minerals

Review

Sustainable Amelioration of Heavy Metals in Soil Ecosystem: Existing Developments to Emerging Trends

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Abstract: The consequences of heavy metal contamination are progressively degrading soil quality in this modern period of industry. Due to this reason, improvement of the soil quality is necessary. Remediation is a method of removing pollutants from the root zone of plants in order to minimize stress and increase yield of plants grown in it. The use of plants to remove toxins from the soil, such as heavy metals, trace elements, organic chemicals, and radioactive substances, is referred to as bioremediation. Biochar and fly ash techniques are also studied for effectiveness in improving the quality of contaminated soil. This review compiles amelioration technologies and how they are used in the field. It also explains how nanoparticles are becoming a popular method of desalination, as well as how they can be employed in heavy metal phytoremediation.

Keywords: heavy metal; remediation; environmental; phytoremediation; nanotechnology

1. Introduction

Today, the world faces many problems, one of which is heavy metal (HM) pollution. During mining from ores, heavy metals are transported and these elements are released into the environment when mined for various purposes. The problem of spills from HM deposits is endangered by the cumulative effects of industrial development and disruption of the regular biogeochemical cycle [1]. Soil is a compound mixture and a non-renewable natural resource, as it can only be restored on a geological timescale. It can be easily defined as the loose inorganic or organic matter of the surface that assists as a natural habitat for terrestrial plants [2]. Heavy metals are very hazardous to the environment and living things. It can be strengthened by the food chain. When the soil is exposed to HM adulteration, landfilling is tough [3]. Potentially toxic elements and metalloids in soil ("heavy metals") have raised serious alarm due to their effects on humans and ecosystems [4–7].

Heavy metals causing soil pollution based on human actions such as mining, steelworks, and electroplating negatively affect human health and ecosystem stabilization [8,9]. From much research in recent years, a large number of studies have described how plants are capable of HM accumulation/elimination. In this review study, the different techniques used for tackling soil adulteration due to HMs, the HMs have been removed using biochar, fly ash, and bioremediation techniques and recent advances suggested in nanotechnology combined with bioremediation which were found to be more effective and some methods cheaper than other techniques were discussed.

Bioremediation is a type of ecological remediation that concentrates on minimizing clean-up actions' environmental footprint. In addition to environmental considerations, sustainable repair covers social and economic factors [10]. Three stages have occurred in the clean-up sector [11]. Because of unreasonable regulatory demands and public pressure, remediation professionals were originally expected to "eliminate every last trace of contamination". By the 1990s, however, many countries had learned that the price of a "remove all" plan would much outweigh the ostensible social gains. Significant biogeophysical restrictions make it impossible to restore polluted soils to their original state, according to remediation practitioners. As a result, a compromise option was proposed, with remediation aimed at making property acceptable for specific uses [11]. Remediation of HM-contaminated soil has gained popularity as a cost-effective and ecologically friendly way of remediation. Additionally, previous research has shown that phytoremediation is environmentally adaptable, and that it can be utilized in tailings, agricultural soils, and industrial land. Furthermore, phytoremediation produces no secondary contamination, and HM-mixed biomass can be treated using a variety of methods, such as composting, pyrolysis, phytomining, thermal upgrade, and liquid withdrawal [12].

Heavy metal pollution and salinity have harmed arid and semiarid regions [13]. Bioremediation is a type of "Green and Sustainable Refurbishment" (GSR) since it is concerned with environmental issues. Green remediation is defined as "the process of examining all environmental aspects of remedy implementation and combining options to optimize net benefit to the environment of clean-up actions" by the U.S. Environmental Protection Agency (USEPA) [14]. Therefore, a risk-based remediation was created. This makes it possible to set repair standards for contaminated sites to more realistic and acceptable levels. This depended on the scientific evidence that remediation actions themselves can have adverse effects (e.g., greenhouse gas emissions, air pollution, groundwater infection, and eutrophication), and the fact that stakeholders consider 'sustainability' as a necessity.

