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# REMEDIATION TECHNIQUE FOR CADMIUM CONTAMINATED GROUNDWATER: A SYSTEMATIC REVIEW

**N. M. T. Jebril*[1]** **R. Boden[2]** **C. Braungardt[3]**
**[1]Department of Biology, College of Sciences for Women, University of Babylon, Iraq.**
**[2]School of Biological and Marine Sciences, University of Plymouth, Drake's Circus, Plymouth PL4 8AA, United Kingdom**
**[3]Consultant at Challenging Habitat**

***Correspondence to:** Nadia M. T. Jebril, Department of Biology, College of Sciences for Women, University of Babylon, Iraq.
**Email:** nadia.tawfiq@uobabylon.edu.iq

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**Review Article**

## Abstract

Heavy metal pollution in soil has seriously affected the living environment of human beings Among all heavy metal pollution, cadmium (Cd) is one of the most difficult to migrate pollutants in soil. Therefore, this systematic review includes the remediation techniques of Cd-contaminated groundwater that using. Different remediation techniques, including pump and treat, permeable reactive barrier, adsorption, biosorption, electrochemical, precipitation, ion exchange and bioremediation are reviewed. The advantages and disadvantages of some remediation technologies for cadmium from groundwater are outlined in order to assist the selection of a suitable technology for a groundwater remediation project. Bioremediation is a common remediation strategy used with low Cd concentrations due to the ability of the bacterial cells to bioremediate Cd.

**Keywords:** Adsorption, Bioremediation, Cadmium, Groundwater, Remediation.

# تقنية معالجة المياه الجوفية الملوثة بالكادميوم: مراجعة منهجية

نادية محمود توفيق جبريل*1 رج بودين2 جارلوت بينكارت3

1قسم علوم الحياة، كلية العلوم للبنات، جامعة بابل، العراق.

2كلية العلوم البيولوجية والبحرية، جامعة بليموث، دريك سيرك، بليموث PL4 8AA، المملكة المتحدة.

3مستشار بمؤسسة Challenge Habitat

***المراسلة الى:** نادية محمود توفيق جبريل، قسم علوم الحياة، كلية العلوم للبنات، جامعة بابل، العراق.

**البريد الالكتروني:** nadia.tawfiq@uobabylon.edu.iq

## الخلاصة

أثر التلوث بالمعادن الثقيلة في التربة بشكل خطير على البيئة المعيشية للإنسان من بين جميع أنواع التلوث المعدني الثقيل، يعد الكادميوم (Cd) من أصعب الملوثات في التربة من حيث الهجرة. لذلك، تتضمن هذه المراجعة المنهجية تقنيات معالجة المياه الجوفية الملوثة بالكادميوم. تتم مراجعة تقنيات المعالجة المختلفة، بما في ذلك المضخة والمعالجة، والحاجز التفاعلي القابل للاختراق، والامتصاص، والامتصاص الحيوي، والكهروكيميائية، والترسيب، والتبادل الأيوني، والمعالجة الحيوية. تم توضيح مزايا وعيوب بعض تقنيات معالجة الكادميوم من المياه الجوفية من أجل المساعدة في اختيار التكنولوجيا المناسبة لمشروع معالجة المياه الجوفية. المعالجة الحيوية هي إستراتيجية علاج شائعة تستخدم مع تركيزات منخفضة من الكادميوم بسبب قدرة الخلايا البكتيرية على المعالجة الحيوية للقرص المضغوط.

**كلمات مفتاحية:** كادميوم، مياه جوفية، التلوث، المعادن الثقيلة.

## Introduction

Human in order to make contaminated groundwater suitable for drinking, agriculture, or domestic and industrial purposes, remediation techniques need to be applied. The selection of the remediation techniques depends on a number of factors: the type of pollutant, the purpose of the remediation project, the financial plan, the period, and the required removal efficiency. In water, Cd occurs in the dissolved state as the hexaaquacadmium (II) complex ($[Cd(H_2O)_6]^{2+}$) and inorganic complexes (e.g., chloro or slufate). Within the water column Cd also occurs and is transported in combination with colloids, either inorganic (clay, oxides) or organic (humic substances) or with biological cells (viruses, bacteria, phytoplankton) (45). The chemistry of these colloids varies according to their origin, functional groups at the surface, and within their structures, which affects the strength of complexes they form with different elements. In rivers and aquifers, Cd transport by colloids can be important and is affected by the water flow rate, pH, presence of competing cations, dissolved organic matter, and the ionic strength of the water (94). Therefore, the design of remedial treatment requires the consideration of both dissolved and colloidal transport of Cd.

