**Novel Approach On Bioremediation by Actinobacteria : A Review**

**Vipul Bhinsara , Sanjay. S. Ingle**

Department of Microbiology and Biotechnology Centre, The Maharaja Sayajirao University of Baroda Gujarat, India

**Abstract**

A significant environmental problem that has created serious difficulties for the agricultural ecology is toxic pollution. Among the most harmful environmental pollutants are heavy metals and insecticides. Bioremediation techniques include Bioaugmentation , Bioinjection , and Phytoremediation. It eliminates and catabolizes environmental contaminants using natural or artificial plants and soil bacteria. Many vital ecological activities are fulfilled by Actinobacteria in nature, including breaking down and recycling complex polymers and generating bioactive chemicals. As a result, biotechnologists are intrigued by the prospect of cleaning up contamination with Actinobacteria. This can be done using the green method of Bioremediation, in which certain microorganisms are introduced into contaminated areas to increase their degradative ability. Thus, Actinobacteria make excellent bioremediation candidates, which is important as more contaminants are released into the environment. This article focuses on the detrimental effects of heavy metals and pesticides on agricultural ecosystems and discusses ways to mitigate these effects by employing Actinobacteria as a Bioremediation agent.

**Keywords:** Actinobacteria, Bioremediation, Pesticides, Heavy metals, Environmental pollution

**Introduction**

Using various microbial species, ecofriendly approaches for cleaning up polluted settings have evolved in the last two decades. This process is known as bioremediation, and it is typically thought to be less intrusive and more beneficial to soil functioning than traditional physicochemical treatments [1, 2]. Importance of bioremediation as a sustainable technology examining the significant discharge of human-made toxins into the environment[3].

Pesticides are chemicals used for pest control and are perhaps the most extensively dispersed environmental pollutants [4]. The dumping of outmoded pesticide stocks has also resulted in the long-term contamination of several locations with extremely high concentrations of chemicals of this sort. Organochlorine (OC) insecticides have been found in Brazil, Argentina, Chile, Poland, Spain, the Netherlands, China, Canada, the United States, and India, according to official reports[5, 6]. Because unlawful polluted storage facilities are still present, these reports understate the true problem. More than 30 tons of OC pesticides, including lindane, chlordane, methoxychlor, aldrin, and DDT, as well as many heavy metals, including Cr(VI), Cu(II), and Cd(II), were discovered illegally disposed of in the area southeast of Santiago del Estero, Argentina [7, 8]. Pollution from farming is thought to be diffuse because the compounds are spread out over large areas and are in very low concentrations. Pesticides have been found in many places around the world, including the air, water, soil, food, milk, fish, and even human blood and fat tissue [9, 10].

Heavy metals are natural components of soil, and some of them are important for plants and animals because they work as cofactors in a variety of enzymes [11]. However, industrial development has exacerbated biosphere contamination by heavy metals, which become very poisonous at large doses. Heavy metal discharge from various industries is a major cause of heavy metal toxicity across the world [12]. Heavy metals including copper, chromium, lead, zinc, and cadmium often found in effluents and waste water discharged by industry can have serious effects on the environment and human health [13, 14]. Heavy metals are extensively distributed in the biosphere and are spread in the air, soil, and water, and their accumulation in living different types of tissues, the food chain, and the food chain leads to a significant health hazard in people [15]. It was well known that long-term exposure to heavy metals led to slow growth in babies, the start of different types of cancer, and damage to the liver and kidneys [16]and exposition to a high quantity of heavy metals that results in mortality. Recent years have seen a fast increase in the danger of heavy metals contamination in the environment, notably in the agricultural sector, due to accumulation in the soil and plant absorption [17]. Heavy metals are needed for several organs of both the plants and humans, they are become toxic when their concentration above the prescribed level. Many studies have been done in this area and found that agriculture, mining, agrochemicals, and industry are the main sources of heavy metals [18, 19]. Heavy metal accumulation is defined as a buildup of components in the environment. Heavy metal ions transferred from the soil must come into touch with plant roots. They have the potential to stabilize and link contaminants in the soil, decreasing their bioavailability [20, 21]. The mechanisms by which heavy metals are transmitted to plants include (I) Phytoextraction: the sub process of phytoremediation in which plants eliminate hazardous components from contaminated soil, (ii) Phytostabilization: the immobilization and reduction of the mobility of heavy metals in the soil, and (iii) Rhizofiltration: the form of phytoremediation that uses plant roots to absorb the various toxic substances. In addition to causing damage to plants, the transfer of these metals down the food chain is detrimental to human health [22, 23]. Based on its branching location in the 16S rRNA gene tree, Actinobacteria is one of the most important and varied phyla within the domain Bacteria. Actinobacteria are Gram-positive or Gram-variable aerobes with a cell wall that is stiff and contains muramic acid. The majorities are chemo-organotrophs, and free-living members of the phylum are commonly recognized as possessing a high G+C content [24]. Actinobacteria have attracted interest as potential bioremediation candidates for several environmental compartments polluted with refractory inorganic and organic pollutants. *Acidimicrobium ferrooxidans* is an extremophile that can thrive at a pH of 1.8 and a temperature of 45°C. The collection strain *Acidimicrobium ferrooxidans* DSM 10331T was tolerant up to Zn(II) 33×103 mg L -1, whereas *A. ferrooxidans* N39 30×103 mg L -1, isolated from a spent copper sulphide heap, was tolerant to higher concentrations of several metals, including Zn(II), demonstrating its robust adaptation to the hostile environment [25]. Microorganisms of the genus Streptomyces, as well as the *Arthobacter* and *Rhodococcus* genera, have garnered substantial attention as a viable biotechnological technique to cleaning up contaminated environments [26]. Streptomyces strains may be well suited for soil inoculation due to their mycelial growth habit, relatively quick growth rates, colonization of semi-selective substrates, and capacity to be genetically altered, in addition to their metabolic variety [27]. *Streptomyces* strains may thrive on and breakdown a variety of pesticides, including pyrethroids, atrazine, and diuron, among others[28]. According to the bibliographies published in the last two decades, the most representative pesticide-degrading actinobacteria include the genera Arthrobacter, Rhodococcus, Streptomyces, Frankia, Janibacter, Kokuria, Mycobacterium, Nocardia, and Pseudonocardia. These bacteria are capable of growing and degrading a variety of pesticide chemical families, including OC, CB, OP, pyrethroids, ureas, and chloroacetanilides[26].