We need such sustanaible amelioration methods which minimize modern society's growing impact on environment, society, and economy [15–17]. A variety of approaches can be used to eliminate HM cotamination. Traditional remediation technologies, including consolidation/stabilization based on Portland cement [18], containment [19], soil washing, electrokinetic remediation [20], thermal desorption [21], and chemical oxidation/reduction [22], have proven effective for immobilizing, removing, or transforming HMs (i.e., arsenic (As), chromium (Cr) and mercury (Hg)), making them almost non-toxic. Attempts have been made to maximize ecological, communal, and economic profits through GSR to ensure the sustainability of the refurbishment process (Table 1). We searched google scholar, PubMed, Microsoft Academic or selecting latest and appropriate research for preparing the current review. The keywords like amelioration of HMs in soil, green remediation, nano bioremediation, biochar mediated amelioration, HM contamination, soil pollutant removal, bioremediation, and phytoremediation were used. A total of 132 papers were used for the present review including the construction of Tables.

Table 1. Advantages and disadvantages of the heavy metals found in soil.

Sr. No.	Metals	Advantages	Disadvantages	Reference
1	Cr	With increase in pH of soil, leachability of Cr(VI) increased	Cr is related with sensitive dermatitis in human beings.	[23]
2	As	Arsenite can absorb or co-precipitate with metal sulphite, showing high empathy for sulphur compound.	Arsenic damage skin, chances of cancer increases and troubles the circulatory system.	[23]
3	Pb	Ionic lead, Pb(II), lead oxides and hydroxides are unconfined on the soil, groundwater and surface water. Most solid form of in soil matrix in Lead sulphide which forms under reducing conditions.	Via inhaling or swallowing, lead builds up in the body (i.e., the brain), leading to poisoning or death. Severe harm to the brain, nervous system, red blood cells, and kidneys.	[24,25]
4	Zn	Zinc is trace element i.e., essential to humal health. Sharp reduction in the mitotic activity.	Water-soluble zinc found in soil contaminates groundwater. Plants often accumulate zinc in the soil and absorb zinc that the system cannot process. Zinc deficiency causes birth defects.	[26,27]
5	Cd	Cadmium is very bio-persistent used in agricultural crops and sewage sludge (Cd-rich biosolids) and use of cadmium enrich phosphate fertiliser.	Cadmium in the body affects enzymes. Kidney damage is thought to cause proteinuria.	[28,29]
6	Cu	Connection between soil and water metal uptake by plants.	Negative effects of metals on crop growth and yield.	[30,31]
7	Hg	Important sorption of soil sediments and hemic material.	Mercury is associated with kidney damage.	[23]

2. Heavy Metals Contamination and Toxicity in Soil Ecosystem

Heavy metal accumulation in the soil is hazardous to the environment and human health, and well-known harmful contaminants have devastating effects on the biological circulation of terrestrial species with variations in the structural composition of nucleic acids, proteins and osmotic balance [32]. Although several remediation techniques such as hardening/stabilization (S/S), soil leaching, electrokinetic remediation, and chemical oxidation/reduction are used to fix, remove, or detoxify HMs in the soil, these traditional approaches do not result in overall sustainability [33].

Metal toxicity not only affects aquatic organisms, but also harmful to soil flora, plants, animals, and humans as well. Oxidative stress results in damage to cell morphology and inhibits cytoplasmic enzymes [34]. Usually, these metals exist in nature individually or in grouping with other elements, but anthropogenic activity increases their concentrations in the environment [35]. Since HMs are water-soluble, they are mainly soluble in solutions. This makes it difficult to remove by physical and chemical separation processes in the soil [36]. Solubility of HMs is determined by their chemical morphology in the environment. So, for improving the remediation efficiency of microbial fuel cell (MFC), appropriate methods for converting HMs into easy-to-move forms (such as acid-soluble fractions) are needed. Some research has used auxiliary reagents like small-molecule organic acids (citric acid, CA; and acetic acid, HAc), inorganic acids (HCl, HNO_3), and synthetic chelating agents (ethylenediaminetetraacetic acid, EDTA) [37,38].

These chemicals help in desorbing and dissolving HMs in the soil, allowing them to move around more freely. Synthetic chelating chemicals pose a risk since polymer chelates migrate slowly in electric fields and secondary ecological settings [39]. This study used two small-molecule organic acids (CA, HAc) that are commonly available, reasonably inexpensive, and ecologically benign, as well as a mineral acid (HCl) [39]. The rate of faster improvement of the industrial sector has raised the HM contamination problem, like a hike in manufacturing purposes for other metals. Heavy metals like Cd, Pb, As, Cr, Cu, and Zn are mainly used in industry and agriculture. Small amounts of these metals are lethal.

