major anthropogenic sources include mining, smelting, electroplating, phosphate fertilizers, and sewage sludge application. In agricultural soils, Cd contamination suppresses microbial activity, disturbs nutrient cycling, reduces crop productivity, and increases human exposure through the food chain. Microbial bioremediation has emerged as a promising, low-cost, and environmentally compatible strategy for restoring Cd-contaminated soils. Among microorganisms, bacteria are especially attractive because of their rapid growth, metabolic versatility, adaptability, and ability to interact with both soil minerals and plant roots. This review summarizes the bioremedial responses of different bacterial genera in Cd-contaminated soil, with emphasis on *Bacillus*, *Pseudomonas*, *Burkholderia*, *Enterobacter*, *Serratia*, and other plant growth-promoting rhizobacteria. Key bacterial mechanisms include biosorption, bioaccumulation, extracellular polymer complexation, precipitation, redox-independent immobilization, pH modification, siderophore production, phosphate solubilization, and ACC deaminase-mediated stress relief in plants. Comparative evidence indicates that bacterial responses differ by genus, strain origin, tolerance threshold, soil chemistry, and whether the desired outcome is Cd immobilization or plant-assisted phytoextraction. Recent studies further show that indigenous isolates from contaminated sites and multi-strain consortia often outperform single strains under realistic soil conditions. Despite encouraging progress, field-scale consistency remains limited by survival, competition with native microbiota, fluctuating soil properties, and regulatory concerns. Future work should prioritize genomics-guided strain selection, carrier-based formulations, stable consortia, and long-term field validation. Overall, bacteria-based remediation represents a viable and increasingly sophisticated approach for mitigating Cd toxicity in soils and improving agricultural sustainability.

Keywords: cadmium, contaminated soil, bacterial bioremediation, biosorption, plant growth-promoting rhizobacteria, *Bacillus*, *Pseudomonas*, *Burkholderia*, heavy metal remediation

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1. Introduction

Cadmium contamination of soil is a major environmental and agricultural concern because Cd is non-biodegradable, easily transferred from soil to plants, and toxic to both soil biota and higher organisms. Agricultural contamination commonly arises from industrial emissions, mining activities, wastewater irrigation, sewage sludge disposal, and long-term use of phosphate fertilizers.[1] Once in soil, Cd can alter microbial community composition, inhibit enzymatic processes, reduce plant growth, and ultimately accumulate in edible plant parts, creating a direct pathway to human exposure. These features make Cd one of the priority contaminants in soil remediation research.[2]

Conventional remediation methods such as excavation, soil washing, vitrification, or chemical stabilization can reduce contamination, but they are often costly, disruptive, and less suitable for large agricultural areas.[3] Microbial bioremediation has therefore gained attention as a more sustainable alternative. Bacteria are of particular interest because they respond rapidly to environmental stress, can colonize the rhizosphere efficiently, and possess multiple mechanisms for tolerating and transforming the bioavailability of heavy metals. Recent reviews describe bacterial remediation as one of the most promising strategies for Cd-polluted soil, especially when integrated with plants or organic/mineral amendments.[4]

The phrase “response of different bacteria” in Cd-contaminated soil refers not only to their survival under Cd stress, but also to how effectively they immobilize, accumulate, sequester, or indirectly regulate Cd through plant interaction. Some bacteria mainly decrease Cd bioavailability and protect crops, while others stimulate plant growth and metal uptake, making them useful in assisted phytoextraction. This review focuses on these distinct bacterial responses and compares the performance of major bacterial groups reported in the literature.[5]

2. Cadmium Toxicity in Soil and Its Impact on Microbial Systems

Cd is highly phytotoxic and interferes with root elongation, nutrient uptake, membrane stability, antioxidant balance, and cellular metabolism. In soil systems, Cd also affects microbial biomass, enzyme activity, and biodiversity.[6] Sensitive microbial populations decline, while resistant organisms may become dominant. This shift has important ecological

*Author for Correspondence: anubhapandey405@gmail.com consequences because soil bacteria regulate decomposition, mineralization, nutrient cycling, and rhizosphere communication. Thus, the bacterial response to Cd is both a stress-survival issue and an ecological adaptation that can be harnessed for remediation.[7]