|  |  |  |  |
| --- | --- | --- | --- |
| **Metal and *Streptomyces*  strain** | **Isolation sample** | **Mechanism** | **Reference** |
| As(V) VITDDK3 | Marine soil samples collected at the Ennore saltpan | ND | [29] |
| B(III) *Streptomyces* sp. | B-contaminated soils, Salta, Argentina | ND | [30] |
| Cd(II) *S. rimosus* | Biomass produced during oxytetracyclin | Biosorption | [31] |
| Cd(II) *S. zinciresistens* | Zincecopper mine, Shaanxi province, Northwestern China | Biosorption/Bioaccumulation | [32] |
| Cr(III) VITSVK9 | Marine sediment, Bay of Bengal, India | Biosorption | [33] |
| Cr(VI) *S. griseus* NCIM 2020 | National Collection of IndustrialMicroorganisms, Pune, India | Reduction | [34] |
| Cr(VI)*S.thermocarboxydus* NH50 | Soil contaminated by leaking drums of metal finishing effluents, Lyon, France | Reduction by agents present in the supertant | [35] |
| Cu(II) *Streptomyces* sp. | Copper filter plant, Tucuman, Argentina | ND | [36] |
| Cu(II) *S. flavovirens* ON3 | Soil exposed to heavy traffic emissions, Brno, Czech | Biosorption | [37] |
| Hg(II) *S. coelicolor* M130 | Culture collection | Enzymatic reduction | [38] |
| Ni(II) *S. aureofaciens* NR-3 | Riparian sediments contaminated with high levels of Ni and U, Steed Pond, USA | Ni-influx and Ni-efflux transporters would be present to maintain homeostasis | [39] |
| Zn(II) *S. rimosus* | Biomass produced by an antibiotic production and collected after fermentation | Biosorption | [40] |
| Pb(II) *S. viridochromogenes* | ND | Biosorption | [41] |
| **Table 1** *Streptomyces* strains beneficial in heavy metal bioremediation | | |  |

|  |  |  |  |
| --- | --- | --- | --- |
| **Microorganism** | **Pesticide** | **Isolation sample** | **Reference** |
| *Arthrobactersp.*strainAK-YN10 | S-triazine (atrazine) | Agricultural ﬁeld repeatedly treated with atrazine in sugarcane cultivation, India | [42] |
| *Arthrobacter sp*. BS1, BS2 and SED1 | Urea (diuron) | Soil from the interface between a vineyard and the Morcille River, Franc | [43] |
| *Rhodococcus* sp*.* BCH2 | S-triazine (atrazine) | Long-term atrazine-treated grape farm soil, India | [44] |
| *Streptomyces* sp. M7 | Organochlorine (lindane) | Wastewater sediment from a copper ﬁlter plant, Argentina | [45] |
| *Streptomyces* sp. AC1-6 and ISP4 | Organophosphorus (diazinon) | Soil exposed to continuous applications of chlorpyrifos, Chile | [46] |
| *Janibacter* sp. AS2 | Pentachlorophenol | Sediments from arid and saline ecosystems, Tunisia | [47] |
| *Gordonia* sp JAAS1 | Organophosphorus (chlorpyrifos) | Soil from a paddy ﬁeld exposed to continuous applications of chlorpyrifos, India | [48] |

**Table 2** Characteristics of the major pesticide-degrading actinobacteria genera

**2. Sources and distribution of pesticides and heavy metals**

**1. Pesticides**

Multiple pesticide residues discharged by industries or as a result of their widespread use in agriculture have been monitored; these residues contaminate river ecosystems, including sediments and aquatic biota, causing harmful effects in humans via food and drinking water [49]. Agricultural fields' subsurface runoff typically carries a variety of fertilizers and pesticides into local rivers [50]. In the last five years, a large number of scientists around the world have reported pesticide residues in groundwater and drinking water. Movement of pesticides in soil compartments is determined by their solubility in water, adsorption by soil particles, and persistence [51]. Pesticide retention in soil and sediments is influenced by the amount of organic matter present, which provides a variety of binding sites for organic pollutants, particularly hydrophobic[52]. It is largely due to organic matter that the retention of HCH isomers differs between soil types. In general, when soil components hold on to contaminants, bioavailability goes down and degradation is slowed[53]. A number of pesticides can evaporate from the soil or foliage and travel long distances. This explains the presence of pesticide traces in pristine areas, which suggests that the atmospheric redistribution rather than direct application is responsible for their occurrence. Spain began monitoring persistent organic pollutants (POPs) in air in 2008, after the Stockholm Convention's Global Monitoring Plan identified air as the primary route for long-distance pesticide transport around the world [54].

Passive air samplers were placed in seven remote points and four urban Spanish locations to assess DDT and hexachlorobenzene (HCB) levels. When urban and remote locations were evaluated together, the results revealed that HCB was the major pollutant, followed in decreasing order by DDTs [55]. Statistically, urban areas had significantly higher concentrations of all studied families with the exception of HCB, indicating that human activities may be source of DDTs [56].

**2. Heavy Metals**

Heavy metals are found naturally and anthropogenically in soil, water, air, and living organisms [57]. Anthropogenic sources produce pollution that continues to increase over time, whereas natural sources are usually seasonal, weather-dependent, and do not produce pollution [58, 59]. Heavy metals come from things made by people, like factories, farms, and wastewater. Heavy metals and pollution in the ecosystem are made worse by these sources. For example, smelting these metals releases Cu, Zn, and Pb [60] the combustion of fossil fuels produces Hg, and car exhaust contributes to the release of Pb [61]. Because they perform several functions in biological systems, some heavy metals are required for the survival of all known living forms. Many others, on the other hand, have no known biological role. Cells have homeostatic mechanisms that regulate heavy metal concentrations and reduce the harmful consequences of high levels. The toxicity of heavy metals is determined by the absorbed dose, the route of exposure, and the duration of exposure. Some heavy metals can be poisoned through drinking water, for example. This is the situation with lead poisoning, which can induce loss of appetite, hypertension, renal failure, weariness, arthritis, hallucinations, and vertigo in people who are exposed to it[62-64]. Mercury is one of the most dangerous heavy metals, and it can react with other elements to generate organic and inorganic mercury. Mercury is discharged into the environment by a variety of sectors, and it is frequently found in larger amounts with rising trophic levels in most marine organisms[65, 66]

