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Nanophytoremediation: An Overview of Novel and Sustainable Biological Advancement

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Abstract

Increased threat of metals simultaneous to the biota well-being and the environs is continually causing a major apprehension worldwide. The phytoremediation technique is highly advantageous involving the natural processes of plants viz., translocation, evapotranspiration, and bioaccumulation, thus degrading contaminants slowly. In particular, nanophytoremediation is a rapid green alternative as it reduces the ancillary impacts of the environment such as green gas emissions, waste generation, and natural resource consumption to the present scenario as there is a great potential of nanoparticles from plants which can be synthesized. Nanophytoremediation is a current methodology for remediation of pollutants, contaminants by using synthesized nanoparticles from plants. In this, the use of different strategies enhances the selective uptake capabilities of plants. The metal elements in excess are affecting the physiological processes in plants; thus, it is necessary to apply nanophytoremediation technology through transgenic plants. In this review paper, we focused on plant species, which can be used as metal tolerant, hyperaccumulators. Due to the insurmountable pressure of a sustainable cleaner environment, bioremediation can be concurrent with nanoparticles for efficient and effective sustainable measures.

Keywords: nanoparticles, phytoremediation technologies, hyperaccumulators, bioelements, contaminants, transgenic plants

1. Introduction

Plants are autotrophic in nature, thus are self-sufficient in the utilization of sunshine and CO₂ as energy and carbon sources. The vegetation mostly depends on its roots for water, nutrients, and minerals from groundwater and soil. The maintenance of the greener environment is mostly integrated with plants. Further, the sustainability of these plants depends on the environment, which is contaminated mostly from anthropogenic activities and pollution. In contrast, plants also absorb

Figure 1.
Illustration of physiological processes occurring in plants during phytoremediation.

Treatment	Mechanism	Medium
Phytodegradation	Degradation of plant uptake organics	Surface and groundwater
Rhizofiltration	Roots can uptake metals	Surface waters and water pumped through troughs
Bioremediation supported by plants	Enhanced microbial degradation in the rhizosphere	Soils and groundwaters within the rhizosphere
Phytoextraction	Metal uptake and the presence of metal concentration directly via plant tissue with the subsequent exclusion of plants for biomass degradation.	Soils
Phytostabilization	Root exudes which causes metal precipitation, thus decreases the bioavailability	Soils, groundwaters, and tailings in a mine
Phytovolatilization	Evapo transpires Se, Hg, and volatile organics	Soils and groundwaters
Phytomining	Inorganic substance extraction from mine ore	Soil
Removal of organics	Volatile organics are left out through the plant	Air
Rhizosecretion	Molecular farming methodology, which secretes natural products and recombinant proteins from roots.	Soil
Vegetative caps	Rainwater is evapotranspiration, preventing contaminant leaching from a waste disposal site	Soil

Table 1.
Technologies related to phytoremediation.

diverse compounds that are toxic in nature, thus can be considered as an efficient detoxification mechanism for the removal of contaminants. Thus, from this viewpoint, plants are employed effectively in the treatment of contaminants viz.,

organic contaminants, polyaromatic hydrocarbons, which are potentially viable in contaminant detoxification. Previously, the traditional remediation of metal-contaminated soil includes on-site management and subsequent disposal of wastes to another landfill site. However, this makes the site hazardous with additional risks of migration of contamination. There are various clean-up techniques for soils that can be categorized as physical, chemical, and biological. There are reports of the chemical and physical processes, which have limitations viz., great price, labor intensive, variations in properties of soil, and disturbance of the native soil microflora, whereas chemical techniques increase secondary pollution problems with large volumetric sludge which increases the cost. The biological remediation processes consist of bioventing, bioleaching, bioremediation, bioreactors, bioaugmentation, biostimulation, and land forming. In this context, the phytoremediation technology has been in existence in par with other remediation technologies as a novel natural ecological, biological remediation process.

Phytoremediation created from Greek prefix “*phyto*” means plant and Latin suffix “*remedium*” means remedy or restore. Phytoremediation is a versatile technology to treat polluted soils, pollutants, deposits, and groundwater, in a profitable as well as environmental welcoming the usage of plants [1], thus can be referred to as natural green biotechnology **Figure 1** denotes the different phytoremediation technologies. Phytoremediation technology is suitable against several types of contaminants [2] in the atmosphere in a variety of media, as mentioned in **Table 1**.