As Cd is an element that cannot be chemically or biologically degraded or oxidised and has low volatility, a range of treatment techniques can be excluded from consideration:

- Air sparging and soil vapour extraction (SVE) techniques are only suitable for volatile and semi-volatile compounds. The air sparging technique (also known as air stripping) involves the injection of compressed air into the saturated zone of groundwater to evaporate compounds, which depends on their Henry's law constant, in the unsaturated area of groundwater (21).
- Chemical oxidation techniques involve the addition of strong oxidising chemicals to degrade oxidisable organic compounds.
- Bioventing and bioslurping techniques involve the aerobic biodegradation of other compounds, such as fuel residuals and volatile organic compounds, by increasing the activities of indigenous microbes, which are present in groundwater and soil, and releasing oxygen or air to improve the process of biodegradation (67).

Pump and treat technique: The pump and treat technique is suitable for volatile and non-volatile compounds, including Cd contamination. It involves pumping groundwater to the surface, where it is treated before returning. Examples of surface treatment options include chemical precipitation, ion exchange, adsorption, and bioremediation (83), some of which will be covered in more detail below.

Permeable reactive barrier techniques: Permeable reactive barrier techniques contribute to the prevention of contaminants from reaching the aquifer by the installation of gates or barriers in the flow path of groundwater. The barriers are installed as a vertical wall, within which groundwater contamination is treated by precipitation or absorption within the barrier materials. The barrier materials can be physical, chemical, or biological, or a combination of these materials (6). Elementary iron has shown efficient Cd removal, such as nanoscale zero-valent iron (nZVI), which is used to remove cadmium by the isolation of the $Cd^{2+}$ ions on nZVI through an adsorption process (7).

Adsorption techniques: Cd adsorption techniques have been applied using a variety of adsorbent materials, such as agricultural wastes, granular activated carbon, and industrial wastewater with specific properties (Table 1). The adsorption process involves the concentration of cadmium on the surface of the surfactants via the van der Waals force (such as hydrogen bonds), which occurs between the adsorbates (i.e., Cd ions) and molecules of the adsorbents (58). In addition, chemical sorption contributes by forming new chemical compounds. Table 1 shows the capabilities of some adsorbent materials, which have been used for Cd adsorption in the range of 0.009 to 0.87 mmol Cd/g surfactant. Surfactants differ in their abilities to bind Cd, whereby the availability of sufficient functional groups with reliable and stable binding characteristics is critical for effective Cd adsorption. For example, bagasse carbon is widely used for Cd adsorption, for which a reasonable adsorption rate (0.04 mmol Cd/g) is recorded, due to having carboxylic and lactonic groups (53). Agricultural waste sorbents showed better adsorption rates, for example, *Cocos nucifera* L. adsorbed 0.38 mmol Cd/g, and sunflower stalks adsorbed 0.37 mmol Cd/g. The adsorption process of these sorbents occurs by Cd binding to various functional groups, such as hydroxyl, carboxyl, amino, sulphate, and phosphate groups.

**Table 1 Cadmium adsorption capacities of some adsorbent materials of different studies.**

| Adsorbent materials | Adsorption capacity (mmolCd/g surfactant) | Reference |
|---|---|---|
| **Carbon nanotubes** | 0.009 | (44) |
| ***Ceiba pentandra* L. (Gaertn hulls)** | 0.17 | (72) |
| ***Cocos nucifera* L.** | 0.38 | (53) |
| ***Radix luteola Lamarck*** | 0.17 | (63) |
| ***Zea mays* L. (raw corn stalk)** | 0.02 | (96) |
| **Sunflower stalks** | 0.37 | (80) |
| ***Olea europaea* (stone carbon)** | 0.04 | (15) |
| ***Prunus persica* (stone carbon)** | 0.04 | |
| ***Limonia acidissima* (wood apple) shell** | 0.24 | (76) |
| ***Olea europaea* (stone carbon)** | 0.05 | (58) |
| ***Zea mays* L. (corncob)** | 0.04 | (43) |
| ***Juglans regia* L. (walnut tree sawdust)** | 0.05 | (60) |
| ***Acidosasa edulis* (bamboo charcoal)** | 0.1 | (87) |