Fig.1 Different Natural sources of heavy metal pollution

Fig.2 Different anthropogenic sources of heavy metal pollution

There are two major sources of heavy metal pollution 1.Natural sources and 2. Agricultural sources where 1.Natural sources : including sedimentary rocks, volcanic eruptions, soil formation, and weathering of rocks Igneous and sedimentary rocks are the most common types of rocks [67, 68] The concentration of heavy metals can be determined based on the type of rock and the surrounding ecosystem conditions. In addition to river sediments, soil formation is regarded as one of the primary causes of heavy metal accumulation and 2.Agricultural sources : Typically, agro ecosystems are impacted by the numerous types of pollutants, including agricultural pollutants, which are known as biotic and abiotic byproducts of farming practices [69]. Agro ecosystems can be contaminated or degraded as a result of these pollutants. Fertilizers, pesticides, and sewage sludge are the most common agricultural sources of heavy metals. Heavy metals accumulate in agricultural soil and plants as a result of fertilizer use. A wide range of nutrients is provided by fertilizers, which help to improve plant growth and increase organic matter in the soil [70]. As a result, fertilizers increase the fertility of the soil. An organic fertilizer is one that is derived from organic matter, while an inorganic fertilizer is one that is synthesized. After the anaerobic digestion (AD) process, ammonium fertilizers (sulphate and nitrate) are produced as organic or bio fertilizers. Chemically manufactured/synthetic fertilizers, also known as inorganic fertilizers, are a mixture of inorganic and chemical substances. For example, organic and inorganic fertilizers, which are responsible for releasing heavy metals into our soil [71]. Phosphorus is used extensively in the production of fertilizer, but it also plays a significant role in the accumulation of heavy metals in soil. Fertilizers containing water-insoluble phosphorus have been shown to produce phosphate rocks, which are crucial in the soil's ability to precipitate metal phosphates and keep them immobilize. Heavy metal accumulation in agricultural soils as a result of prolonged overuse of fertilizers reduces soil fertility, which in turn reduces plant growth and productivity [72, 73]. After heavy metals have contaminated the soil, it is extremely difficult to restore its natural environment.

**3. Effect of Pesticides and Heavy Metals Toxicity on Agricultural soil and Plants**

**1. Heavy Metals Toxicity**

Metalliferous minerals and substances interact with root exudates in the rhizosphere, where heavy metals first affect plants. In the rhizosphere, carbonate formations on plant roots are a sign of mineral dissolution and oxidation. Rhizosphere solutions have been found to contain higher concentrations of metals as a result of these processes. Due to the wide range of physiological and biochemical deficiencies that can result from a high concentration of Pb, Bioavailability of nutrients can be affected by the interactions between Cu and Zn, which influence each other [74, 75]. Heavy metals' action pathway and mechanism, starting with soil accumulation and progressing through plant uptake to different parts of the plant. Heavy metals produce free radicals, which cause oxidative stress and damage to biological molecules by raising intracellular levels of reactive oxygen species (ROS) (e.g., proteins, nucleic acids, lipids, and enzymes) [76-78]. The problem with all of these biological molecules causes a lot of problems in the plant's body, such as damage to DNA and cells and the stopping of enzyme activities, which could lead to the death of the whole plant.

**2. Pesticides Toxicity**

When pesticides are used in large amounts and without control on different types of crops, they hurt beneficial organisms. Also, these effects throw off the balance of biodiversity in the whole ecological system. Many pesticides, their byproducts, and metabolites are studied to see if they are somewhat safe for beneficial organisms, especially beneficial insects, to come into direct contact with when they eat plant tissue [79, 80]. The transmission of systemic pesticides through the plant's vascular system contaminates floral and extra floral nectar, resulting in high mortality rates for honeybees and nectar-feeding parasitoids[81, 82]. Endrin, hexachloro benzene dioxy pyrimidine, and other pesticides with chemical structure similar to chlordane can persist in the environment for decades without degrading [83]. In addition, persistent pesticide residues can bio accumulates and reach a bio concentration greater than 70,000 times the initial concentration. Pesticide mechanistic pathway beginning with application and ending with photo degradation, absorption by plant parts, or sorption at the soil level. Once in the soil, pesticides go through several biodegradation processes, including chemical decomposition and biological degradation. Pesticide residues and degradation by-products are taken up by roots via xylem to plant parts, causing some negative effects on soil and plant. These effects include excessive ROS production, oxidative stress, DNA damage, photosynthetic blockage, necrosis, chlorosis, leaf twisting, and plant death[84, 85].

**4. Bioremediation: a solution to the heavy metals and pesticide pollution problem**

Typically, environmental biotechnology is defined as "the use of living organisms to remove pollutants from soil, water, or wastewater" [86]. In general, bioremediation can be defined as "the use of naturally occurring organisms to convert hazardous substances into less toxic substances". According to ancient records, the Romans were the first to use bioremediation to treat their waste water. Since 1972, however, bioremediation has been used extensively to clean up polluted systems [87]. In most cases, bioremediation of toxic organic compounds is less controversial than bioremediation of heavy metals [88]. This is due to the fact that an organic compound can be completely degraded to carbon dioxide and water via the mineralization process. In some instances, however, microorganisms may fail to complete mineralization and produce intermediates that are more toxic than the original compound. This can be resolved through additional bio treatments[11, 89]. In order to meet the fundamental requirements of the world's population, there must be a rise in both the rate of food production and the amount of activity in the industrial sector. The fact that areas all over the world have been found to be contaminated with toxic organic and inorganic compounds is one of the consequences that have resulted from these human-caused activities. This type of simultaneous contamination is referred to as co-contamination [90] as represents the true difficulty that grey biotechnology faces at the moment. The removal of organic compounds and heavy metals through bioremediation has been demonstrated to be effective, despite the fact that, for the time being, each process is typically carried out separately. For bioremediation of co-contaminated sites, a multifunctional biological process is unquestionably required. In this regard, bacteria belonging to the phylum actinobacteria hold a great deal of potential because it has been established that they are effective instruments for the bioremediation of pesticides and heavy metals[91]. Because of their potential to bio remediate soils that have been contaminated with multiple pollutants, members of the phylum actinobacteria are currently the subject of research.

**5. Actinobacteria utilizing diverse bioremediation strategies**

Actinobacteria use different ways to clean up waste such as Cell immobilization,Use of plant-microbe partnerships and Use of microbial produced surface-active compounds.