Although these metals are present naturally in the environment, tampering occurs when there are large amounts of these metals on land due to continuous mining as well as smelting [7,40]. As industrialization progresses and the natural biogeochemical cycle are disrupted, the issue of HM contamination becomes more and more serious. Heavy metals, unlike biological compounds, seldom biodegrade and hence gather in the environment. Accumulation of HMs takes place in the tissues of an organism (bioaccumulation), and their concentrations increase as they transition from low to high trophic levels (biomagnification). Heavy metals in the soil have toxicological consequences on soil microorganisms, which leads to reduced numbers and activity [1].

3. Sustainable Remediation Strategies

A number of remediation strategies have been successfully tested and fruitful results have been obtained (Table 2). The following subsections discuss some of the potential approaches.

Table 2. Remediation period and efficiency of heavy metals in soil.

Sr. No	Heavy Metals	Total Metal Content	Method	Remediation Period (Days)	Remediation Efficiency	Ref.
1	Cu	800 mg kg^{-1}	Cu spiked as well as equilibrated with additional Cu in a Cu-contained sandy soil and the effect of CMB amendment was tested	14	Reduced Cu by 73%	[41]
2	As	120 mg kg^{-1}	Biochar applied to an As-contained paddy soil under anaerobic conditions to see how it affected As release	30	Increased As by 234.5%	[42]
3	Cd and Pb	5 mg kg^{-1} Cd and 100 mg kg^{-1} Pb	The effect of biochar on metal immobilisation was studied	1095	Reduced Cd and Pb by 59%	[43]
4	Pb	1945 mg kg^{-1}	In a polluted soil modified with charcoal, Pb was immobilised whereas As was mobilised	90	Reduced Pb by 95%	[44]
5	Hg	1000 mg kg^{-1}	The activation of PS through the nanocomposite material resulted in degradation of DTZ. DTZ was practically completely removed using nanocomposite material.	10	Reduced Hg by 94%	[45]
6	Cr	12,285 mg kg^{-1}	To evaluate the immobilising potential and bioaccumulation of Cr, a pot experiment was done with three BC application rates	77	Reduced Cr between 28–68%	[46]
7	Cu	100 mg kg^{-1}	The effect of biochar from different sources at two rates of application on the Cu distribution in a Cu-contained soil in two years incubation	730	Reduced Cu by 28%	[47]

Table 2. *Cont.*

Sr. No	Heavy Metals	Total Metal Content	Method	Remediation Period (Days)	Remediation Efficiency	Ref.
8	As and Cd	212 mg kg^{-1} As and 10.8 mg kg^{-1} Cd	With varying application rates, the effects of rice-straw biochar and iron-impregnated biochar on Cd as well as As mobility in the rice rhizosphere, soil to rice transfer were examined	96	Increased As concentration, while decreased Cd	[48]
9	Cd and Cu	3.8 mg kg^{-1} Cd and 134.6 mg kg^{-1} Cu	The efficiency of *Phyllostachys pubescens* biochar for immobilising Cd, Cr, Cu, Ni, Pb, and Zn by lowering the bioavailable percentage was examined	20	Reduced Cd by 31.2% and Cu by 79.7%	[49]
10	Pb	1445 mg kg^{-1}	Pb immobilisation in biochar-treated soils gathered near an old mine was tested	45	Reduced Pb by 87%	[50]
11	Hg	129 mg kg^{-1}	The effects of adding two biochars (RSB and WSB) to soil at different doses on Hg mobility in the pore water of a contaminated paddy soil were investigated	118	Reduced Hg by 44%	[51]
12	Cr	50 mg kg^{-1}	Metals such as Cd and Cr were artificially added to air-dried soil and the effect of biochar-amendment was evaluated	120	Reduced Cr by 48.1%	[52]
13	Cu	1805 mg kg^{-1}	Using a naturally contained shooting range as well as spiked soils, the immobilisation and phytoavailability of Cd, Cu, and Pb were investigated with biochar made from chicken dung and green garbage were used	14	Reduced Cu 79%	[53]
14	As	1945 mg kg^{-1}	The effects of ten different biochars on rice growing in polluted soil were studied.	90	Increased As concentration	[44]
15	Cd	1.36 mg kg^{-1}	To immobilise Pb in polluted sediment, biochar-supported nano-chlorapatite (BC-nClAP) was produced and tested	6	Reduced Cd by 65.7%	[54]
16	Pb	589.7 mg kg^{-1}	At varying application rates of polluted paddy soil, looked into the impact of biochar alteration in lowering soil CO_2, CH_4, and N_2O releases and lowering Cr uptake by rice grains.	30	Whole Reduction	[55]