The degree of Cd toxicity in soil depends strongly on pH, cation exchange capacity, organic matter, redox conditions, clay content, and interactions with other ions. Because of these variables, the same bacterial strain may perform differently across soils. Recent soil-remediation studies repeatedly emphasize that changes in pH, organic carbon characteristics, and microbial community structure can strongly influence Cd availability and plant uptake. This is why bacterial remediation must be evaluated not only by laboratory tolerance, but also by its effect on soil chemistry and crop response.[8]

3. Why Bacteria Are Useful for Cd Bioremediation

Bacteria are useful in Cd remediation because they multiply quickly, adapt to local conditions, and employ several metal-handling mechanisms simultaneously. These mechanisms include passive adsorption on cell walls, active transport and intracellular sequestration, extracellular polymeric substance binding, precipitation with anions such as phosphate or carbonate, and modulation of the rhizosphere through pH changes and metabolite release. Reviews published in 2023–2025 consistently identify bacteria as central players in sustainable heavy-metal remediation due to this mechanistic diversity.[9]

Another reason bacteria are valuable is their close association with plant roots. Plant growth-promoting rhizobacteria, or PGPR, can increase root biomass, improve nutrient acquisition, reduce ethylene-mediated stress via ACC deaminase, and regulate Cd uptake or translocation. Depending on the strain and plant system, this can either enhance phytoextraction or reduce Cd movement into edible tissues. Thus, bacterial remediation is especially powerful when considered as a soil-plant-microbe interaction rather than a single-organism process.[10]

4. Mechanisms of Bacterial Response to Cadmium

4.1 Biosorption

Biosorption is generally considered the earliest and fastest bacterial defense response against cadmium because it takes place at the cell surface before Cd enters the cytoplasm. In this process, Cd^{2+} ions are passively bound by negatively charged functional groups located on the outer layers of the bacterial cell envelope. These include carboxyl groups, phosphate groups, amino groups, hydroxyl groups, and sulfhydryl groups present in peptidoglycan-associated polymers, membrane proteins, and extracellular biomolecules. Since this mechanism is largely metabolism-independent, even inactive or dead bacterial biomass may retain substantial Cd-binding capacity. The process mainly involves electrostatic attraction, ion exchange, surface complexation, and coordination interactions, which collectively decrease the freely mobile and bioavailable fraction of Cd in soil.[11,12]

At the mechanistic level, biosorption begins when hydrated Cd^{2+} ions diffuse from the soil solution toward the bacterial surface. Once near the cell wall, the metal ions interact with deprotonated ligands such as carboxylate and phosphate groups. These groups can replace lighter cations like H^+, Na^+, Ca^{2+}, or Mg^{2+} through ion-exchange reactions. After this initial contact, Cd may form either weak outer-sphere complexes or stronger inner-sphere coordination complexes with the bacterial surface. In some conditions, this interaction may proceed further toward localized precipitation or stable immobilization. Thus, biosorption should not be viewed as a single adsorption step, but rather as a sequence of physicochemical events leading from rapid surface binding to more persistent Cd stabilization.[11,13]

Gram-positive bacteria such as Bacillus are often more effective biosorbents because their cell wall is thick and rich in metal-binding ligands. The multilayered peptidoglycan network contains abundant reactive sites, while teichoic acids and lipoteichoic acids contribute strongly negatively charged phosphodiester groups that show high affinity for divalent metal ions such as Cd^{2+}. This dense wall architecture acts like a natural ion-exchange matrix, enabling Bacillus cells to retain cadmium on the cell surface and reduce its intracellular entry. Such surface retention is particularly important because it minimizes direct toxic damage to intracellular enzymes, proteins, and nucleic acids.[12,14]

A further extension of this mechanism involves extracellular polymeric substances (EPS), which enlarge the biosorption zone beyond the cell wall. EPS is composed of polysaccharides, proteins, uronic acids, and other macromolecules carrying functional groups capable of trapping Cd ions. In soil, this forms a protective barrier around bacterial cells and biofilms, limiting metal diffusion toward the membrane. EPS-mediated biosorption also promotes aggregation and complexation of Cd into less mobile fractions, thereby reducing phytotoxicity and leaching potential. Recent studies suggest that Cd-resistant bacteria often combine direct cell-wall adsorption with EPS-assisted binding and microprecipitation, making biosorption part of a broader extracellular immobilization strategy.[13,15]