Nanoparticles	Plant
Silicon-Germanium (Si-Ge) nanoparticles	Freshwater diatom <i>Stauroneis</i> sp.
Au and Ag nanoparticles	<i>Pelargonium graveolens</i> , <i>Hibiscus rosasinensis</i> , <i>Citrus sinensis</i> , <i>Diospyros kaki</i> (Persimmon), <i>Embllica officinalis</i> , <i>Phyllanthium</i> , Mushroom extract, <i>Coriandrum sativum</i>
Ag nanoparticles	<i>Elettaria cardamom</i> , <i>Parthenium hysterophorus</i> , <i>Euphorbia hirta</i> , <i>Ocimum</i> sp., <i>Nerium indicum</i> , <i>Brassica juncea</i> , <i>Azadirachta indica</i> , <i>Pongamia pinnata</i> , <i>Clerodendrum inerme</i> , <i>Opuntia ficus-indica</i> , <i>Gliricidia sepium</i> , <i>Desmodium triflorum</i> , <i>Carica papaya</i> , <i>Coriandrum sativum</i> , <i>Peargoneum graveolens</i> , <i>Avicennia marnia</i> , <i>Aloe vera</i> extract, <i>Capsicum annum</i> , <i>Rhizophora mucronata</i> , <i>Ceriops tagal</i> , <i>Rumex hymenosepalus</i> , <i>Pterocarpus santalinus</i> , <i>Sonchus asper</i>
Au nanoparticles	<i>Terminalia catappa</i> , Banana peel, <i>Mucuna pruriens</i> , <i>Medicago sativa</i> , <i>Allium cepa</i> L., <i>Camellia sinensis</i> L., <i>Chenopodium album</i> L., <i>Justicia gendarussa</i> L., <i>Macrotyloma uniflorum</i> (Lam) Verde, <i>Azadirachta indica</i> A. Juss, <i>Magnolia kobus</i> and <i>Diospyros kaki</i> , <i>Cinnamomum zeylanicum</i> , <i>Mentha piperita</i> L., <i>Mirabilis jalapa</i> L., <i>Syzygiuma romaticum</i> , <i>Terminalia catappa</i> L., and <i>Amaranthus spinosus</i>
Ag, Ni, Co, Zn and Cu nanoparticles	<i>Brassica juncea</i> , <i>Medicago sativa</i> , and <i>Helianthus annuus</i>
Platinum nanoparticles	<i>Diospyros kaki</i> and <i>Ocimum sanctum</i> L.,
Palladium nanoparticles	<i>Cinnamomum zeylanicum</i> Blume, <i>Cinnamomum camphora</i> L., <i>Gardenia jasminoides</i> Ellis., <i>Soybean</i> (<i>Glycine max</i>) L.,
Lead nanoparticles	<i>Vitis vinifera</i> L. and <i>Jatropha curcas</i> L.
Indium oxide nanoparticles	<i>Aloe vera</i> (<i>Aloe barbadensis</i> Miller),
Gold/Silver bimetallic nanoparticles	<i>Azadirachta indica</i> (Neem)

Table 2.
Numerous nanoparticles synthesized from the plants.

Figure 2. Publication trends for phytoremediation as per the ScienceDirect database—year-wise publications, (a) category wise and (b) journal wise.

Phytoremediation technique has its own limitations:

- a. Slow remediation time
- b. Plant waste after phytoremediation

It is seen previously that plants [3] have a tendency to produce nanoparticles under appropriate conditions, as mentioned in **Table 2**. The deployment of contained contaminants remains equally *in situ* and *ex situ*. One of the newer techniques of *in situ* remediation, nanotechnology has been in focus with the usage of nanomaterials in various laboratory investigations and field applications, mostly in North America and Europe. But in India, nanophytoremediation is not practiced. Although nanophytoremediation can be an economically viable process, proper utilization can be ecologically useful.

Several studies report the usage of nanoparticles to have an affirmative effect on plants. Mixed TiO_2 (nano) and SiO_2 (nano) were presented into soybean (*Glycine max*) increasing activity of nitrate reductases, which sped the plant propagation by increasing the water absorption and fertilizer utilization (Lu et al., 2001).

Similarly, it was found by studies that carbon dots (CDs) promote growth in mung bean at 0–1.0 mg/mL concentration (Li et al., 2016). This result supports that nanoderivatives like carbon dots can absorb and utilize nutrients that induce a physiological response. Although there are studies on nanoparticles that can cause toxicity, it has not been yet elucidated for most nanoparticles. It is vividly important to study nanoparticles and their effect on plant growth mechanisms to prevent the ecological risk of nanoparticles and to promote sustainable development of nanotechnology in the near future, particularly in the Indian context. Thus, the different integrated approaches to producing nanoparticles and apply nanoderivatives eliminating the metal impurities from soil and water; thus, a flawless, in-depth study of nanoparticles is required, which can be applied. Nanophytoremediation study is based as an alternative remediation advanced technology in addition to the phytoremediation, the current scenario of reducing the contaminants in a safer way.

1.1 Publications

Publications wise not many were found in the literature databases; for example, probing ScienceDirect database, it has found none on nanophytoremediation. Since the year 1995 to date, 2018, the number of publications found to be 764. Of which highest published were found to be research articles (567) followed by review articles (78), short communications (34), and rest others.

Among journal trends, the highest number was found to be in journal: Chemosphere (99) followed by Ecotoxicology and Environmental Safety (61), Ecological Engineering (52), the lowest number published was in Journal of Biotechnology (18) over the years 1995–2018. Publication trends for phytoremediation, as observed from the ScienceDirect Database year-wise publications: (a) category wise and (b) journal wise were shown in **Figure 2**. Nanophytotechnological remediation was published in the *J. of Environ. Protec.* (JEP) (2016, <http://dx.doi.org/10.4236/jep.2016.75066>).