Biosorption techniques: In addition to the surfactants mentioned above, plants, algae and microorganisms have been used as biosorbents for Cd. Biosorption involves the adsorption of molecules or elements on the surface of biosorbents, which may be inactive, dead, or living biomass. Adsorption occurs via the functional groups on the surface wall of the biomass, including carboxyl, ketones, and aldehyde groups. Biosorption can be more effective in dormant (inactive) organisms than live ones because the inactivation process may increase the number of anionic ligands at the cell surface (22, 36 and 39). Different processes are involved in the biosorption, in addition to the adsorption process, which includes ion exchange, chelation, complexation, and surface precipitation. Ion exchange is well-known for being the central part of the biosorption, which involves the exchange of elements existing on the surface of the organism, with dissolved Cd (85). Following the adsorption or ion exchange processes, chelation and complexation can occur, whereby stable bonds between an adsorbed Cd ion and the ligand(s) on the organism`s surface are formed.

The specific process and capacity of biosorption generally depend upon the composition of the biosorbent, in particular, the type of molecules in the cell walls and density of available functional groups that act as ligands. Table 2 shows the wide range (spanning seven orders of magnitude) of biosorption capacities of some plants, algae, fungi, yeasts, and bacterial species that have been used previously for the removal of Cd. Alga recorded high biosorption rates, ranging from 117 to 810000 nmol Cd/g dry biomass. Cell walls of algae are mainly composed of alginate ($C_{12}H_{20}O_{12}P_2$, Figure 1A),. Some fungi also recorded high biosorption rates, reaching up to 730 µmol Cd /g dry biomass, facilitated by chitin in their cell wall (Figure 1B). Chitin contains two molecules of beta-1, 4-linked *n*-acetylglucosamine, which provides enough groups for binding Cd (75).

Plants and bacteria have recorded biosorption capacities ranging from 0.038 to 133 and 101 to 2473 (nmol Cd /g dry biomass), respectively. The main binding sites on plant cell walls are hemicellulose ($C_5H_{10}O_5$), pectin ($C_6H_{10}O_7$), and cellulose ($C_6H_{10}O_5$) (Figure 1C). Bacterial cell walls are mainly composed of peptidoglycan ($C_9H_{17}NO_7$), which contains two molecules of *n*-acetylglucosamine (NAG) and *n*-Acetylmuramic acid (NAM), which provide ligands for binding Cd.

**Table 2 Biosorption capacities for Cd of some plants, algae, fungi, yeasts and bacterial species derived biomass, used as biosorbents for the removal of cadmium.**