**1. Cell immobilization**

Cell immobilization is defined as the physical confinement of viable microbial cells to a certain defined space in order to limit their free migration, while maintaining the catalytic activities and enhancing both the biological and physical stabilities of the cells. Cell immobilization is also referred to as cell encapsulation [92]. When compared to conventional suspension systems, this method has several advantages, including the retention of higher concentrations of microorganisms in the reactor, easier solid-liquid separation, high metabolic activity, and higher cell viability. In addition, the technique is simpler to implement [93]. Additionally, the immobilization matrix has the capability of overcoming physicochemical obstacles, such as temperature, pH, and toxic substances; the latter of these is particularly intriguing for its application in bioremediation processes [94]. According to the findings of a number of studies, the immobilization of microbial cells for the purpose of bioremediation led to improved performance, increased production of derivative enzymes, increased tolerance to high concentrations of toxic compounds, elimination of the need to wash the cells, and an extension of the amount of time needed for biochemical or biotransformation reactions[95]. Degradation efficiency and operational stability are both improved when microbial cells are used. Cell immobilization relies heavily on the choice of support. Several properties, such as non-biodegradability, non-toxicity, and non-pollutivity, as well as mechanical and chemical stability, high diffusivity, minimal attachment to other organisms, and a low cost price, are required for the treatment of polluted sites [96]. An actinobacteria encapsulation method has proven successful in the mineralization of pesticides and other pollutants, among other things. Atrazine concentrations in soil and liquid medium can be reduced by using *Rhodococcus erythropolis* NI86/21, which was encapsulated on alginate beads [97]. Adding bentonite and skimmed milk to the beads' formulation resulted in faster cell release and longer cell survival, respectively. Pesticide removal and actinobacteria immobilization also provided good results for metal bioremediation, providing higher metal resistance and enhanced metal accumulating ability[98]. In this particular scenario, a chromate-reducing bacterium known as *Microbacterium liquefaciens* MP30 was successfully entrapped in polyvinyl alcohol (PVA)-alginate beads, which proved to be the most appropriate support for cell immobilization and chromate reduction. In addition, the removal of chromate from a solution containing 2.6 mg L-1 was maintained at 90-95 percent over a period of 20 days without any signs of bead breakdown; however, the immobilization techniques had very little impact on the biological activity [99, 100]. In contrast, the best immobilization matrices for *Microbacterium* sp. NCIMB 13776 for the reduction of Cr (VI) were found to be agar and agarose [101]. Therefore, it is possible to draw the conclusion that the microorganism that was utilized may have a greater effect on the removal of the metal than the immobilization method did. The use of immobilized actinobacteria is a promising alternative for the bioremediation of polluted sites, being efficiently reused for the removal of metals as well as pesticides, according to various reports, which confirm that the use of immobilized actinobacteria is a viable option. Nevertheless, a significant amount of research is required to determine the most appropriate support the efficiency of the process can be affected by a variety of factors, including the pollutants that are present, the longevity and reusability of the immobilized cells, and a number of other factors.

**2. Use of plant-microbe partnerships**

In recent years, there has been a growing interest in the impact of microorganisms on plant growth, bioavailability, and degradation of contaminants. Increasing numbers of studies are examining the effect of plant-associated microorganisms on phytoremediation efficiency. It has been proposed that phytoremediation techniques, which are based on the interactions between plants and microorganisms, are cost-effective and environmentally friendly methods for decontaminating polluted soils [102, 103]. The release of plant root exudates (REs), which contain enzymes, amino acids, carbohydrate, low-molecular-mass carboxylic acids, and phenolic compounds, causes an increase in microbial activity, which is attributed to the rhizosphere effect [104]. Endophytic bacteria contribute to the biodegradation of toxic compounds, according to several authors, and the plant endophyte association can be used to remediate polluted systems [105]. Additionally, the degradation of atrazine was demonstrated by inoculating contaminated soil microorganisms with *arthrobacter* sp. DNS10 alongside the plant Pennisetum. The authors demonstrated the effectiveness of the plant-*arthrobacter* interactions, which resulted in a 98 % reduction in atrazine levels when compared with the effects of a single strain and a single plant [106, 107]. Trace element plant-microbe interactions have been studied predominantly in the context of phytoremediation. It has been hypothesized that the microorganisms in the soil, and in particular the active rhizosphere bacteria, could help plants better mobilize and absorb metals. Several actinobacteria are like this, because members of this phylum are spread out in different ways in the rizosphere, where secondary metabolite producers are more common. This is usually due to the production of things that help plants grow, like indole acetic acid, or to the production of things that bind or chelate metals, like siderophores [108]. In this study, the bacteria that were obtained were, for the most part, resistant to both Cr and Co; however, other tolerance combinations were also found, which indicates that heavy metal resistance evolved independently on multiple occasions[109]. The inherent weaknesses associated with the application of isolated elements can be addressed by developing phytoremediation systems where microorganisms-primarily actinobacteria-interact with plants.

**3. Use of microbial produced surface-active compounds**

Bioremediation is a term that refers to the removal or neutralization of contaminants using biological agents such as plants and microorganisms, as well as products derived from them [110]. The use of microbial products rather than whole cells for environmental remediation could have undeniable advantages, as the producer microorganisms do not need to be able to grow and survive in contaminated environments. There is a wide variety of surface-active compounds (SACs) that can be found among the microbial products that have the potential to be used in bioremediation technologies. These are amphiphilic molecules that can be separated into two categories: low-molecular-weight SACs, also known as bio surfactants (lipopeptide, glycolipids, and phospholipids), which lower the surface tension at the air-water interface; and high-molecular-weight SACs, also known as bio emulsifiers (polysaccharides, lipopolysaccharides, proteins, lipoproteins, and complex mixtures of these compounds[111, 112]. It's common for bio surfactants to have emulsifying properties, but bio emulsifiers don't always bring about a reduction in surface tension. Surface-active compounds of biological origin are in high demand as natural alternatives to their counterparts produced synthetically. This is due to the fact that biologically derived surface-active compounds have lower levels of toxicity and higher biodegradability than their synthetically produced counterparts[113]. Their high stability in extreme conditions of pH, temperature, and salinity, properties that increase their application scope in a variety of biotechnological areas is another distinguishing feature of these proteins. In the field of bioremediation, it is possible to encourage in-situ microbial production of SACs in order to boost the bioavailability of organic and inorganic pollutants [114]. In the absence of producer microorganisms in the washing process, a more pragmatic approach would be to produce these biomolecules through microbial culture, isolate them, and use them in soil washing technologies. Surface-active molecules can form complexes with pollutants attached to the soil matrix, allowing them to desorb into the aqueous phase. The hydrophobic pollutants, such as pesticides, are stabilized inside the micelles of bio-surfactants once they reach the aqueous phase, which improves their solubility and removal during the washing process[115, 116]. Inorganic pollutants like heavy metals, for example, can be removed from soil by forming micelles with surface-active compounds (SACs). In the last case, however, SAC polar groups can bind, mobilize, and stabilize micelle metals. Numerous actinobacteria capable of producing SACs have been isolated, and subsequent analysis has revealed that they belong to a wide variety of genera. The marine actinobacterium *Nocardiopsis* sp. B4, which was isolated from the western coast of India, was cultivated on a variety of carbon and nitrogen sources. The researchers found that olive oil and ammonium chloride, combined at a C/N ratio of 2:1, resulted in the highest level of production [117]. Isolated from a marine sponge, the *Brachybacterium paraconglomeratum* MSA21 strain is notable for its capacity to produce bio surfactants through the utilization of both industrial and agro-industrial wastes when grown in solid state culture[118] , This discovery could be crucial for promoting the large-scale, cost-effective production of microbial SACs. Consequently, the selection of microorganisms capable of growing and producing surfactant/emulsifier molecules from inexpensive raw materials is one of the most alluring strategies for promoting sustainable production [119].