Table 2. *Cont.*

Sr. No	Heavy Metals	Total Metal Content	Method	Remediation Period (Days)	Remediation Efficiency	Ref.
17	Cr	432.8 mg kg^{-1}	The effect of rice straw biochar on leaching of DOC and phosphate across a variety of biomass feedstock was tested	122	Reduced Cr by 22.3%	[56]
18	Cu	100 mg kg^{-1}	Biochars tested for their long lasting effect on lowering the bioavailability of Cd in paddy soils.	180	Reduced Cu by 41%	[57]
19	As	92.3 mg kg^{-1}	To stabilise methylmercury(MeHg) in soil and also limit MeHg accumulation in rice grains, SSB applied to 2 Hg-contained soils	35	Increased As concentration	[58]
20	Cd	2.04 mg kg^{-1}	The immobilisation of Cr(VI) in soil was investigated using a biochar CMC stabilised nanoscale iron sulphide (FeS) composite	180	Reduced Cd by 50.4%	[59]
21	Hg	2.1 mg kg^{-1}	For understanding the impact of feedstock, pyrolysis temperatures, as well as production circumstances on Pb immobilisation capabilities of variety of biochars was tested	119	Increased Hg by 67%	[60]
22	Cr	308 mg kg^{-1}	The immobilisation of Cr(VI) in soil was investigated by a biochar-supported CMC stabilised nanoscale iron sulphide (FeS) composite.	180	Reduced Cr between 47.1%–65.5%	[61]
23	As	0.3 mg kg^{-1}	In the presence of biochar, anaerobic microcosms was created with As-contained paddy soil for studying As changes	20	Increased As concentration	[62]
24	Cu	338 mg kg^{-1}	Cu-contaminated soil was incubated with CMB or OHB. Over the course of one season, the metallophyte *Oenothera picensis* was cultivated (six months). Using the same soils, same procedure was performed for three more seasons	730	68% (exchangeable fraction)	[63]
25	Cr(VI)	100 mg kg^{-1}	For extracting Cr(VI) from groundwater and soils, *Platanus acerifolia* leaves were used in an unique reactor that combined adsorption with a microbial fuel cell	14	Reduced Cr(VI) by 40%	[64]

Table 2. *Cont.*

Sr. No	Heavy Metals	Total Metal Content	Method	Remediation Period (Days)	Remediation Efficiency	Ref.
26	Pb and Zn	291.1 mg kg^{-1} Pb and 814.2 mg kg^{-1} Zn	SMFCs with various amounts of wheat straw were tested and compared in a variety of setups	100	Reduced Pb by 37.2% and Zn by 15.1%	[65]
27	Cr(VI)	100 mg kg^{-1}	Applying microbial fuel cell technology in fed-batch mode, Cr(VI)-contained wastewater treatment was examined	150 h	Whole reduction	[66]

Abbreviations used in the table: biochar (BC), chicken manure-derived biochar (CMB), rice shell biochar (RSB), wheat straw biochar (WSB), dissolved organic carbon (DOC), oat hull biochar (OHB), solid-phase microbial fuel cells (SMFC), diltiazem (DTC), and carboxymethyl cellulose (CMC).

3.1. Nano-Bio Remediation of Heavy Metals: Application and Implications

In the modern era, the usage of nanoparticles (NPs) in industry, medicine, agriculture and cosmetics has increased significantly [67–80]. Materials with at least one dimension smaller than 100 nm are commonly referred to as NP. NPs with various particle sizes, shapes, as well as functions are produced as per requirement [81]. Compared to conventional materials, NPs possess a lot of advantages, including increased surface activity, extra reactive sites on the surface, increased catalytic efficiency, and special optical as well as magnetic properties [82–84]. The environmental impact of NPs is discussed in previous research: Hao et al. showed that even at 10 mg L^{-1}, rice contained endophytic fungi sensitive to carbon-based NPs [85]. It is reported that exposure to Ag NPs at a dose of 50 mg kg^{-1} adversely affects the biomass and quality of peanuts [86]. In addition, low dosages (5 and 50 mg kg^{-1}) of NiO had no effect on the survival, reproduction as well as rate of growth of adult earthworms, whereas high dosages (200 and 500 mg/kg) expressly affects physiological and biochemical effects and turned out to be the endpoint [80]. As many field studies (pilot and life-size) and laboratory studies show, the use of nanotechnology for water remediation, used for drinking purification and pollution control, is very favorable.