From a bioremediation perspective, the significance of biosorption lies in its capacity to alter Cd speciation in soil. By shifting Cd from the dissolved and exchangeable pools into cell-bound or EPS-bound fractions, bacteria reduce the fraction most readily available for plant uptake. Although biosorption alone may not completely remove cadmium from soil, it serves as a rapid front-line stabilization mechanism that supports slower downstream processes such as intracellular sequestration, biomineralization, and plant-microbe-assisted remediation. A novel concept emerging from recent studies is that biosorption is not merely passive metal sticking, but an adaptive extracellular defense system linked with stress-induced EPS secretion, cell-surface remodeling, and biofilm-mediated stabilization. This modern view gives biosorption greater mechanistic and applied significance in cadmium bioremediation research.[11,13,15]

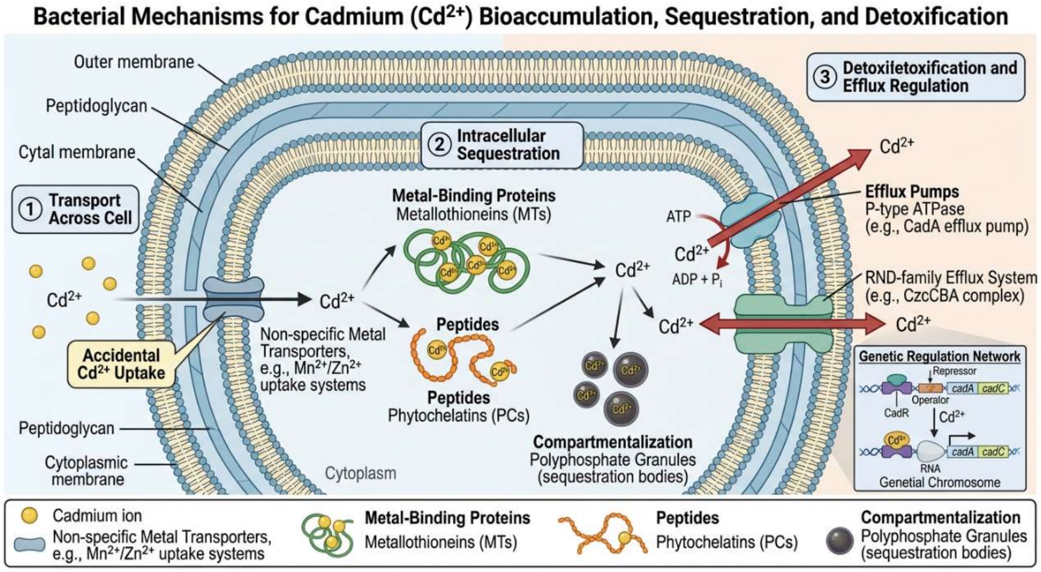
Table. Mechanism of bacterial biosorption of cadmium in contaminated soil

S. No.	Mechanistic aspect	Detailed explanation	Major novelty / significance	Example bacterial group	Ref.
1	Initial surface interaction	Biosorption is the earliest bacterial response to Cd stress because Cd^{2+} first contacts the outer cell envelope before entering the cytoplasm. This first interaction rapidly lowers the dissolved Cd fraction in the surrounding soil solution.	Shows that detoxification can begin immediately, even before active metabolism is induced.	General Cd-resistant bacteria	[11,12]
2	Role of functional groups	Negatively charged functional groups such as **carboxyl, phosphate, amino, hydroxyl, and sulfhydryl** groups present on cell walls, membrane proteins, and extracellular materials bind Cd^{2+} through electrostatic attraction and ligand interaction.	Explains why bacterial surfaces behave like natural bioadsorbents without chemical modification.	*Bacillus*, *Burkholderia*, *Pseudomonas*	[11,13]
3	Ion exchange mechanism	Cd^{2+} replaces lighter cations such as H^+, Na^+, Ca^{2+}, and Mg^{2+} already associated with the bacterial surface. This ion exchange is one of the major physicochemical routes for Cd immobilization.	Important because it links soil chemistry and bacterial cell-wall chemistry directly.	Cd-tolerant rhizobacteria	[11,13]
4	Surface complexation	After the initial attraction, Cd forms outer-sphere and inner-sphere complexes with functional groups on the bacterial surface. These interactions may become stronger and more stable with time.	Demonstrates that biosorption is not only “sticking” but a coordinated metal-binding process.	*Bacillus* spp.	[11,14]
5	Gram-positive cell-wall advantage	Gram-positive bacteria such as *Bacillus* possess thick peptidoglycan layers rich in reactive sites. Teichoic acids and lipoteichoic acids provide abundant negatively charged phosphodiester groups that strongly attract Cd^{2+}.	Gives Gram-positive bacteria a naturally high adsorption potential and makes them promising biosorbents for soil remediation.	*Bacillus* spp.	[12,14]
6	Prevention of intracellular toxicity	By retaining Cd on the outer surface, bacteria reduce metal entry into the cytoplasm. This protects intracellular enzymes, proteins, DNA, and membrane integrity from Cd-induced toxicity.	Shows biosorption as a protective barrier, not just a removal process.	*Bacillus*, other resistant bacteria	[11,12]
7	EPS-assisted biosorption	Extracellular polymeric substances (EPS) contain polysaccharides, proteins, and uronic acids with reactive binding sites that trap Cd outside the cell. EPS enlarges the adsorption zone beyond the wall itself.	Novel because EPS turns the bacterial microenvironment into an extended metal-capturing matrix.	*Bacillus*, *Burkholderia*	[13,15]
8	Biofilm-mediated sequestration	In biofilms, EPS and clustered bacterial cells create a three-dimensional barrier that captures	Biofilm formation improves long-term immobilization under soil conditions.	Soil and rhizosphere biofilm-	[15,16]