**6. Conclusion**

Environmental pollution is a growing global issue that poses a significant threat to human health and well-being. Biological remediation, which employs living microorganisms, is gaining popularity and is a viable alternative to other hazardous techniques. Due to their physiological and metabolic versatility, Actinobacteria have demonstrated their potential as bioremediation tools for a variety of contaminants, including oil, rubber, plastics, pesticides, and heavy metals, among others. In the past 15 years, significant advancements have been made in the use of Actinobacteria for waste removal. Bio-augmentation, bio- stimulation, cell immobilization, phytoremediation, bio-surfactant production, and the use of defined mixed cultures were developed to improve the bioremediation capabilities of Actinobacteria.

**7. Future prospects**

Due to the constant development of industrial operations, pollutants spread worldwide due to insufficient monitoring of their detrimental environmental consequences. This led to studies on improving contaminated areas. Actinobacteria Bioaugmentation is a green way to rehabilitate the environment. Actinobacteria can metabolise toxins in polluted soils for growth. Actinobacteria may degrade pesticides and remove heavy metals, highlighting their potential as Bioaugmentation techniques[120, 121].

**Declarations**

**Acknowledgements**

We are greatful to the Maharaja Sayajirao University of Baroda's Department of Microbiology and Biotechnology Centre for their assistance.

**Disclosure statement**

The authors declare no potential conflict of interest.

**References**

1. Kumar, V., S. Shahi, and S. Singh, *Bioremediation: an eco-sustainable approach for restoration of contaminated sites*, in *Microbial bioprospecting for sustainable development*. 2018, Springer. p. 115-136.

2. Pande, V., et al., *Bioremediation: an emerging effective approach towards environment restoration.* Environmental Sustainability, 2020. **3**(1): p. 91-103.

3. Alvarez, A., et al., *Actinobacteria: current research and perspectives for bioremediation of pesticides and heavy metals.* Chemosphere, 2017. **166**: p. 41-62.

4. Tudi, M., et al., *Agriculture development, pesticide application and its impact on the environment.* International journal of environmental research and public health, 2021. **18**(3): p. 1112.

5. Srivastav, A.L., *Chemical fertilizers and pesticides: role in groundwater contamination*, in *Agrochemicals detection, treatment and remediation*. 2020, Elsevier. p. 143-159.

6. Li, Z. and A. Jennings, *Worldwide regulations of standard values of pesticides for human health risk control: A review.* International journal of environmental research and public health, 2017. **14**(7): p. 826.

7. Fuentes, M., et al., *Isolation of pesticide-degrading actinomycetes from a contaminated site: bacterial growth, removal and dechlorination of organochlorine pesticides.* International Biodeterioration & Biodegradation, 2010. **64**(6): p. 434-441.

8. Benimeli, C.S., et al., *Lindane uptake and degradation by aquatic Streptomyces sp. strain M7.* International biodeterioration & biodegradation, 2007. **59**(2): p. 148-155.

9. Jayaswal, K., V. Sahu, and B. Gurjar, *Water pollution, human health and remediation*, in *Water remediation*. 2018, Springer. p. 11-27.

10. Donkor, A., et al., *Pesticide residues in fruits and vegetables in Ghana: a review.* Environmental Science and Pollution Research, 2016. **23**(19): p. 18966-18987.

11. Mishra, S., et al., *Heavy metal contamination: an alarming threat to environment and human health*, in *Environmental biotechnology: For sustainable future*. 2019, Springer. p. 103-125.

12. Ashar, A., et al., *Remediation of Metal Pollutants in the Environment*, in *Advanced Oxidation Processes for Wastewater Treatment*. 2022, CRC Press. p. 223-234.

13. Khan, J., et al., *Geo-statistical assessment of soil quality and identification of Heavy metal contamination using Integrated GIS and Multivariate statistical analysis in Industrial region of Western India.* Environmental Technology & Innovation, 2022: p. 102646.

14. Gazuwa, S.Y. and O.E. Olotuche, *Evaluation of the levels of selected heavy metals in leafy vegetables from irrigation farming sites in Jos, Plateau, Nigeria.* Journal of Toxicology and Environmental Health Sciences, 2021. **13**(2): p. 28-36.

15. Oladoye, P.O., O.M. Olowe, and M.D. Asemoloye, *Phytoremediation technology and food security impacts of heavy metal contaminated soils: A review of literature.* Chemosphere, 2022. **288**: p. 132555.

16. Sholehhudin, M., et al., *Analysis of Heavy Metals (Cadmium, Chromium, Lead, Manganese, and Zinc) in Well Water in East Java Province.* Malaysian Journal of Medicine and Health Sciences, 2021. **17**(2): p. 146-153.

17. Jayakumar, M., et al., *A review of heavy metals accumulation pathways, sources and management in soils.* Arabian Journal of Geosciences, 2021. **14**(20): p. 1-19.

18. Munishi, L.K., et al., *Toxic metals in East African agro-ecosystems: key risks for sustainable food production.* Journal of Environmental Management, 2021. **294**: p. 112973.

19. Naccarato, A., et al., *Agrochemical treatments as a source of heavy metals and rare earth elements in agricultural soils and bioaccumulation in ground beetles.* Science of The Total Environment, 2020. **749**: p. 141438.

20. Yaashikaa, P., et al., *A review on bioremediation approach for heavy metal detoxification and accumulation in plants.* Environmental Pollution, 2022: p. 119035.

21. Munir, N., et al., *Heavy Metal Contamination of Natural Foods Is a Serious Health Issue: A Review.* Sustainability, 2021. **14**(1): p. 161.

22. Ramezani, M., et al., *A study of different strategical views into heavy metal (oid) removal in the environment.* Arabian Journal of Geosciences, 2021. **14**(21): p. 1-16.

23. Akash, S., et al., *Remediation techniques for uranium removal from polluted environment–Review on methods, mechanism and toxicology.* Environmental Pollution, 2022. **302**: p. 119068.

24. Leth, M.L., et al., *Glycan Utilization Strategy of the Butyrate Producing Gut Symbiont Roseburia intestinalis.* 2019.

25. Vardanyan, N.S. and A.K. Vardanyan, *Thermophilic chemolithotrophic bacteria in mining sites*, in *Extremophiles in Eurasian ecosystems: ecology, diversity, and applications*. 2018, Springer. p. 187-218.

26. Farda, B., et al., *Actinomycetes from caves: an overview of their diversity, biotechnological properties, and insights for their use in soil environments.* Microorganisms, 2022. **10**(2): p. 453.