2. Phytoremediation classification

Phytoremediation technologies are classified in general into:

- a. **Phytoextraction:** Metal concentration reduction in the soil through plants that can accumulate metals in the shoots.
- b. **Phytostabilization:** Immobilize the utilization of soil metals via adsorption onto roots; rhizosphere precipitation.
- c. **Phytostimulation:** The process where root releases certain compounds enhancing the microbial activity in the rhizosphere of the plant. It is a type of rhizosphere phytoremediation which is used as an inexpensive approach to remove soil organic pollutants.
- d. **Phytovolatilization:** A technique, where the soil contaminants are cleaned up by plants and discharge them as atmospheric volatiles through transpiration.
- e. **Phytotransformation/phytodegradation:** Breaking down of organic contaminants seized through plants via

- i. *Plant metabolic processes or*
- ii. *The outcome of metabolites, such as enzymes, produced by the plant*

f. **Phytoresaturation:** Re-vegetation of the drylands by plants can prevent the spread of pollutants into the environment [4].

Type of nanoparticles	Biochemical agents	Size/morphology	Environmental applications
Stabilized bimetallic Fe/Pd nanoparticles	Starch	14.1 nm distinct, well dispersed	Degradation of chlorinated hydrocarbons in water
Fe ₃ O ₄	Na-Alginate	27.20 nm spherical	Urea decomposition
Fe ₃ O ₄ -Polymer Composite	Agar (reducing and stabilizing agent)	50–200 nm spherical, 24 nm diameter and hexagonal	Magnetic storage media
Nano-shell (Fe, Cu)	Ascorbic acid (antioxidant)	<100 nm cubic	Functions in catalysis, biosensors, energy storage problems, nanodevices
nZVI	Ascorbic acid (Vit-C)	20–75 nm, spherical	Cd removal
Superparamagnetic Iron oxide (coatings and functionalization)	Ascorbic acid (Vit-C)	5–30 nm (hydrodynamic size)	Contrast enhancement agent for MRI applications
Fe ₃ O ₄ (MNPs)	L-Lysine (A. Acid)	17.50 nm and spherical crystalline	Biosensors, drug delivery
nZVI	L-Lysine (A. Acid) L-Glutamic Acid L-Glutamine L-Arginine and L-Cysteine	—	Low molecular, biocompatible
FeNPs	Hemoglobin and myoglobin	2–5 nm aggregates, crystalline	Bioconjugated nanoparticles for biological applications
Fe ₃ O ₄	D-glucose gluconic Acid	12.5 nm roughly spherical, crystalline	Drug delivery, cell transplantation
Fe ₃ O ₄	Glucose & Glyconic acid	4–16 nm crystalline	Removal of waste in the biomedical field
Carbon capsulated Iron NPs	Wood-derived sugar	100–150 nm nanospheres, 10–25 nm diameter of iron core	Acts as catalysts in the conversion of wood-derived syngas to liquid hydrocarbons
Iron oxide	Tannic acid	<10 nm	Utilization of biomass causes the reduction of metal ions
Fe core-shell structure	Chitosan-gallic acid	11 nm cubic	Increased thermal stability of drug gallic acid, anticancer activity was higher for HT29 and MCF7 cell lines

Table 3.
Synthesis of iron nanoparticles/derivatives.

An overview of metal contaminants in several phytoremediation processes is provided in **Table 3**. In the case of contaminated water, the following processes in phytoremediation technologies are utilized as:

- a. **Rhizofiltration:** Roots were used to remove aqueous toxic metals, mainly the heavy metals like, lead (Pb) and radioactive elements [5]. The plants are employed as filters in wetlands or as a hydroponic setup [6]. Wetlands are often widely considered as sinks for pollutants, and there are countless instances where the wetlands plants are considered to remove contaminants [7] used which include metals viz., Se, perchlorate, cyanide, nitrate, and phosphate [8].
- b. **Hydraulic control:** It is a process in which bulk amount of water is absorbed by the wildy growing plants preventing the increase of pollutants into the unpolluted surrounding zones [4].

The phytoremediation methods chosen depend upon:

- i. Specifically high growth rates in the polluted sites
- ii. Huge surface area proportionately in contact with the water body
- iii. High translocation potential [9]

These factors say both the bioconcentration factor (BCF) and translocation potential (TP) are related to plants' sensitivity for phytoremediation.

In Brake fern (*Pteris vittata*), the best phytoremediation process is established as it consists of a high root to shoot metal transduction; thus, it is observed that the BCF value is greater than one. Out of the several phytoremediation technologies, phytoextraction is the most effective, which depends upon hyperaccumulation of metals into the whole plants. For phytoextraction, a heavy metal tolerant plant that grows rapidly with high biomass yield per hectare also should possess a prolific root system. When the cultivation is over by the season's end plants are harvested, dehydrated and the enriched mass with contaminants is dumped or sent into the smelter. To be active phytoextraction, the dehydrated biomass, ash extracted from the above-ground parts of a phytoremediator crop, consists of a greater concentration of the pollutants than the contaminated soil [10]. The biomass rich product exudes as the secondary metabolic waste, which requires further treatment. The phytoextraction process can be natural and induced. The energy can be recovered from biomass burn or pyrolysis; thus, phytoextraction can be used as a cost-effective technology by giving biomass yields. *Salix* and *Populus* species are also used for phytoremediation technology.