		Cd, slows diffusion, and enhances stable sequestration.		forming bacteria	
9	Microprecipitation and extracellular immobilization	After adsorption, Cd may further convert into less mobile forms through extracellular complexation or precipitation near the bacterial surface. This helps reduce exchangeable Cd in soil.	Indicates that biosorption can progress into stronger and more persistent immobilization.	*Bacillus* sp. 6–6, *Burkholderia* sp. 1–22	13,15
10	Effect on soil Cd bioavailability	Biosorption shifts Cd from dissolved/exchangeable fractions to cell-bound or EPS-bound fractions, thereby reducing plant uptake and leaching risk.	Highly relevant for agricultural soils where the goal is crop safety.	Rhizosphere bacteria	13,15,17
11	Metabolism-independent character	Since biosorption is largely passive, even non-living or inactive bacterial biomass may still bind Cd effectively.	Makes bacterial biomass useful as a low-cost biosorbent material in remediation systems.	Live and dead bacterial biomass	11,12
12	Adaptive surface remodeling	Recent work suggests that bacterial surfaces are dynamic and may respond to Cd stress through changes in EPS secretion, wall chemistry, and biofilm formation, thereby enhancing biosorption efficiency.	This is the modern novelty: biosorption is now seen as an **adaptive extracellular defense system**, not merely passive adsorption.	Stress-adapted indigenous Cd-resistant bacteria	15,16

4.2 Bioaccumulation and Intracellular Sequestration

Some bacteria transport Cd into the cell and sequester it intracellularly using metal-binding proteins, peptides, or compartmentalization processes. Although intracellular accumulation can be risky for cell survival, resistant strains manage this through detoxification systems and efflux-regulation networks. The 2025 review on Cd bioaccumulation highlights that both biosorption and intracellular handling are central to bacterial Cd removal and should be studied together rather than separately.[12]



This figure 1 is a conceptual summary of how bacteria handle cadmium (Cd^{2+}) after exposure. It organizes the response into three linked stages: (1) entry of Cd^{2+} into the cell, (2) intracellular sequestration to reduce free toxic Cd^{2+}, and (3) active detoxification by efflux pumps and genetic regulation. The figure is best read as a generalized model, not as one pathway used identically by every bacterium. In reality, different strains rely on different combinations of uptake control, sequestration, and export, and the "outer membrane" shown in the figure is most consistent with a Gram-negative-like envelope, whereas some mechanisms shown, such as CadA-type systems, are also well known in other bacteria.[18-21]

4.2. 1. Transport across the cell: how cadmium gets in

The left side of the figure shows Cd^{2+} outside the cell and its movement inward through a transporter labeled as a non-specific metal transporter. This reflects an important principle of cadmium toxicology: bacteria usually do not possess a dedicated "cadmium importer." Instead, Cd^{2+} often enters the cell accidentally by exploiting transport systems that normally carry essential divalent cations such as Mn^{2+}, Zn^{2+}, and sometimes Mg^{2+}. That is why the image labels this step as "accidental Cd^{2+} uptake." Once cadmium enters, it can displace physiologically useful metals from enzymes and proteins and disturb metal homeostasis. This accidental entry is one of the reasons cadmium is so damaging even at relatively low concentrations.[18,19]