27. De Corato, U., *Disease-suppressive compost enhances natural soil suppressiveness against soil-borne plant pathogens: A critical review.* Rhizosphere, 2020. **13**: p. 100192.

28. Kumar, M., et al., *Biodiversity of pesticides degrading microbial communities and their environmental impact.* Biocatalysis and Agricultural Biotechnology, 2021. **31**: p. 101883.

29. Lakshmipathy, T.D., A.A. Prasad, and K. Kannabiran, *Production of biosurfactant and heavy metal resistance activity of Streptomyces sp. VITDDK3-a novel halo tolerant actinomycetes isolated from saltpan soil.* Adv Biol Res, 2010. **4**(2): p. 108-115.

30. Moraga, N.B., et al., *Isolation and characterization of indigenous Streptomyces and Lentzea strains from soils containing boron compounds in Argentina.* Journal of basic microbiology, 2014. **54**(6): p. 568-577.

31. Selatnia, A., et al., *Biosorption of lead (II) from aqueous solution by a bacterial dead Streptomyces rimosus biomass.* Biochemical Engineering Journal, 2004. **19**(2): p. 127-135.

32. Lin, Y., et al., *Bioaccumulation characterization of zinc and cadmium by Streptomyces zinciresistens, a novel actinomycete.* Ecotoxicology and environmental safety, 2012. **77**: p. 7-17.

33. Saurav, K. and K. Kannabiran, *Biosorption of Cr (III) and Cr (VI) by Streptomyces VITSVK9 spp.* Annals of microbiology, 2011. **61**(4): p. 833-841.

34. Poopal, A.C. and R.S. Laxman, *Chromate reduction by PVA-alginate immobilized Streptomyces griseus in a bioreactor.* Biotechnology letters, 2009. **31**(1): p. 71-76.

35. Desjardin, V., et al., *Utilisation of supernatants of pure cultures of Streptomyces thermocarboxydus NH50 to reduce chromium toxicity and mobility in contaminated soils.* Water, Air and Soil Pollution: Focus, 2003. **3**(3): p. 153-160.

36. Albarracín, V.H., M. Amoroso, and C.M. Abate, *Isolation and characterization of indigenous copper-resistant actinomycete strains.* Geochemistry, 2005. **65**: p. 145-156.

37. Majzlik, P., et al., *Influence of zinc (II) and copper (II) ions on Streptomyces bacteria revealed by electrochemistry.* Int. J. Electrochem. Sci, 2011. **6**(1): p. 2171-91.

38. NAKAHARA, H., et al., *Mercuric reductase enzymes from Streptomyces species and group B Streptococcus.* Microbiology, 1985. **131**(5): p. 1053-1059.

39. Van Nostrand, J.D., et al., *Isolation and characterization of four Gram-positive nickel-tolerant microorganisms from contaminated sediments.* Microbial ecology, 2007. **53**(4): p. 670-682.

40. Mameri, N., et al., *Batch zinc biosorption by a bacterial nonliving Streptomyces rimosus biomass.* Water research, 1999. **33**(6): p. 1347-1354.

41. Park, J.-y. and J.-h. Kim, *Heavy Metal Biosorption and its Significance to Metal Tolerance if Streptomycetes.* Journal of Microbiology, 2002. **40**(1): p. 51-54.

42. Sagarkar, S., et al., *s-triazine degrading bacterial isolate Arthrobacter sp. AK-YN10, a candidate for bioaugmentation of atrazine contaminated soil.* Applied microbiology and biotechnology, 2016. **100**(2): p. 903-913.

43. Devers-Lamrani, M., et al., *Evidence for cooperative mineralization of diuron by Arthrobacter sp. BS2 and Achromobacter sp. SP1 isolated from a mixed culture enriched from diuron exposed environments.* Chemosphere, 2014. **117**: p. 208-215.

44. Kolekar, P.D., S.S. Phugare, and J.P. Jadhav, *Biodegradation of atrazine by Rhodococcus sp. BCH2 to N-isopropylammelide with subsequent assessment of toxicity of biodegraded metabolites.* Environmental science and pollution research, 2014. **21**(3): p. 2334-2345.

45. Benimeli, C., et al., *Lindane removal induction by Streptomyces sp. M7.* Journal of Basic Microbiology, 2006. **46**(5): p. 348-357.

46. Briceño, G., et al., *Removal of the insecticide diazinon from liquid media by free and immobilized Streptomyces sp. isolated from agricultural soil.* Journal of Basic Microbiology, 2015. **55**(3): p. 293-302.

47. Khessairi, A., et al., *Pentachlorophenol degradation by Janibacter sp., a new actinobacterium isolated from saline sediment of arid land.* BioMed Research International, 2014. **2014**.

48. Abraham, J., A. Shanker, and S. Silambarasan, *Role of Gordonia sp JAAS 1 in biodegradation of chlorpyrifos and its hydrolysing metabolite 3, 5, 6‐trichloro‐2‐pyridinol.* Letters in applied microbiology, 2013. **57**(6): p. 510-516.

49. Aylaz, G., et al., *Recent developments on magnetic molecular imprinted polymers (MMIPs) for sensing, capturing, and monitoring pharmaceutical and agricultural pollutants.* Journal of Chemical Technology & Biotechnology, 2021. **96**(5): p. 1151-1160.

50. Brinkmann, R., *Protecting Our Water Resources*, in *Practical Sustainability*. 2021, Springer. p. 159-175.

51. Syafrudin, M., et al., *Pesticides in drinking water—a review.* International Journal of Environmental Research and Public Health, 2021. **18**(2): p. 468.

52. Ogbeide, O., et al., *Relationship between geosorbent properties and field-based partition coefficients for pesticides in surface water and sediments of selected agrarian catchments: implications for risk assessment.* Journal of environmental management, 2018. **217**: p. 23-37.

53. Liu, Y., et al., *Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: a review.* Science of the total environment, 2018. **645**: p. 60-70.

54. Kumari, K., S. Swamy, and A. Singh, *Global Monitoring Plan on Persistent Organic Pollutants (POPs).* Persistent Organic Pollutants: Gaps in Management and Associated Challenges, 2021: p. 227.

55. Prats, R.M., et al., *Changes and distribution of gas-phase polycyclic aromatic hydrocarbons and organochlorine compounds in a high-mountain gradient over a three-year period (Pyrenees, 2017–2020).* Science of The Total Environment, 2022. **829**: p. 154602.

56. Amir, S., et al., *Impact of organochlorine pollutants on semen parameters of infertile men in Pakistan.* Environmental Research, 2021. **195**: p. 110832.

57. Ali, H., E. Khan, and I. Ilahi, *Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation.* Journal of chemistry, 2019. **2019**.