| **Species** | **Removal capacity (nmol Cd/g dry biomass)** | **Reference** |
|---|---|---|
| Plant | | |
| ***Luffa cylindrica*** | 0.038 | (14) |
| ***Techtona grandis*** | 88 | (71) |
| ***Triticum aestivum*** | 133 | (60) |
| Algae | | |
| ***Chlorella coloniales*** | 40000 | (30) |
| ***Scenedesmus obliquus*** | 338 | (14) |
| ***Parachlorella* sp.** | 810000 | (17) |
| ***Mucor rouxii*** | 117 | (90) |
| ***Padina* sp.** | 530 | (38) |
| ***Spirulina platensis*** | 622 | (70) |
| ***Sargassum glaucescens*** | 200 | (57) |
| Fungi | | |
| ***Aspergillus terreus*** | 10856 | (50) |
| ***Trichoderma koningii*** | 729653 | |
| ***Tetraselmis suecica*** | 70284 | (66) |
| ***Phanerochaete chrysosporium*** | 622 | (63) |
| ***Lentinus sajor-caju*** | 1094 | (9) |
| ***Trametes versicolor*** | 106 | (5) |
| ***Agaricus bisporus*** | 61 | (58) |
| ***Lactarius piperatus*** | 58 | |
| Yeast | | |
| ***Saccharomyces cerevisiae*** | 7.6 | (48) |
| ***Saccharomyces cerevisiae* pYD1-T68CadR** | 5.3 | (81) |
| Bacteria | | |
| ***Bacillus cereus* RC-1** | 275 | (29) |
| ***Bacillus circulans*** | 231 | (92) |
| ***Pseudomonas putida*** | 71 | (64) |
| ***Halomonas* BVR 1** | 106 | (69) |
| ***Streptococcus equisimilis*** | 560 | (15) |
| ***Bacillus cereus* S5** | 662 | (89) |
| ***Streptomyces lunalinharesii*** | 195 | (84) |
| ***Caulobacter crescentus* JS4022/p723** | 142 | (65) |
| ***Corynebacterium glutamicum*** | 391 | (47) |
| ***Pantoea* TEM18** | 462 | (62) |
| ***Brevundimonas* ZF12** | 435 | (49) |
| ***Lactarius scrobiculatus*** | 472 | (3) |
| ***Escherichia coli* JM109** | 560 | (16) |
| ***Pseudomonas* sp.** | 2473 | (97) |
| ***Staphylococcus xylosus*** | 2224 | |
| ***Enterobacter* J1** | 409 | (46) |
| ***Brevibacterium jeotgali* U3** | 1138 | (24) |

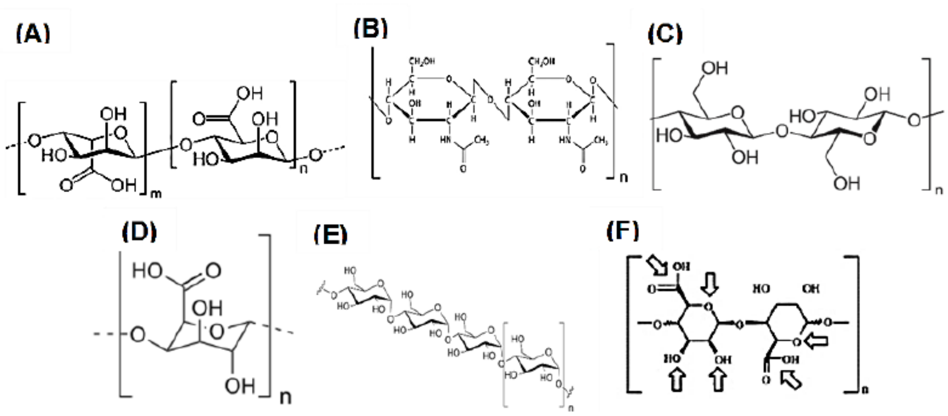

**Figure 1 Chemical structures of (A) alginate (4), (B) chitin (75), (C) cellulose (55), (D) pectin (54). (E) Polysaccharides (7) and (F) possible Cd binding sites on functional groups.**

Cellulose or hemicelluloses makes up 20 – 30 % of the dry biomass of plants, while pectin contributes more than 30% (Figure 1D). The main property of pectin enables it to adsorb ions, and Cd is less powerfully bound to pectin. The limited number of yeasts that have been investigated show a relatively low biosorption capacity (<10 nmol Cd/g biomass) compared to algae, fungi, and bacteria. Polysaccharides ($C_6H_{10}O_5$) (Figure 1E) are the main component of their cell walls, and these contain molecules of alkali-insoluble $\beta$-glucans, mannan, alkali-soluble $\beta$-glucans and minor chitin, providing the groups to bind with Cd ions (Figure 1F).