In structural terms, the figure depicts Cd^{2+} crossing the cell envelope and reaching the cytoplasm. The message here is that membrane transport is the first intracellular bottleneck of Cd toxicity. If a bacterium reduces entry, it lowers internal damage; if entry still occurs, the cell must rapidly buffer or expel Cd^{2+}. The figure therefore places uptake at the beginning of the detoxification chain.[18,19]

4.2.2. Intracellular sequestration: how the cell neutralizes free Cd^{2+}

The center of the image is labeled "Intracellular Sequestration." This means that after Cd^{2+} enters the cytoplasm, the bacterium tries to lower the concentration of free, reactive cadmium ions by binding them to cellular ligands or by storing them in less harmful forms. This is crucial because free Cd^{2+} can interact with thiol-containing enzymes, membranes, nucleic acids, and redox systems, leading to metabolic collapse.[18,19]

a) Metal-binding proteins: metallothioneins

One branch in the figure shows metal-binding proteins, especially metallothioneins (MTs). Metallothioneins are small, cysteine-rich proteins that bind heavy metals through their thiol groups. In bacterial cadmium resistance, MT-like proteins function as cytoplasmic metal buffers: they capture Cd^{2+} and reduce the amount of free ion available to damage other cellular targets. Reviews of microbial Cd resistance specifically identify bacterial metallothioneins as one of the important intracellular detoxification strategies, although this mechanism is not equally dominant in all species.[18,22]

Mechanistically, MTs act like molecular sponges for Cd^{2+}. Because sulfur in cysteine has high affinity for soft metal ions such as cadmium, Cd–thiolate complexes are relatively stable. In the context of this image, the MT cluster in the middle represents the idea that bacteria can convert freely diffusing Cd^{2+} into a protein-bound, less toxic intracellular pool.[18,22]

b) Peptides: thiol-rich chelators and the "phytochelatin" label

Another branch shows peptides and labels them as phytochelatins (PCs). The important idea here is correct: thiol-rich peptides can chelate Cd^{2+} and sequester it inside cells. However, one nuance is worth noting. Classical phytochelatins are better established in plants, algae, and fungi than as a universal native bacterial mechanism. In bacteria, glutathione-based protection is common, and phytochelatin-like systems have also been demonstrated in engineered bacterial strains, where expression of phytochelatin synthase substantially increased Cd accumulation. So, in this image, the "PCs" label is best interpreted as representing thiol-peptide-mediated cadmium chelation, including native glutathione-related buffering and, in some systems, engineered phytochelatin production.[18,19,23]

This part of the figure is mechanistically important because it shows that bacteria do not rely on a single protein family. Instead, they can use multiple sulfur-rich intracellular ligands to trap Cd^{2+}. That gives the cell time to activate slower genetic and membrane-export responses.[18,23]

c) Compartmentalization: polyphosphate granules

The image also includes "compartmentalization" and depicts polyphosphate granules (sequestration bodies). The core meaning is that some microbes can reduce Cd toxicity by transferring metal into less reactive intracellular stores or by associating it with polyphosphate-rich material. Polyphosphate is increasingly recognized as a contributor to heavy-metal sequestration in microbes because it can participate in metal binding and in the formation of metal-phosphate associations that reduce free cytosolic metal stress. In the figure, these dark granules symbolize that cadmium is not left free in the cytoplasm but is redirected into safer intracellular reservoirs.[18,19]

Taken together, the whole middle compartment of the image illustrates a common principle: the toxic threat is not only total Cd, but especially free intracellular Cd^{2+}. Binding to MTs, peptides, or polyphosphate-like stores decreases that free fraction and therefore lowers toxicity.[18,22,23]

4.2. 3. Detoxification and efflux regulation: how the cell pumps cadmium out

The right side of the figure is the active detoxification module. It shows that once cadmium is sensed internally, bacteria can use efflux pumps to export Cd^{2+} out of the cell. This is one of the best-characterized cadmium resistance mechanisms in bacteria. Reviews consistently identify P-type ATPases, RND-family exporters, and CDF-family transporters as major components of bacterial Cd resistance.[18,19]

a) P-type ATPase (CadA)