58. Priyadarshini, A. and A.K. Mohapatra, *A REVIEW OF INDIA SCALE ANALYSIS OF FOREST FIRE AND TOXIC EMISSION.* 2022.

59. Mohite, V.T., *Pollution and Pollution Control*, in *Emerging Trends in Environmental Biotechnology*. 2022, CRC Press. p. 11-21.

60. Xu, L., et al., *Integrated survey on the heavy metal distribution, sources and risk assessment of soil in a commonly developed industrial area.* Ecotoxicology and Environmental Safety, 2022. **236**: p. 113462.

61. Meng, Z., X. Bai, and X. Tang, *Short− Term Assessment of Heavy Metals in Surface Water from Xiaohe River Irrigation Area, China: Levels, Sources and Distribution.* Water, 2022. **14**(8): p. 1273.

62. Singh, R., et al., *Heavy metals and living systems: An overview.* Indian journal of pharmacology, 2011. **43**(3): p. 246.

63. Hemme, C.L., et al., *Metagenomic insights into evolution of a heavy metal-contaminated groundwater microbial community.* The ISME journal, 2010. **4**(5): p. 660-672.

64. Martin, S. and W. Griswold, *Human health effects of heavy metals.* Environmental Science and Technology briefs for citizens, 2009. **15**: p. 1-6.

65. Hosseini, M., S.M.B. Nabavi, and Y. Parsa, *Bioaccumulation of trace mercury in trophic levels of benthic, benthopelagic, pelagic fish species, and sea birds from Arvand River, Iran.* Biological trace element research, 2013. **156**(1): p. 175-180.

66. Rehan, M., et al., *Degradation of atrazine by Frankia alni ACN14a: gene regulation, dealkylation, and dechlorination.* Applied microbiology and biotechnology, 2014. **98**(13): p. 6125-6135.

67. Daher, M., et al., *Geochemistry of semi-arid Cryosols on volcanic and sedimentary materials from James Ross Island, Antarctica.* Geoderma Regional, 2022. **28**: p. e00490.

68. Smith, R., et al., *X‐ray amorphous components in sedimentary rocks of Gale crater, Mars: Evidence for ancient formation and long‐lived aqueous activity.* Journal of Geophysical Research: Planets, 2021. **126**(3): p. e2020JE006782.

69. Alengebawy, A., et al., *Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications.* Toxics, 2021. **9**(3): p. 42.

70. Pahalvi, H.N., et al., *Chemical fertilizers and their impact on soil health*, in *Microbiota and Biofertilizers, Vol 2*. 2021, Springer. p. 1-20.

71. Iqbal, A., et al., *Co-incorporation of manure and inorganic fertilizer improves leaf physiological traits, rice production and soil functionality in a paddy field.* Scientific Reports, 2021. **11**(1): p. 1-16.

72. Eid, E.M., et al., *Monitored Sewage Sludge Application Improves Soil Quality, Enhances Plant Growth, and Provides Evidence for Metal Remediation by Sorghum bicolor L.* Journal of Soil Science and Plant Nutrition, 2021. **21**(3): p. 2325-2338.

73. Jahangir, M.M.R., et al., *Bio-Compost-Based Integrated Soil Fertility Management Improves Post-Harvest Soil Structural and Elemental Quality in a Two-Year Conservation Agriculture Practice.* Agronomy, 2021. **11**(11): p. 2101.

74. Al Jabri, H., et al., *Zinc Oxide Nanoparticles and Their Biosynthesis: Overview.* Life, 2022. **12**(4): p. 594.

75. Saboor, A., et al., *Zinc nutrition and arbuscular mycorrhizal symbiosis effects on maize (Zea mays L.) growth and productivity.* Saudi journal of biological sciences, 2021. **28**(11): p. 6339-6351.

76. Horie, M. and Y. Tabei, *Role of oxidative stress in nanoparticles toxicity.* Free Radical Research, 2021. **55**(4): p. 331-342.

77. Sharma, C. and S.R. Kim, *Linking oxidative stress and proteinopathy in Alzheimer’s disease.* Antioxidants, 2021. **10**(8): p. 1231.

78. Mukherjee, S., et al., *A Comparative Analysis of Heavy Metal Effects on Medicinal Plants.* Applied Biochemistry and Biotechnology, 2022: p. 1-36.

79. Lahlali, R., et al., *Biological Control of Plant Pathogens: A Global Perspective.* Microorganisms, 2022. **10**(3): p. 596.

80. Shahzad, A., et al., *Nexus on climate change: Agriculture and possible solution to cope future climate change stresses.* Environmental Science and Pollution Research, 2021. **28**(12): p. 14211-14232.

81. Tlak Gajger, I. and S.A. Dar, *Plant allelochemicals as sources of insecticides.* Insects, 2021. **12**(3): p. 189.

82. dos Reis, D.A., *The potential of sugar resources in the reproductive biology of wheat stem sawfly parasitoids*. 2018, Montana State University-Bozeman, College of Agriculture.

83. Zaka, S.M., et al., *Toxic effects of some insecticides, herbicides, and plant essential oils against Tribolium confusum Jacquelin du val (Insecta: Coleoptera: Tenebrionidae).* Saudi journal of biological sciences, 2019. **26**(7): p. 1767-1771.

84. Maldani, M., L. Nassiri, and J. Ibijbijen, *Biodegradation and Remediation of Pesticides in Contaminated Agroecosystems: Special Reference to Glyphosate and Paraquat*, in *Microbial BioTechnology for Sustainable Agriculture Volume 1*. 2022, Springer. p. 489-545.

85. Bondareva, L. and N. Fedorova, *Pesticides: Behavior in Agricultural Soil and Plants.* Molecules, 2021. **26**(17): p. 5370.

86. Gomathi, T., et al., *Bioremediation: A Promising Xenobiotics Cleanup Technique.* Encyclopedia of Marine Biotechnology, 2020: p. 3139-3172.

87. Tripathi, M., et al., *Bioremediation of Dye Contaminated Soil.* Soil Bioremediation: An Approach Towards Sustainable Technology, 2021: p. 115-142.

88. Rahman, Z. and V.P. Singh, *Bioremediation of toxic heavy metals (THMs) contaminated sites: concepts, applications and challenges.* Environmental Science and Pollution Research, 2020. **27**(22): p. 27563-27581.

89. Mallikarjunaiah, S., M. Pattabhiramaiah, and B. Metikurki, *Application of nanotechnology in the bioremediation of heavy metals and wastewater management*, in *Nanotechnology for food, agriculture, and environment*. 2020, Springer. p. 297-321.

90. Ceci, A., et al., *Roles of saprotrophic fungi in biodegradation or transformation of organic and inorganic pollutants in co-contaminated sites.* Applied microbiology and biotechnology, 2019. **103**(1): p. 53-68.