3. Bioelements and their effects on pollution

Pollution is an undesirable change observed, which is deteriorating our raw materials, especially land and water. An overall representation of the contamination process, which can cause microorganisms to pollute soil and surface water, is shown in (**Figure 3**). At normal concentration, soil comprises bioelements, particularly metals. These bioelements serve as micronutrients and macronutrients for the soil. They can be classified as light metals (Mg and Al) metalloids (As and Se)m and heavy metals viz., Cd, Hg, Pb, Cr, Ag, and Sn. Light metals have a greater significance to health and environment [11], whereas substantial metals are the bioelements

Figure 3.
An overall representation of the contamination process—that can cause microorganisms to pollute soil and surface water.

(At. No., $Z > 20$) with a density > 5.0 g/cc and have definite metal properties such as conductivity, ductility, ligand specificity, cationic stability. Beneficial heavy metals include elements such as Cu, Cr, Zn, Mn, Fe, Co, and Ni, which are essential in smaller amounts in metabolism but may be lethal in higher concentrations. Geogenic and anthropogenic contaminations by heavy metal is shown and can cause microorganisms [12] to affect the normal molecular process as shown in (Figure 4). Heavy metals sieve through the soil and are terminated into the soil by geogenic and anthropogenic processes [13].

Geogenic contamination can be exemplified by extensive arsenic contamination, as seen in the ground waters of Indian state of West Bengal and Bangladesh [14]. The other contamination source includes anthropogenic activities like generating huge amounts of effluents, which is a constant threat to environmental pollution. Fertilizers incorporate phosphate compounds containing Cd, which are being used in horticulture, agriculture as well as in animal industries as a trace element nutrient. Cd, Hg, and Pb metals attack the activity of the enzyme, which contains the $-SH$ group which initiates chronic diseases. These heavy metals/metalloids and organics form a grave danger to animals (including humans) and plants. Heavy metal pollution on land and water shows a severe impact on the ecosystem. In Western Europe, a large mass of approximately 14,00,000 sites affected as the reports of [15], out of which 3,00,000 are contaminated, but the projected number in Europe could be greater, as the problem was progressively occurring in the Central and East European countries. In the United States, around 600,000 contaminated brownfields with heavy metals requiring reclamation [16]. Land pollution has been a great challenge in the Asian continent as seen in China, where one-sixth of arable land is with heavy metal pollution, and over 45% has been ruined either due to erosion or desertification. This becomes the consequence because of human-dominated ecological problems viz., urban ecology and agricultural ecology [17]. Thus, it is vital to eliminate these pollutants from the contaminated sites in which phytoremediation is one of the processes that include complexation, accumulation, volatilization, and degradation of pollutants both of organic and inorganic origins.

Figure 4.
Geogenic and anthropogenic contaminations by heavy metal is shown and can cause microorganisms to affect the normal molecular process.

4. Biosynthesis of nanoparticles from plants

Nanoparticles are aggregates between 1 and 100 nm; this particular size that alters the physicochemical properties equated to other material. A variety of nanoparticles are produced by bacteria, fungi, and plants [18], which have wider applications in several sectors. Plants are more appropriate than bacteria or fungi toward the synthesis of NPs, as less incubation time is required for metal ion reduction. The procedures such as plant tissue culture (PTC) and downstream processing techniques make more promising in synthesizing metal and oxide NPs at a larger scale. The documentation of hyperaccumulator exclusive genes and their succeeding transfer to the other species of transgenic plants can improve phytoremediation capacity. The plant's remediation volume shall be greatly enhanced by genetic manipulation and other viable plant-based transforming techniques. In plants, it is seen to have an inherent ability to lessen metals through their specific metabolic pathways [19]. Stampoulis et al. [20] have examined the impact of ZnO, Cu, Si, and Ag NPs on the root elongation, seed germination, and biomass production of *Cucurbita pepo* grown as hydroponics. Accordingly, experimental findings suggested that root length is reduced by 77% when seeds are exposed to Cu nanoparticles and 64% when exposed to bulk Cu powder when equated to the untreated controls.

Plant biomass was reduced by 75% when exposed to Ag NPs. Shekhawat and Arya [21] used *Brassica juncea* seedlings to produce Ag NPs *in vitro*. There are reports from synthesized gold nanoparticles by *Terminalia catappa* leaf extract in an aqueous medium [22]. The authors [4, 23] examined metal ions Ag^+ and Au^{3+} to Ag^0 and Au^0 NPs in *Brassica juncea* for the reduction sites. Nevertheless, Ag NPs in plants are mostly modeled as Ag not only forms NPs in plants but it also exhibits higher catalytic properties as it consists of high electrochemical reduction potential and several additional useful properties. Although the research on the production of nanoparticles is in a nascent stage in plants,

more qualitative work is required to realize the physiological, biochemical, and molecular mechanistic process relative to nanoparticles.