Electrochemical technique: The electrochemical technique involves using an electrode for the collection of the Cd ions by applying low electricity or potential gradient into the groundwater zone. There are four methods involved in the electrochemical technique: electro-osmosis; diffusion; electrophoresis, and electro-migration. Electro-migration is reported as the primary electrochemical technique for Cd treatment due to the transfer efficiency of Cd ions towards the anode, which has a negative charge, $OH^-$. The electro-migration technique involves the gradual movement of Cd ions and electrons in a conductor or electrolyte due to the momentum transfer caused by an electric field between electrodes. The efficacy of this reaction depends on the pH. Under acidic conditions, the $H^+$ increases, and the cadmium speciation is dominated by the $Cd^{2+}$ ion in solution, which readily transfers toward the anode (23).

Precipitation technique: The precipitation technique is a common technique used to treat Cd contaminated groundwater due to its high efficiency of removal. This is a chemical process that involves the creation of a solid mineral or oxide by controlling the Cd solubility through the addition of chemical precipitants. The efficiency of this technique in the precipitation of Cd is generally determined by the solubility constant ($K_{sp}$), pH, and the presence of other substances. Groundwater is mostly anoxic, and its pH is 6 – 7. The change of pH is the most common procedure of modifying Cd solubility limits with the addition of alkali, such as quicklime (CaO), slaked lime ($Ca(OH)_2$) or limestone ($CaCO_3$). The reaction of precipitation is reversible, as shown in the following reaction:

$Cd^{2+} + 2OH \rightleftharpoons Cd(OH)_2$, $\Delta G^o = -138.7$ kJmol$^{-1}$ of $Cd^{2+}$ (60).

This formation of cadmium hydroxides at pH $\geq 10$ occurs with a $K_{sp}$ of 7.2 X10$^{-15}$, lower than the $K_{sp}$ of $CdCO_3$ (1.0 X10$^{-12}$) (65). The addition of limestone or slaked lime was found to be very useful for Cd hydroxide precipitation at pH 8.5 (88). The reduction of pH $< 4$ remobilises the precipitated Cd.

The presence of an additional ion was also found efficient for the precipitation of Cd. For example, high concentrations of calcium in the presence of Cd results in the precipitation of cadmium calcite. Calcium minerals, such as hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), have also been used for the precipitation of Cd (52). As a result of this, the mechanism of cadmium precipitation consequences from the formation of hydroxypyromorphite [$Cd_{10}(PO4)_6(OH)_2$] as shown in the following reaction:

$Cd^{2+} + 9Ca^{2+} + 6HPO_4{}^{2-} + 2H_2O \rightarrow Ca_9Cd_x(PO_4)_6(OH)_2 + 8H^+$

$Cd_3(PO_4)_2$, $K_{sp} = 2.53$ X10$^{-33}$.

Similarly, the precipitation of Cd as cadmium sulphide (CdS) has shown reasonable precipitation rates due to the $K_{sp}$ of CdS is 1 X 10$^{-28}$ (74). Sulfide minerals, such as pyrite ($FeS_2$), have been used for precipitation of cadmium due to the formation of CdS, as shown in the following reaction:

$FeS_2 + 4HCl \rightarrow FeCl_2 + 2H_2S + 2Cl^-$

$Cd^{2+} + H_2S \rightarrow CdS + 2H+$, $\otimes G^o = -45.33$ kJmol$^{-1}$ of $Cd^{2+}$ (95).

This reaction occurs at relatively low pH (3 □ 6) due to the generation of $H_2S$. Alternatively, chelating precipitants such as potassium/sodium thiocarbonate, trimercaptotriazin, and sodium dimethyldithiocarbamate have been used to precipitate Cd from water at low pH (3.5-4.5) (69). (68) used EDTA, nitrilotriacetic acid (NTA), citric acid and $H_2S$, and an *S*-isomer of ethylenediamine succinic acid ([S-S]-EDDS) to precipitate Cd. The mechanism for Cd precipitation results from the formation of a Cd complex, for example, Cd(EDTA), as shown in the following reaction:

$Cd^{2+} + H_4EDTA \rightleftharpoons [Cd(EDTA)]^- + 4H^+$

Cd(EDTA) is a stable complex with log $K = 5.93$ (56), and is readily soluble, preventing Cd precipitation. This is also the case for precipitation of Cd in groundwater due to complex formation with ligands, which are naturally present in the groundwater. These include chloride, sulfate, carbonate, and bisulfide anions, have relatively high stability constants with Cd (log $K$: 1.98, 3.5, 6.4, and 20.9, respectively) (74) and may be present at sufficient concentrations.