There are many reviews of applications based on nanotechnology. However, in order to further elucidate its significance as well as guide development, it is necessary to directly compare existing therapeutic methods with new approaches using nanotechnology. In this review, the effectiveness of nanotechnology and old technologies for water purification as well as environmental improvement to provide industries, researchers, and policy makers with insight into the status of water purification methods, are compared. Contaminants were classified into a wide range of classes and the most gainful methods were compared in each class described in the literature. A case study is also presented that directly compared conventional techniques to nanotechnology-based techniques for similar contaminants. Nanotechnology-based methods are generally considered costly, but many of these offer inexpensive and more operative options to traditional technologies. Additionally, nano-based technologies can be critical to complying with progressively stringent water quality standards, especially to remove new and low-concentration pollutants [87].

All latest techniques as well as industries in pharmaceutical departments are interfaced by nanotechnology [88,89], textile industry [90], electrical industry [91,92], mechanical technology, and environment-related industries. Nanotechnology is considered as the synthesis and processing of nanoscale materials [93]. Their small size is the only cause that increases the cost of these materials [94]. Due to their small size, the surface area to volume ratio is significantly improved and the bandgap is clean and wide. As a result, their optical, physical, and electrical properties differ significantly from large volumes of material. Nanomaterials can be metal, semiconductors, or organic [95]. The generation of artificial NPs is attracting attention as an effective recovery method. In addition to other environmental uses, NPs can be inserted underground in the form of sediment to offer conditions for chemical recovery of pollutant columns and for use as adsorbents and catalysts in wastewater treatment processes. Its efficiency is based on its chemical composition, well-defined shape and high specific surface area. Today, many NP products are formulated to effectively remove contaminants. However, there is rising concern about the probable impacts in the secondary life cycle linked with production [96,97].

Biosynthetic NPs help green remediation in a variety of methods. Iron-based NPs should be used directly as a fixative. For example, nano zero ferrous iron (nZVI) by waste tea can be used to reduce Cr (VI) in soil. Iron oxide NPs made from leaf extract can steady Cd and As in soil by coprecipitation [98,99]. For additional data on the use of nZVI NPs as well as iron oxide, refer to the reader [100]. Green NPs indirectly aid in soil regeneration. Ag NPs mediated by plant extracts can promote plant growth by increasing soil pH value, nutrient bioavailability and water retention capacity [65,68,101]. Naturally benign nano-sized mineral built soil conditioners can be organized with feldspar and lime consuming a mild hydrothermal method [102]. Their use in NPs synthesis is attracting more and more attention. Summarizing the current report on the synthesis of NPs for environmental restoration with the help of plant extracts (bud system). NP recovery in vivo is attained through the occurrence of biomolecules contained in plant extracts.

The precise mechanism of this procedure is not yet fully understood, but amino acids, citric acid, phenol, sugar, membrane protein, tartaric acid, as well as functional groups (alcohols, aldehydes, amines, and ketones of carboxylic acids) also reduce and block reducing agents [67,103–105].

3.2. Biochar Based Sustainable Amelioration of Soil

In recent times, biochar has gained increasing courtesy as an environmentally friendly tactic, especially as a weather protection strategy [106] (Figure 1). Biochar is considered as a carbon-rich, fine-grained, porous material formed by the thermal decay of biomass at relatively low temperatures under oxygen-restricted conditions (<700 C) [76,79,107]. It is also considered as a predominantly stable and stubborn organic carbon (C) compound formed when biomass (raw material) has a temperature typically between 300 °C and 100 °C at low oxygen levels.