4.1 Nano-iron and its derivatives

Reactive nanoscale iron product (RNIP) and nanoscale zero-valent iron (NZVI) are mostly the elementary forms of iron (nano) technology [24]. Nano zero-valent iron because of its nano-size (1–100 nm) enables high-level remedial adaptability. NZVI, a product of nanotechnology, is used to treat a range of impurities in perilous wastewater (see **Table 3**) and represents the synthesis of iron nanoparticles [25]. As for example, NZVI was tested in the removal of As(III) seen in groundwater. NZVI can be used in permeable reactive barriers (PRBs) form to intercept plumes on the subsurface and remediate them. The sustained zero-valent iron nanoparticle “*ferragels*” swiftly dispersed and immobilize Cr(VI) and Pb(II) from aqueous solutions, reducing the Cr(VI) to Cr(III) and Pb(II) to Pb(0) while oxidizing Fe to goethite (α -FeOOH) [26]. Anionic hydrophilic carbon (Fe/C) and poly (acrylic acid)-supported (Fe/PAA); Fe(0) NPs were further considered as a sensitive material for the dehalogenation of chlorinated HCs in soils and ground waters [27]. Nickel-iron NPs in the ratio 1:3 were employed in the dehalogenation of trichloroethylene (TCE) [28].

4.2 Single-enzymed nanoparticles

Enzymes serve as effective biocatalysts in bioremediation. Nevertheless, less stability as a result of diminutive catalytic lifetimes of enzymes limits their effectiveness being inexpensive due to oxidation. The usage of nanotechnology provides a novel method where the enzymes are stabilized in the form of single enzyme nanoparticles (SENs). Enzymes can be devoted to the magnetic iron NPs increasing stability, longevity, and reusability. The enzyme separation from the magnetic iron NPs is usually done by the use of a magnetic field. The two different catabolic enzymes—trypsin and peroxide subjected to unvarying core-shell magnetic nanoparticles (MNPs). SEN requires the involvement of modification of enzyme surface, vinyl polymer growth from the enzyme surface. There are immobilized enzymes in biopolymers and carbon nanotubes, which can add as environmental biosensors.

4.3 Exopolysaccharides

Exopolysaccharides (EPSs) are polymers of the polysaccharide of high molecular weight, secreted by microorganisms. EPSs are sustainable as it has good adsorption capacity and environmental friendly. Therefore, the usage of EPS for bioremediation in the metallic and dye-based environmental pollution attracted researchers in the past years. Polysaccharides are very rich in –OH groups using them as a stabilizer for the production of metal NPs, an environment friendly alternate for the chemical-reducing method [29].

EPSs are used as a reducing agent and stabilizer. They are further used for the synthesis of metal NPs viz., lentinan, carboxymethylated chitosan, glucan, carboxymethyl cellulose, and carboxylic curdlan [30]. Apart from exopolysaccharides, the Au and Ag nanoparticles also consist of good dispersible capability and uniformity. EPS produced from *A. fumigatus*, [31] *Lyngbya putealis*, *Lactobacillus plantarum* [32], and *Bacillus firmus* [33] removed heavy metals viz., Cu^{2+} , Pb^{2+} , Cr^{4+} , Cd^{2+} , and Zn^{2+} within the adsorption capability of 50–1120 mg/g. EPS-605 obtained from newly identified *L. plantarum*-605 was obtained from a Chinese fermented food, Fuyuan pickles. When EPS-605 was self-assembled in H_2O ,

monodispersed nanoparticles were detected that are useful for bioremediation and record heavy metal and dye adsorption.

4.4 Dendrimers

Dendrimers are multivalent, globular, highly branched, and monodispersed molecules with synthetic elasticity. Dendrimers have proper architecture and controlled composition, which consist of three components and have an extensive assortment of applications ranging from catalysis, electronics to drug release. With unique structural characteristics viz., nanoscopic size, spheroidal surface, vast interior with exhilarating properties which consists of low viscosity, extraordinary solubility, and reactivity. Dendrimers' first dendrimers were synthesized by Fritz Vogtle in 1978 [34] consists of three constituents—a vital core, internal branch cells or radiated symmetry, and terminal branch cell or marginal group. The void spaces in dendrimers interact with nanoparticles, which enhances the catalytic activity. The dendrimer nanocomposites were also set for treatment of water and dye removal from industrial waters to enhance the reactivity by creating more surface area with a reduced amount of toxicity. PAMAM dendrimers using group of hydroxyl-terminated (G4-OH) poly (amidoamine) also acts as templates in the production of Cu NPs formed by coordination of Cu ions with dendrimer interior amines and subsequent reduction forming dendrimer-encapsulated Cu NPs (Cu-DEN).

Cowpea mosaic virus (CPMV), a plant virus, is adequate to endorse the templated mineralization of metal and metal oxide. CMV particles used for templated fabrication of metallic NPs by an electron less deposition metallization process. In the virus capsid, Pd ions are electrostatically bound to the virus capsid and upon reduction acts as a nucleation site to deposit metal ions from solution. Further, dendrimer-modified and plain magnetite nanoparticles (MNPs) have been widely studied in environmental decontamination. Dendrimers can enhance drug targeting efficacy mainly to be used in drug delivery systems [34].