Ion exchange technique: Since The ion exchange technique involves exchanging cations (e.g., $Cd^{2+}$) in the electrolyte solution with cations (e.g., $H^+$) at an insoluble electrolyte in the solid (resin) component, which fills the column reactor (1) and provides a polyanion surface. Resins may be natural, such as inorganic zeolites, or synthesised, organic resins, such as dolamite, amberlite IR120, amberlite IRC 718, and dowex 50 W. Artificial resins are the most common type used, due to their optimised characteristics for particular applications. In this technique, two mechanisms could occur, firstly exchange of $Cd^{2+}$ from the water with the cations bound to the polyanions, and secondly, the coordination between $Cd^{2+}$ with functional groups (hydroxyl groups) of the polyanions. These mechanisms are affected by the Cd solubility, where $Cd^{2+}$ is the species that can be exchanged or coordinated by polyanions, compared with other species of Cd, due to its high affinity (11). The cadmium exchange efficiencies of different solid polyanions vary depending on their acidic ability, resulting from varied acid groups. The stronger or weaker properties of the functional group of polyanions are determined by their acid dissociation constant (p*K*a). If the functional group has a strong p*K*a, it is referred to as a strong ion exchange polyanion, while if it has a weak p*K*a, it is referred to as a weak ion exchange polyanion. The functional groups have been classified according to their p*K*a from strong to weaker acid, such as hydrochloric acid (p*K*a = - 8), carboxylic acids (p*K*a = 5), protonated amines (p*K*a = 10), water (p*K*a = 14), alkyne (p*K*a = 25), amine (p*K*a = ~35), and alkane (p*K*a = ~50) (78).

The most common cation exchangers are strongly acidic resins with sulfonic acid groups ($SO_3H$) and weak acid resins with carboxylic acid groups (COOH). Hydrogen ions in the sulfonic group or carboxylic group of the resin can provide exchangeable ions for metal cations, as shown in the following reactions (34):

$$nR\text{-}SO_3H + Cd^{2+} \rightarrow (R\text{-}SO_3^-)_nCd^{2+} + nH^+$$

$$nR\text{-}COOH + Cd^{2+} \rightarrow (R\text{-}COO^-)_nCd^{2+} + nH^+$$

The pH of an aqueous solution affects the chemistry of Cd, the activity of the functional groups on the polyanions and the competition of Cd ions in the solution. Free $Cd^{2+}$ ions dominate in the pH of the range of 4.5 to 5.5, and its solubility decreases significantly at a pH > 7.5 (82). The pH also affects the acidic properties of various functional groups on the polyanions, alkaline ligand groups, such as carboxyl, imidazole, phosphate, and amino groups (negative charge). At more acid pH, these alkaline ligand groups will combine with $H^+$ in a process called protonation, resulting in changing their charge, progressively, from negative, to neutral, and, in some instances, to positive. Therefore, (42) found that ion exchange enables the uptake of Cd from a solution at a low pH, mainly 3 to 4. The efficiency of the ion exchange process may be reduced due to the formation of competitive complexes on ion exchange resins. For example, in a study by (86), the resins duolite GT73 and amberlite IRC-748 were used in the remediation of cadmium-contaminated groundwater, the presence of high concentrations of elements, especially those responsible for hardness (magnesium, calcium, sodium, chloride, and potassium), in addition to organic matter, reduced the efficiency of the process.

Bioremediation technique: Bioremediation techniques utilise living organisms, such as microorganisms and plants, for the removal, transformation, or immobilisation of contaminants, such as hydrocarbons, agrochemicals, other organic toxicants or metals from soils or aquatic environments (19).