Biochar is rich in carbon, porous, and has a large exact surface area, and this exact structure has been shown to be capable of enhancing soil moisture and nutrient retention [108]. Biochars range from crop residues (corn stalks, rice straw, rice husks, rapeseed stalks, etc.), grass, wood, sewage sludge, anaerobic digests, and animal excrement (poultry litter, pig manure, etc.). It can be produced by heat treatment of biological waste, and chicken manure) [109–111]. Biochar interacts with HMs in many ways. Complex formation of the outer sphere, complex of the inner sphere, electrostatic interactions, surficial precipitation, and exchange of ion are potential mechanisms of metal fixation [20,112]. A new trend has appeared in biochar pyrolysis as well as post-pyrolysis transformation plans to increase the metal binding capacity of biochar adsorbents (Table 1) [113].

Figure 1. Modified figure of Biochar based sustainable Amelioration of soil figure is adapted from [114–116] with due copyright permission under CC license.

3.3. Fly Ash- Industrial-Based Materials for Sustainable Remediation

Since they are mass-produced every year, industrial by-products are attracting attention. Reuse as a soil conditioner is a viable method to the sustainable use of these minimum value by-products. Fly ash from coal combustion is a distinctive byproduct of the coal industry. About 780 million tons are made yearly. The chemical composition of fly ash differs due to its dissimilar source and composition of burned coal, but all types include significant amounts of SiO_2, Al_2O_3, Fe_2O_3, and CaO [73,116,117]. It has a similar mechanism of metal immobilization by oxides (i.e., lime and precipitation, surface complexion). The Bayer process in the alumina industry gives red mud as a by-product [118].

However, industrial waste can contain large amounts of poisonous metals as well as organic pollutants. When applied to the soil, these pollutants are out and can move over the long term, posing a danger to the environment [119]. Agriculture, livestock as well as food industries in particular are the major producers of organic waste. Sludge from the sugar industry alone accounts for 30 million tons worldwide [120]. In India alone, the paper industry, which uses large amounts of water and plant cellulose materials, produces 3.033 tons of bio-waste by-products annually from paper mills [121]. In fact, Asian countries have deprived reprocessing systems and faced more ecological problems. Industrial waste is composed of various harmful substances, especially HMs as well as other organic pollutants that affect the quality of the soil. Currently, more than 40% of bio-waste is landfilled, producing both carbon dioxide and methane [122]. Unlimited greenhouse gas creation from bio-waste landfills that endanger the environment and environmental issues require scientific intervention. As shown, the origin as well as industrial biowaste production can be manageable in a variety of ways, ultimately leading to agriculture. The wastes which are polluted dispose in open places that risk to the environment. Generally, pollutants can be separated into two subgroups: (i) organic and (ii) inorganic [66,123,124]. Currently, contaminated bio-waste is disposed of in vacancies, which are a major cause of environmental pollution, especially water and soil pollution. Therefore, restoration techniques are needed to manage some bio-waste [125] (Figure 2).

Figure 2. Modified figure of fly ash Industrial-Based Materials for sustainable remediation adapted from [126,127] with due copyright permission under CC license.

3.4. Employing Bioremediation for Remediation of Contaminated Soil

Biotechnology which utilizes plants' potential to improve the health of the environment is called phytoremediation. Applied research shows that plants have the capability to eliminate and degrade a range of HM toxicants. Due to being cost effective, simple, sustainable, and being compatible with the environment it is considered as more aesthetic than traditional technologies. Remediation of large amounts of toxic groundwater and treatment of large volumes of diluted wastewater can be implemented in situ. Plants respond differently to metal adulteration in soil and should be divided into different groups depending on their response to metal adulteration in the rooting medium. Plants should be divided as accumulators, indicators, or excluders, dependent on the uptake and movement of metal into the ground by the plant [20]. The phytoremediation technique is simple, inexpensive, sustainable, companionable, environment friendly as well as one of the key contents of green technology.

Plants have the natural capability to break down the HMs through a variety of procedures such as bioaccumulation, translocation, and storage/decomposition of pollutants. Phytoremediation is 10 times more inexpensive than traditional technical approaches because it is field-based, photovoltaic, and can function with minimal post-installation maintenance [75,77,128]. Plants have been reported to be highly resistant to HM pollution without causing serious harm; these properties of plants suggest that they could be used to detoxify pollutants through novel approaches to agriculture and genetic engineering. Some of the plants have the natural capability to break down many awkward xenobiotic substances and are therefore considered "green livers" that serve as an essential source of absorption of environmentally harmful chemicals. Nature gives plants the excellent ability to defuse these poisonous elements in the growing matrix, whether in soil or water (Figure 3) [129].