4.5 Nanocrystals and carbon nanotubes

Nanomaterial-based applications in the field of environment are in multiples that provide both large and portable scale and also clean up impurities that are present in our environment. Carbon-based nanomaterials viz., nanocrystals and carbon nanotubes (CNT) have wider applications as antimicrobial agents, environmental sensors, biosensors, sorbents, depth filters, renewable energy technologies, high flux membranes, and in pollution prevention [35]. CNTs are both single walled (SWCNT) or multiwalled (MWCNT); functionalized hybrids were evaluated for the elimination of Et-C₆H₆ from aqueous solution and remediating pollution to avert diseases from ethylbenzene (Et-C₆H₆) viz., cyclodextrins (CD). Nickel ions from water were remediated using MWCNT-based materials [36]. CNT-based polymeric materials incorporating nanomaterials, Calixarenes, and Thiocalixarenes were synthesized to remove both organic (p-NO₂-C₆H₅OH) and inorganic contaminants (Cd²⁺, Pb²⁺) from water bodies [37]. CNTs immobilized by calcium alginate (CNTs/CA) materials investigated the Cu removal efficiency (69.9% at pH 2.1) via equilibrium studies [37]. Magnetic-MWCNT nanocomposites reported eradicating cationic dyes in aqueous solutions [38].

4.6 Engineered polymeric nanoparticles application in bioremediation for removal of hydrophobic contaminants

Hydrophobic contaminants, say, polycyclic aromatic hydrocarbons (PAHs), are globally persistent in the atmosphere. PAHs are hydrophobic, strongly sorbed to

the soil; thus, sorption limits the bioavailability of these pollutants on the surface. Sequestration in nonaqueous phase liquids (NAPLs) shrinks the mobility and bioavailability of hydrophobic contaminants [39]. Though surfactant micelles have shown an increased rate of PAHs and hydrocarbon solubilization in contrast also causes biodegradation.

Synthesis of nonionic amphiphilic polyurethane (APU) NPs from a mixture of polyethylene glycol (PEG) altered polyurethane acrylate (PMUA), and polyurethane acrylate precursor chains solubilize PAHs from the contaminated soil. Unlike surfactant micelles, PMUA NPs are cross-linked, so not easily breakable when it comes in contact with soil interacting with liposomes of microorganisms but have excellent properties to improve desorption and the agility of phenanthrene (PHEN) in aquifer sand [40].

4.7 Polymeric nanoparticles used in soil remediation

Research based on nanoparticles usage in soils and groundwater remediation processes increased greatly with promising results. Using nanotechnologies, polluted soils remediation becomes an emerging area with an enormous impeding to advance the performance over traditional remediation technologies in a large way [41, 42]. Effective application for soil contaminants contexts, predominantly, for heavy metals, other inorganic and organic contaminants, and emerging contaminants, such as pharmaceutical, cosmetic, personal care products.

Polynuclear aromatic hydrocarbons (PAHs) that absorb intensely to soil are very challenging to eliminate. In such cases, amphiphilic polyurethane (APU) nanoparticles are used in soil remediation which is polluted with PAHs. Desired properties of APU particles can be achieved by engineering, and experimental results have shown that these designed particles make sure hydrophobic interior regions that confer a high affinity for PHEN and hydrophilic surfaces that encourage soil particle mobility. APU NPs (17–97 nm) are prepared of polyurethane acrylate (PA) and ionomer (UAA) or PEG, modified urethane acrylate (PMUA) precursor chains which are emulsified and cross-linked in water. APU particles are stable, independent to their concentration in the aqueous phase, and have interiors regions exhibiting hydrophobic property enhances PAH desorption. APU particles contrived to give the anticipated properties. APU particles affinity toward pollutants like PHEN is precisely managed by varying hydrophobic segment size required for the chain propagation. Mobility of soil APU suspensions is controlled by the charge density or the size of the water-soluble chains [40].

4.8 Biogenic uraninite nanoparticles

There is evidence of the widespread prevalence of uranium in India's groundwater. A variety of sources and studies have indicated the link between exposures to uranium in drinking waters which causes chronic kidney diseases. Although the main source is geogenic but still anthropogenic factors play their part in the decline in groundwater table and nitrate pollution promote uranium mobilization. The term *Uraninite* defines compositionally complex, nonstoichiometric, cation-substituted forms of UO_2 , which are found in nature. Biogenic uraninite being nanoscale biogeological material is significant due to usage in bioremediation strategies. Uraninite is utmost preferred product in situ stimulated subsurface uranium U(VI) and has its solubilization much lesser compared to other uranium species.

Uraninite nanoparticles have its properties viz., solubility and dissolution kinetics, which are crucial for microbial bioremediation which mitigates subsurface uranium contamination through uranium reduction. Uraninite exhibits structural chemistry, thus derives its properties from its open fluorite structure. Biogenic

uraninite forms by reduction of U(VI) to U(IV) considered as the first stage. After the reduction process, the second step formation requires the precipitation of the mineral. In situ U(VI) reduction has been observed and reported at a large number of contaminated U.S. Department of Energy (DoE) nuclear legacy sites and has shown potential results. The success in uranium bioremediation should be maintained strictly in anaerobic conditions. The surface chemistry of nanoparticulate uraninite is important for the construction of geochemical models of uranium behavior, which follows the bioremediation. This may be challenging for research in nano-bio geosciences in the future [43].