Bioremediation is an eco-friendly process through the use of materials and organisms that are not toxic or pathogenic. Plants and microorganisms have evolved different strategies to survive in environments that present stress factors (e.g., extremes of pH, salinity, temperature, desiccation, toxic substances, etc.). These include detoxifying mechanisms for metals, such as biosorption, bioaccumulation, biotransformation and biomineralisation, all of which can be utilised in bioremediation techniques (20, 25, 32, 33 and 36). Bioremediation (also known as bioremoval) efficiencies of organisms vary, depending on their detoxification mechanisms (e.g., active bioaccumulation or passive adsorption) and concentration or density of active sites or cells, which result in different affinities to Cd (73). As covered in the previous section, the biosorption capacity of microbial cells is afforded by their constituents being mainly polysaccharides, lipids and proteins, which provide functional groups for metal binding, such as carboxylate, hydroxyl, amino and phosphate groups (85).

The type of genus and species of the organism and their tolerant capacity are important parameters. For example, specific species that belong to the same family may have a different bioremoval efficiency, due to their different tolerant capacities, which result in different bioremoval mechanisms (59). The biomass concentration is an important factor in the process, which motivates bioremoval efficiency. Generally, it has been observed that the efficiency of Cd bioremediated by bacterial biomass from aqueous solutions was noticeably enhanced by increasing the amount of active biomass surface or binding sites, which available for Cd bioremoval (48).

In addition to the character and concentration of biomass, the characteristics and concentrations of Cd and the environmental conditions affect the bioremoval efficiency. The speciation of Cd, which depends on pH and other constituents in the water, is key to obtain the binding of Cd that leads to efficient bioremoval (88). The ionic strength of the water is the critical parameter influencing the Cd bioremediation process. At high ionic strengths, Cd tends to complex with anions and free Cd ions in solution, are rare; however, at lower ionic strength, this complex tends to dissociate due to an increase in their electrophoretic mobilities, providing free ions in solution (91). Similarly, environmental conditions, such as pH and temperature, are abiotic factors influencing the efficiency of the cadmium bioremediation process. The pH of an aqueous solution affects the chemistry of Cd, the activity of the functional groups on the biomass cell surfaces, and the competition of Cd ions in the solution. Cd is predominantly mobile (free ions, inorganic complexes) in the pH of the range of 4.5 to 5.5, and its solubility decreases at a $pH > 7.5$ (88). The pH also affects the acidic properties of various functional groups on the microorganism. Alkaline ligand groups, such as carboxyl, imidazole, phosphate, and amino groups (negative charge), which are on the microorganism cell wall, are more common. At more acid pH, these alkaline ligand groups will combine with hydrogen ions in a process called protonation, resulting in changing their charge, progressively, from negative, to neutral and, in some instances, to positive. The functional groups of the cell wall of *Shewanella putrefaciens* under different pH values are shown in Figure 2 (26).

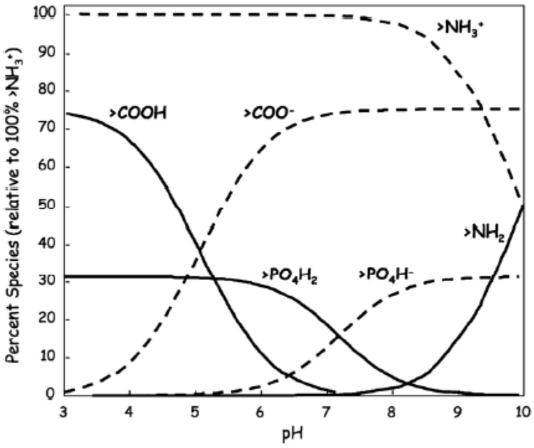

**Figure 2 The relative proportion of species of the main functional groups of the wall in Shewanella putrefaciens at different pH values (26).**

Usually, Cd bioremoval occurs under thermodynamic control (71), the nature of which depends on the type of binding between the Cd ions and other functional groups on the cell wall of the microorganism. Mainly, the interactions of Cd ions with carboxyl groups are endothermic, while the interactions with amine groups are exothermic. Therefore, high temperatures enhance the Cd bioremoval if the binding is endothermic. (93) reported that an increase in temperatures from 4.85, 14.85, and 24.85 to 39.85 $^{o}$C increases Cd adsorption.

Advantages and disadvantages of some remediation technologies of cadmium from groundwater: The advantages and disadvantages of the techniques mentioned above are listed in Table 3 in order to assist the selection of a suitable technology for a groundwater remediation project. Bioremediation is a common remediation strategy used with low Cd concentrations due to the ability of the bacterial cells to bioremediate Cd.