The upper pump in the image is labeled P-type ATPase, with CadA given as the example. CadA is a classic ATP-driven metal exporter. It uses the energy of ATP hydrolysis to move toxic Cd^{2+} away from the cytoplasm. In mechanistic terms, CadA is often considered the fast-response exporter: when intracellular Cd^{2+} rises, CadA can rapidly decrease cytoplasmic metal burden before severe damage occurs. The ATP → ADP + Pi shown next to the pump indicates that this transport is energy-dependent.[18,20,21]

b) RND-family efflux system (CzcCBA)

The lower exporter is labeled RND-family efflux system, specifically CzcCBA. This is especially important in Gram-negative bacteria, where the CzcCBA system forms a trans-envelope efflux complex that can move metal out of the cell more completely than a single-membrane pump. In Pseudomonas putida and Pseudomonas aeruginosa, the Czc and Cad systems are now understood to be cooperative rather than redundant. CadA responds quickly, while CzcCBA provides strong outward transport once the system is fully induced.[20,21]
This division of labor is exactly what the image is trying to communicate: rapid first defense plus high-capacity export. In other words, bacteria first buffer the shock and then establish sustained detoxification.[20,21]

4.2.4. Genetic regulation network: how the cell senses cadmium and turns resistance genes on

The small panel at the bottom right of the image shows a genetic regulation network, including a regulator and operator region controlling genes such as cadA and cadC/cadR-related elements. The biological point is that cadmium resistance is inducible: bacteria do not always express all detoxification proteins at maximum levels. Instead, metal-responsive regulators sense Cd^{2+} or related metal stress and activate transcription of efflux and resistance genes.[18,20,21]

In Pseudomonas, studies show that CadR can activate cadmium-responsive export systems and also influence the expression of Czc machinery. This creates a regulatory cascade in which Cd entry leads to sensing, sensing leads to gene induction, and gene induction leads to active export. That is why the image places gene regulation next to the efflux pumps rather than separately: transcriptional control is part of the detoxification response, not just background genetics.[20,21]

4.2.5. What the whole image means biologically

Overall, the figure presents cadmium detoxification as a sequential but overlapping defense system:

1. Cd^{2+} enters accidentally through transporters for essential divalent metals.
2. The cytoplasm buffers Cd^{2+} using MTs, thiol-rich peptides, and sequestration bodies.
3. Efflux systems remove Cd^{2+}, while regulatory proteins switch resistance genes on.[18-21]

The deeper message is that bacterial cadmium resistance is not a single event like “adsorption” or “pumping out.” It is a layered survival program integrating accidental uptake, intracellular binding, stress sensing, and active export. That integrated response is what makes cadmium-resistant bacteria useful in bioremediation: they can survive in contaminated environments and convert highly bioavailable Cd^{2+} into cell-bound, sequestered, or expelled forms that are less damaging to the cell and sometimes less bioavailable in the surrounding environment.[18,19]

4.3 Efflux Systems and Metal Resistance Machinery

A major bacterial response to Cd is active efflux. Cd-resistant bacteria possess transporters and resistance genes that pump toxic ions out of the cytoplasm, reducing intracellular damage. Reviews on microbial Cd resistance emphasize that tolerance is often gene-regulated and linked to broader metal-resistance networks, which explains why some isolates tolerate Zn, Cd, and other metals simultaneously.[13]

4.4 Extracellular Polymeric Substances and Complexation

Extracellular polymeric substances, or EPS, can trap Cd outside the cell by forming stable complexes. This mechanism is particularly important in soil because it reduces freely exchangeable Cd and helps form less bioavailable pools. In the 2024 rice-rhizosphere study, Burkholderia sp. 1–22 and Bacillus sp. 6–6 reduced Cd bioavailability through precipitation, bacterial adsorption, and complexation with extracellular polymers in both leachate fermentation and pot experiments.[14]

4.5 Precipitation and Immobilization

Some bacteria alter local chemistry so that Cd precipitates as less soluble mineral forms. This can happen through phosphate release, carbonate generation, pH modification, or interaction with microbial metabolites. Immobilization is particularly desirable in food-crop soils where the goal is to reduce plant uptake rather than extract Cd. Several recent studies highlight this route as one of the most practical bacterial contributions under field-like conditions.[15]