5. Soil trace element biomonitoring plants

Soil contamination manifested by trace elements, organic, and inorganic compounds is an extensive problem occurring worldwide. Common techniques in soil remediation include waste disposals, incinerations, leaching of soil thermal desorption, and vapor abstraction, but all these types of actions may be responsible for secondary pollution, which ultimately affects soil properties. Plants are the major factors to keep our environment clean and green by remediation of soil and water. The soil organic and inorganic contaminants are removed by phytoremediation. Ryegrass, oat plant, tall fescue, sunflower, and green gram grow in diverse contaminated conditions useful for phytoremediation. Certain plants known as hyperaccumulators are good in phytoremediation in particularly toward heavy metal removal. Some hyperaccumulator families represent their metal content [44].

Table 4 defines the hyperaccumulator plants of various families, which are used to accumulate specific metals at different concentrations. Phytoextraction seems to be a feasible alternate to the traditionally conventional practice used in the decontamination of soils with heavy metals [45]. In phytoextraction, methodology plants absorb pollutants from soil. Metals that are deposited as ions in the plant's roots, stems, leaves, and inflorescences are burnt to recover metals, and the subsequent biomass is removed to dispose of safely. The build-up of heavy metals is connected to the total concentration of the metals and suggestively segregated as macro nutrients and micronutrients and soil acidity.

5.1 Vascular plants

Water pollution is dangerous, and one of the ecological risk factors suggests the need to cultivate water plants that absorb trace elements. Usually, there is a quick dilution of the contaminants in water; thus, investigating the plant tissues provides combined evidence about the quality and components of water and the method of phytoremediation [46]. The various nanomaterials that can be synthesized through several methods have been represented in **Table 5**. Further, it is observed that species viz., duckweed (*Lemna gibba*), water spinach (*Ipomoea aquatica*), and fern (*Azolla pinnata*) are prominent to phytoremediate metals [47]. like boron, chromium, and manganese, respectively [48–50]. Aquatic macrophytes such as water hyacinths are used extensively in phytoremediation of water contaminated with dyes [51]. Hasan et al. [52] stated the efficacy of water hyacinth in sorption of Zn(II) and Cd(II) from the water. The species from Lemnaceae family, eliminate dyes such as acid blue (azo dye, AB92) undergoes a transformation to form dissimilar transitional compounds [53]. Aquatic plants viz., *Azolla pinnata* (water-fern) and *Hydrilla verticillata* (water-thyme) are used for elimination of fly ash and uranium, respectively [54, 55]. *Micranthemum umbrosum* observed [56] removal of As and Cd by phytofiltration method. *Oenothera picensis* plant was quite extensively

Metals	Plant species	Accumulated metal concentration (mg/kg)
Cadmium		
<i>Thlaspi caerulescens</i>	Brassicaceae	2130
Zinc		
<i>Thlaspi caerulescens</i>	Brassicaceae	43,710
<i>Thlaspi rotundifolium</i>	Brassicaceae	18,500
<i>Dichapetalum gelonioides</i>	Brassicaceae	30,000
Nickel		
<i>Thlaspi Sps.</i>	Brassicaceae	2000-2031,000
<i>Allyssium Sps.</i>	Brassicaceae	1280-29,400
<i>Berkheya codii</i>	Asteraceae	11,600
<i>Pentacalia Sps.</i>	Asteraceae	16,600
<i>Psychotria coronata</i>	Rubiaceae	25,540
Copper		
<i>Ipomoea alpina</i>	Convolvulaceae	12,300
Lead		
<i>Minuartia verna</i>	Caryophyllaceae	20,000
<i>Agrostis tenuis</i>	Poaceae	13,490
<i>Vetiveria zizanioides</i>	Cyperaceae	>1500
Cobalt		
<i>Crotalaria cobalticola</i>	Fabaceae	30,100
<i>Haumaniastrum robertii</i>	Lamiaceae	10,232

Table 4.
Hyperaccumulator plants for varied metals.

Nanomaterials	The methodology used in the synthesis	Examples
Nanoparticles biosynthesis from metals (NPs)	Photochemical	Cu, Au, CoNi, CdTe, CdSe, ZnS, Rh, Pt, Ir, Pd, Co, Ag, Au, Cu, Fe & Ni
	Biochemical	
	Electrochemical	
	Thermochemical	
Nanomaterials from carbon	Arc-discharge	Cylindrical nanotubes (SWNT, MWNT) Fullerenes
	Chemical vapor deposition	
	Laser ablation	
Nanomaterials from polymers	Electrochemical Polymerization	Nanowires of PPy, PANI, Poly (3–4 ethylene dioxy thiophane, PAMAM, dendrimers
Metal oxide Nanoparticles	Hydrothermal	BaCO ₃ , BaSO ₄ , TiO ₂ ,
	Reverse micelles solvo-thermal	ZnO, Fe ₂ O ₃ , Fe ₃ O ₄ , MgO
	Sol-gel method	
	Electrochemical deposition	
Bionanomaterials	Biological	Plasmids, nanoparticles from protein viruses

Table 5.
Synthesis of diverse nanomaterials.

considered toward phytoextraction of copper [57]. Algae such as charaphytes viz., *Chara aculeolata* and *Nitella opaca* were used to remove Pb, Cd, and Zn [58].