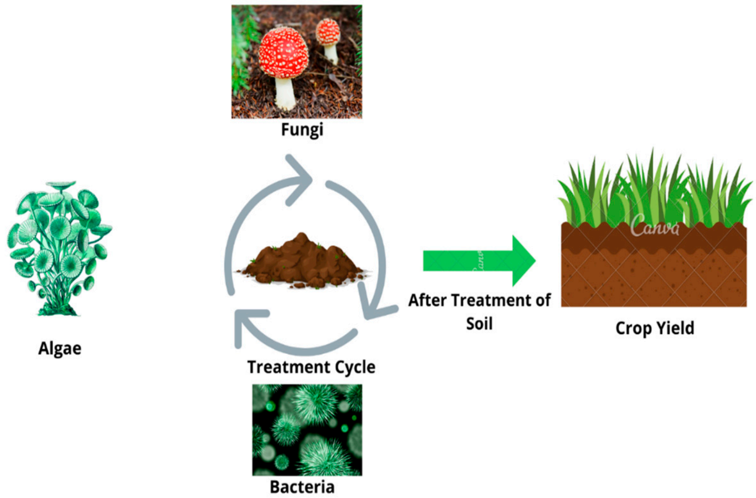

Figure 3. Bioremediation process showing the role of algae, fungi, and bacteria for the enhancement of soil health.

4. Emerging Trends Challenges and Limitations of Remediation

Bioremediation is a relatively low-cost solar power field approach. It also produces no secondary waste and is generally accepted by the general public [130]. However, eco-friendly repairs can take longer to set up and fully function than engineering repairs [131]. Another concern is the potential for toxic plants to enter the food market as contaminated wood tissue from the animal food and fuel markets. The depth of pollution is another matter. Reaching contaminants often requires the correct root depth. If root depth is limited, planting in boreholes or pumping contaminated water to shallower depths may be a good alternative. Pollutant heterogeneity is another problem that arises from the spatial and temporal variation of pollutants. In many cases, this requires accurate repair management that combines different methods [131–133].

Green recovery approaches, such as the use of green resources, renewable resource approaches, nature-based resolutions and energy efficiency policies, have received considerable attention. To rehabilitate soils polluted by HMs. However, there are some challenges in this area that can affect overall sustainability: first, post-harvest metal-rich plant tissue can be a source of contamination for plant restoration methods if not disposed of properly. Plant stabilization is only effective inside the biosphere, which cannot clean up the soil deeply. In addition, phytochemical reactions of Hg lead to air pollution, and the volatile Hg (mainly elemental mercury) in the atmosphere can arrive to the ecosystem by dry as well as wet deposits. Second, bioremediation materials, like biochar manufactured from contaminated biomass (e.g., plants were used in phytoextraction) and materials derived from industrial wastes containing metals, which can lead to metal dissolution and mobilization. Although many studies have shown that green restoration materials are effective in immobilizing soil metals, their long-lasting stability has not been totally examined. Numerous natural forces such as freezing, erosion, dry-wet cycles, UV radiation, plant growth, and groundwater flows can displace stable metals, posing serious risks in the long term [33].

5. Conclusions

Due to the potentially hazardous impacts on humans and soil environments, heavy metal poisoning in soil has sparked a lot of concern. Plants as well as microorganisms plays a vital part in these technologies, the use of green additives like biological and industrial wastes, natural minerals, oxides, and green synthetic nanomaterials that enhance environmental, social, and economic benefits. While some biological remediation strategies, such as plant remediation and soil remediation, are already widely used commercially, other laboratory-proven techniques include biocarbon-based stabilization, low-temperature thermal desorption with citrate, and bio-electrodynamic recovery. In both cases, however, practical application-based testing of these green remediation solutions should be done in the future. Due to new methodologies in engineering-based remediation, the use of green remediation to decrease soil salinity is a very promising strategy. The removal of cadmium, chromium, and copper using biochar and fly ash has been found to be an effective technique. On the other hand, HMs like mercury and arsenic were found to be removed with higher efficiency by nano-bioremediation based technologies than by plant or microorganism-based methods. The removal of zinc and lead has been mainly done by using fly ash-based techniques. To bring flexibility in the removal of HMs from soil, traditional techniques combined with nanotechnology can be researched in the future. Bioremediation's biological, physical, and chemical mechanisms, as well as their effects on contaminated soils and streams, will require further research in the future.

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