4.6 Plant Growth Promotion Under Cd Stress

PGPR can reduce the physiological damage of Cd to plants by producing indole compounds, siderophores, phosphatases, and ACC deaminase, and by improving root architecture and nutrient uptake. The classical Brassica juncea work showed a positive correlation between ACC deaminase activity and root growth promotion in Cd-stressed plants, indicating that bacterial stress-modulation traits can be as important as direct metal binding.[16]

5. Response of Different Bacterial Genera in Cd-Contaminated Soil

5.1 *Bacillus*

Bacillus species are among the most studied Cd-remediating bacteria because they are robust, spore-forming, and easy to formulate as inoculants. Their thick cell walls support strong biosorption, and many strains also produce siderophores, enzymes, and extracellular polymers. Recent work from Cd-contaminated mining areas identified two Bacillus cereus strains, C9 and C27, that tolerated Cd concentrations from 100 to 500 mg/L in isolation media and showed maximum adsorption around 36–48 h, with strong siderophore production suggested as one contributor to their Cd resistance.[17]

The 2024 rhizosphere study also found that Bacillus sp. 6–6 reduced Cd bioavailability through adsorption, precipitation, and EPS-mediated complexation, while also improving rice seedling dry weight under Cd stress. These findings support the view that Bacillus is especially useful when the aim is stabilization and plant protection rather than maximal Cd mobilization.[18]

5.2 *Pseudomonas*

Pseudomonas species are important because they colonize roots efficiently, respond rapidly to environmental change, and often influence rhizosphere pH and enzyme activities. In rice, Pseudomonas TCd-1 was reported to reduce Cd uptake and accumulation, and this effect was associated with changes in soil pH, enzyme activities, and Cd availability. That makes Pseudomonas particularly valuable for crop-safety approaches in contaminated agricultural soils.[19]

Some Pseudomonas strains also act as classic PGPR, producing siderophores and phytohormone-related metabolites that improve plant vigor under heavy metal stress. Because of these traits, Pseudomonas often performs best in rhizosphere-assisted remediation rather than as a free-soil inoculant alone.[20]

5.3 *Burkholderia*

Burkholderia has received increasing attention because many strains combine Cd tolerance with strong plant-growth-promoting activity. In the 2024 rice-rhizosphere study, Burkholderia sp. 1–22 significantly promoted rice growth under both control and Cd conditions and reduced Cd bioavailability through multiple mechanisms. This multi-mechanistic behavior is important because successful field remediation usually requires both metal stabilization and biological compatibility with the crop system.[21]

5.4 *Enterobacter*

Enterobacter species are often isolated from industrial or agrochemically impacted soils and can show strong Cd tolerance. A 2023 study identified Enterobacter hormaechei SFC3 from contaminated soil as the most Cd-tolerant among tested isolates, highlighting the importance of selecting native strains adapted to local stress conditions. Separate reports on Enterobacter cloacae also support its potential as a potent Cd-bioaccumulating bacterium. Together, these findings suggest that Enterobacter may be particularly useful where fast growth and metal accumulation are desired.[22]

5.5 *Serratia*

Serratia species have been reported as Cd-resistant PGPR with benefits for crop growth under metal stress. Studies on Serratia marcescens showed enhanced phytoremediation potential and improved stress tolerance in plants exposed to Cd, while more recent work in rice has suggested that Serratia can help mitigate Cd toxicity by modulating uptake and antioxidant responses. This makes Serratia a relevant genus for plant-associated remediation, especially where maintaining crop vigor is important.[23]

5.6 Other Cd-Resistant and Rhizosphere Bacteria

Beyond the major genera above, studies continue to report useful Cd responses in Variovorax, Flavobacterium, Acinetobacter, and mixed indigenous communities from contaminated soils. The classical Brassica juncea study identified several Cd-tolerant root-associated bacteria and showed that ACC deaminase activity correlated with root-growth promotion. More recent reviews likewise emphasize that remediation performance often reflects trait combinations rather than taxonomy alone.[24]

6. Single Strains Versus Bacterial Consortia

Single strains are useful for mechanistic studies, but consortia often perform better in complex soils because different species contribute complementary functions such as adsorption, pH buffering, phytohormone support, and nutrient mobilization. A 2025 review of bacterial consortia concluded that consortia are often more effective than individual strains for pollutant removal because they combine metabolic diversity and improve resilience under fluctuating conditions. This principle is highly relevant to Cd-contaminated soils, where no single mechanism is usually sufficient.[25]