91. Jagannathan, S.V., et al., *Marine actinomycetes, new sources of biotechnological products.* Marine Drugs, 2021. **19**(7): p. 365.

92. Kaushik, S., P.D. Thungon, and P. Goswami, *Silk fibroin: An emerging biocompatible material for application of enzymes and whole cells in bioelectronics and bioanalytical sciences.* ACS Biomaterials Science & Engineering, 2020. **6**(8): p. 4337-4355.

93. Mahto, K.U. and S. Das, *Bacterial biofilm and extracellular polymeric substances in the moving bed biofilm reactor for wastewater treatment: A review.* Bioresource Technology, 2022. **345**: p. 126476.

94. Mehrotra, T., et al., *Use of immobilized bacteria for environmental bioremediation: a review.* Journal of Environmental Chemical Engineering, 2021. **9**(5): p. 105920.

95. Partovinia, A. and B. Rasekh, *Review of the immobilized microbial cell systems for bioremediation of petroleum hydrocarbons polluted environments.* Critical Reviews in Environmental Science and Technology, 2018. **48**(1): p. 1-38.

96. Madhu, A., *Immobilization as Sustainable Solutions to Textiles Chemical Processing*, in *Sustainable Approaches in Textiles and Fashion*. 2022, Springer. p. 21-67.

97. Barra Caracciolo, A. and P. Grenni, *Bioremediation of Soil Ecosystems from Triazine Herbicides*. 2022, Springer.

98. Sandhya, M., et al., *Biofilm-mediated bioremediation is a powerful tool for the removal of environmental pollutants.* Chemosphere, 2022: p. 133609.

99. Fazal, T., et al., *Bioremediation of textile wastewater and successive biodiesel production using microalgae.* Renewable and Sustainable Energy Reviews, 2018. **82**: p. 3107-3126.

100. Behera, H.T., A. Mojumdar, and L. Ray, *Biology, genetic aspects and oxidative stress response of actinobacteria and strategies for bioremediation of toxic metals*, in *Microbial Biodegradation and Bioremediation*. 2022, Elsevier. p. 181-192.

101. Wani, P.A., et al., *Role of NADH-dependent chromium reductases, exopolysaccharides and antioxidants by Paenibacillus thiaminolyticus PS 5 against damage induced by reactive oxygen species.* Chemistry and Ecology, 2020. **36**(7): p. 663-684.

102. Saraswat, S. and J. Rai, *Integrative Agronomic Paradigm for Efficient Phytoremediation of Metal-Contaminated Soil: Agronomic Practices for Efficient Phytoremediation*, in *Handbook of Research on Green Technologies for Sustainable Management of Agricultural Resources*. 2022, IGI Global. p. 246-266.

103. Augusta, A.C., E.-E.C. Bertha, and A.S. Eromosele, *Plant-Microbe Interaction: Prospects and Applications in Sustainable Environmental Management.* 2022.

104. Bhat, R.A., et al., *Aquatic Environmental Bioengineering: Monitoring and Remediation of Contamination*. 2022: John Wiley & Sons.

105. Saeed, M., et al., *Advances in Biochar and PGPR engineering system for hydrocarbon degradation: A promising strategy for environmental remediation.* Environmental Pollution, 2022: p. 119282.

106. Urseler, N., et al., *Atrazine behavior in an agricultural soil: adsorption–desorption, leaching, and bioaugmentation with Arthrobacter sp. strain AAC22.* Journal of Soils and Sediments, 2022. **22**(1): p. 93-108.

107. Sarker, A., et al., *Remediation of chemical pesticides from contaminated sites through potential microorganisms and their functional enzymes: Prospects and challenges.* Environmental Technology & Innovation, 2021. **23**: p. 101777.

108. Khanna, K., et al., *Unsnarling Plausible Role of Plant Growth-Promoting Rhizobacteria for Mitigating Cd-Toxicity from Plants: An Environmental Safety Aspect.* Journal of Plant Growth Regulation, 2021: p. 1-29.

109. Shang, D., et al., *Conjugative IncHI2 plasmid harboring novel class 1 integron mediated dissemination of multidrug resistance genes in Salmonella Typhimurium.* Food Control, 2021. **122**: p. 107810.

110. Behbudi, G., K. Yousefi, and Y. Sadeghipour, *Microbial Enzymes Based Technologies for Bioremediation of Pollutions.* Journal of Environmental Treatment Techniques, 2021. **9**(2): p. 463-469.

111. Gupta, V.K., et al., *Biomolecules from Natural Sources: Advances and Applications*. 2022: John Wiley & Sons.

112. Sangwan, N., A. Chauhan, and P.K. Avti, *Application of biosurfactants in the treatment of Mycobacterium tuberculosis infection*, in *Green Sustainable Process for Chemical and Environmental Engineering and Science*. 2022, Elsevier. p. 351-374.

113. Johnson, P., et al., *Effect of synthetic surfactants on the environment and the potential for substitution by biosurfactants.* Advances in Colloid and Interface Science, 2021. **288**: p. 102340.

114. Nazir, A., M. Shafiq, and F.-e.-. Bareen, *Fungal biostimulant-driven phytoextraction of heavy metals from tannery solid waste contaminated soils.* International Journal of Phytoremediation, 2022. **24**(1): p. 47-58.

115. da Silva, A.F., et al., *Fungal biosurfactants, from nature to biotechnological product: bioprospection, production and potential applications.* Bioprocess and Biosystems Engineering, 2021. **44**(10): p. 2003-2034.

116. Sarubbo, L.A., et al., *Biosurfactants: Production, properties, applications, trends, and general perspectives.* Biochemical Engineering Journal, 2022: p. 108377.

117. Sayyed, R. and H.A. El-Enshasy, *Microbial Surfactants: Volume 2: Applications in Food and Agriculture*. 2022: CRC Press.

118. Ibrahim, Z., et al., *Biosurfactant from Oil Producing Plant.* Biorefinery of Oil Producing Plants for Value‐Added Products, 2022. **2**: p. 421-444.

119. Ortega-Berlanga, B., C. Gonzalez, and G. Navarro-Tovar, *Recent advances in the use of lipid-based nanoparticles against glioblastoma multiforme.* Archivum Immunologiae et Therapiae Experimentalis, 2021. **69**(1): p. 1-20.

120. Dueholm, M.S., et al., *Survival and activity of individual bioaugmentation strains.* Bioresource Technology, 2015. **186**: p. 192-199.

121. Garbisu, C., et al., *Plasmid-mediated bioaugmentation for the bioremediation of contaminated soils.* Frontiers in microbiology, 2017. **8**: p. 1966.