**Table 3 The advantages and disadvantages of some remediation technologies of cadmium removal.**

| Technique | Advantages | Disadvantages |
|---|---|---|
| **Pump and treat** | **An efficient technique for removal of Cd-contaminated groundwater from the aquifer, controlling the spread of the contaminant.** | **It is an expensive technique due to the cost of the construction and operation and the combination with aboveground treatment techniques for the removal of Cd.**<br>**Technique efficiency can be affected by the precipitation of other minerals in the withdrawal wells (12).** |
| **Permeable reactive barriers** | **Cost-effective subsurface barrier.**<br>**Highly efficient technique.** | **The effectiveness of the reactive wall can be affected by constraints such as pH, minerals, in addition to biological activity (94).** |
| **Electrochemical technique** | **Efficient technique.** | **It is an expensive technique due to the cost of the construction and operation of the equipment.**<br>**Its combination with below-ground treatment techniques for the removal of Cd.**<br>**In order to solubilise the Cd hydroxide, the pH must be controlled, which adds more cost.**<br>**It needs an electricity supply.** |
| **Adsorption** | **High Cd holding capacity.**<br>**Cost-effective materials.** | **Desorption of Cd under high acidic conditions could happen, leading to the leaching of Cd.** |

| | | |
|---|---|---|
| | | **The Cd-loaded adsorbent is finally removed and landfilled, increasing the risk of hazard compounds in the environments.<br>Adsorption efficiency decreases due to the blockage of the permeability of adsorbent materials by solids, which are present in the groundwater constituents, and possibly the biofilm formation (2).** |
| **Precipitation** | **The cost-effective technique for the removal of Cd at a high concentration.<br>The stable technique for the removal.<br>Efficient technique.** | **The not cost-effective technique for the removal of Cd at a low concentration<br>It produces a waste product.** |
| **Technique** | **Advantages** | **Disadvantages** |
| **Ion exchange** | **A useful technique for the removal of Cd at low concentrations.<br>A suitable technique for the final treatment after the application of other techniques.** | **Resins are expensive.<br>Eventually, Cd-resins are disposed into landfills.<br>Ion exchange efficiency can be affected by the high concentration of Ca ions in the water, resulting in increasing the ion exchange of Ca instead of Cd; therefore, it is not a suitable technique for removing Cd in hard water, groundwater (10).** |
| **Bioremediation** | **Cost-effective technology, simple to install and uses available biomaterials.<br>Lowest energy requirement.** | **Immobilisation of biomaterials.<br>The selective technique requires preliminary studies to confirm the applicability of biomaterials and is dependent on water conditions.<br>Treatment is slow, requiring long term monitoring and maintenance.<br>Biomaterials efficiency decreases due to the inhibition of biomaterials by certain chemicals.<br>Require conditioning of conditions such as nutrient and pH.<br>Desorption of the Cd under high acidic condition.<br>Cd-loaded biomaterials are lastly removed and landfilled, increasing the risk of hazard compounds in the environments, depending on their hazard assessment (27)** |

**Conclusion:** Cadmium treatment is needed for water and more effective methods. Water treatment through physical, chemical, and biological techniques is an important aspect of water cleansing, and many studies have been undertaken to identify and develop treatment technologies. Cadmium is listed as a priority hazardous substance in the European Water Framework Directive and the health risks are associated with cadmium in groundwater. The cadmium mobility increased with the decrease of groundwater pH, while the hardness and salinity cause the cadmium immobilisation. Depending on the composition of the groundwater, free $Cd^{2+}$ comprises 55 % to 90 % of the total soluble Cd, while the remaining forms of Cd are inorganic complexes. Cadmium is a non-essential element for life, and it is toxic to *Homo Sapiens*. The United States Environmental Protection Agency (US EPA) and the International Agency for Research on Cancer (IARC) classified some elements, including Cd, As, Hg, and Pb, as human carcinogens. Furthermore, chronic exposure to low levels of Cd is associated with several diseases.

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