However, consortia are not automatically superior. Their success depends on compatibility, persistence, and competition with native microbiota. Poorly designed mixtures may lose activity after introduction to real soil. As a result, the best performing consortia are usually assembled from indigenous or site-adapted isolates with verified complementary traits.[26]

7. Bacteria-Assisted Phytoremediation

One of the strongest current directions in Cd remediation is bacteria-assisted phytoremediation. In this approach, bacteria are not expected to solve contamination alone; instead, they improve the efficiency of suitable plants by enhancing root development, stress tolerance, and metal handling in the rhizosphere. Reviews published in 2023 and 2024 show that PGPR can either increase plant Cd extraction or decrease Cd translocation to edible organs, depending on plant type and microbial mechanism.[27]

For example, Cd-tolerant PGPR associated with Brassica juncea improved root elongation and were proposed as inoculants for phytoremediation systems. Similarly, work with Solanum nigrum and Cd/Pb-resistant bacteria showed improved plant growth and phytoextraction performance. These studies demonstrate that bacterial response should be judged not only by Cd removal from soil solution, but also by whole-plant outcomes.[28]

8. Factors Influencing Bacterial Bioremedial Response

The performance of bacteria in Cd-contaminated soil is shaped by both biological and physicochemical factors. Soil pH is especially important because it controls Cd solubility and bacterial surface charge. Organic matter, clay minerals, competing ions, salinity, moisture, and temperature also affect metal availability and microbial activity. Several recent studies on rice systems show that changes in pH, cation exchange capacity, and organic carbon complexity can meaningfully alter Cd behavior and bacterial community composition.[29]

Strain origin also matters. Indigenous isolates from polluted sites often show better survival and performance than non-native laboratory strains because they are already adapted to mixed stressors. The 2025 Bacillus cereus mining-soil study is a good example: the isolated strains combined Cd resistance with salt tolerance and multiple useful physiological traits, making them more realistic candidates for application.[30]

9. Current Limitations

Despite promising laboratory and pot results, several limitations still restrict large-scale bacterial remediation. First, many studies use sterile or simplified systems that do not reflect field competition. Second, bacterial survival after inoculation can decline sharply because of predation, nutrient limitation, or incompatibility with native communities. Third, many papers report short-term decreases in Cd bioavailability but fewer provide long-term field validation across seasons and soil types. Reviews in this area repeatedly identify formulation stability, field persistence, and reproducibility as unresolved challenges.[31]

Another limitation is that “remediation” may mean different things in different studies. Some aim to immobilize Cd and reduce crop uptake; others aim to increase plant extraction. These goals are not identical and may even require opposite microbial effects on Cd mobility. Therefore, bacterial efficacy should always be interpreted in relation to the remediation objective and crop context.

10. Future Prospects

Future research is moving toward genomics-guided screening, function-based selection, and engineered inoculant formulations. Reviews from 2025 emphasize the need to identify genes and enzymes associated with Cd bioaccumulation, resistance, and survival in real soil systems. Carrier-based delivery, microbe-plus-biochar systems, and tailored consortia are also likely to improve persistence and field performance.

There is also growing interest in linking microbiome structure with crop safety. Root endophytic community studies in rice suggest that more complex microbial networks may reduce Cd uptake by plants, indicating that future remediation may involve steering microbial communities rather than simply adding one strain. This systems-level approach is likely to define the next phase of bacterial Cd bioremediation.

11. Conclusion

The literature clearly shows that different bacteria exhibit distinct and useful responses in Cd-contaminated soil. *Bacillus* is frequently effective for adsorption, stabilization, and persistence; *Pseudomonas* is particularly strong in rhizosphere regulation and reduction of crop Cd uptake; *Burkholderia* combines growth promotion with multi-mechanistic Cd immobilization; *Enterobacter* shows high tolerance and accumulation potential; and *Serratia* is valuable in plant-associated stress mitigation. Across studies, the strongest remediation outcomes usually arise when bacterial metal-resistance traits are combined with plant-growth-promoting functions and, increasingly, when compatible strains are assembled into consortia. Although field translation remains challenging, bacteria-based remediation is now a mature and promising strategy for reducing Cd toxicity, protecting crop systems, and restoring contaminated soils.

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