Cystoseira indica (brown algae) after its chemical treatment become greatly effective against chromium. Metal uptake is seen in algae species such as *Spirulina* used for chemisorptions of metals with few heavy metals like chromium and copper [59]. *Ranunculus peltatus*, *Ranunculus trichophyllus*, *Lemna minor*, *Azolla caroliniana* viz., serve as an arsenic indicator [60]. *Ulothrix cylindricum* (green algae) has biosorption capacity of 65.6 mg/g, forming an inexpensive method for biosorption of As(III) [61]. Aquatic macrophytes grow quickly, and due to their high biomass production, the greater capacity in accumulating heavy metals widely used for wastewater treatment compared to soil-grown plants.

A macrophyte grows in or near the water body and is emergent, submerged or floating. Aquatic plants have adjusted to living in aquatic environments (hydrophytes or macrophytes) to differentiate from algae and other microphytes. Water hyacinth (*Eichhornia crassipes*), Sensitive Plant (*Neptunia aquatica*), Lucky 4-Leaf Clover (*Marsilea mutica*) water lettuce (*Pistia stratiotes*), Moneywort (*Bacopa monnieri*), Mosaic Flower (*Ludwigia sedoides*), Water poppy (*Hydrocleys nymphoides*), and duckweed (*Lemna minor*) are a few of the aquatic macrophytes widely intended for heavy metal phytoremediation [62]. *Pistia stratiotes* have relatively high growth rate thus ideally chosen in phytoremediation study as it is proposed to accumulate As [63]. Water lettuce is observed to be a probable plant for phytoremediation for manganese contaminated waters [62]. In the elimination of Pb, Cd, Cr from the water, *Lemna minor*, a native of Europe, North America, Asia, and Africa is naturalized for its advantage to grow in several climatic conditions and also a potential accumulator of Cd to remediate the aquatic environment. *Eichhornia crassipes* was used for the tertiary treatment of wastewater phytoremediation as it has broader leaves and fibrous root system which assists in the absorption of heavy metals [64]. There has been experimentation on water hyacinth (*Eichhornia crassipes*), two algal species (*Chlorodesmis* sp. and *Cladophora* sp.) found in As-contaminated water bodies are used to determine the arsenic tolerance capability. *Cladophora* species are found to be appropriate for co-treatment of sewage and As-contaminated brine in algal ponds. *Typha latifolia* and *Eichhornia crassipes* are freshwater plants used to clean up the effluents that usually contain high concentrations of Co, Cd, and As. *Eleocharis acicularis* commonly known as dwarf hair grass and needle spike rush acts as hyperaccumulators as it uptakes several metals Fe, Pb, Mn, Cr, and Zn from drainages and mines [65, 66]. *Myriophyllum aquaticum* consists of enzymes that play a vital part in the transformation of organic compound contamination and is effective in the phytoremediation of an aquatic environment [9]. *Ludwigia palustris* (marsh seedbox; creeping primrose) and *Mentha aquatica* (water mint) effectively remove Cu, Fe, Hg, and Zn. Among the freshwater vascular plants, the most efficacious plants are *E. crassipes* and *L. minor*.

6. Hyperaccumulator plants for different metals

Bioconcentration factor and factor of translocation are multiplied to get the phytoextraction efficiency. It is observed that accumulated metal concentration in soil modifies its biological properties. Different plant species vary with regard to uptake of heavy metal. The hyperaccumulation of heavy metals mainly rest on several factors viz., plant species, soil circumstances (pH, temperature, humidity, soil organic content, and cation capacity), and types of heavy metals. The uptake of metals is determined by the metal type and metal chemical speciation and habitat characteristics of the plant [67]. Hence, the plant selection became significant for

the remediation of the containment location. The accumulation efficacy of heavy metals in any plant species is calculated via a bioconcentration factor [68]. The willow plant consists of the highest biomass, thus identified itself as an appropriate plant for soil remediation [69]. In a prior experiment, plant species of Brassicaceae family, such as *Brassica juncea* L., *Brassica napus* L., and *Brassica rapa* L. are able to accumulate Zn and Cd moderately. In *Brassica juncea*, the nuts showed the bioaccumulation ability toward Cu [70]. *Pistia stratiotes* L. (water lettuce) has the potential to remove Cd from surface water [71]. Canola (*Brassica napus* L.) is very effective with respect to Cu, Cd, Pb, and Zn in comparison to *B. juncea* L. (Indian mustard). Application of Ethylene diamine tetra acetic acid (EDTA) increases heavy metal availability, thus making the plant uptake showing the prominence of organic chelates in increasing metal solubility/availability, thus applicable to enhancing the efficiency of phytoremediation technique.

Table 6 represents the advantages and limitations of phytoremediation technologies. In Brassicaceae family, plants are used for biofumigation. *Helianthus annuus* (Sunflower) has the capability for soil remediation contaminated by Pb. Soybean plants characteristically synthesize homophytochelatins alternative to phytochelatins when heavy metals are exposed. For the soybean seeds and young seedlings, Cr metal is found to be extremely toxic at higher concentrations [72]. Crops are affected as it is seen that soil contamination by heavy metals causes a considerable loss in seed production of soybean canopies [73]. Agricultural soils accumulate toxic metals in edible portions of crops which grow in contaminated soils that described in crops viz., rice, soybean, maize, and vegetables.

Advantage	Limitation
Phytoextraction	
Plant with high biomass within lesser time should be successful to remove contaminants from soil.	<div>1. Hyperaccumulators exhibit slow growth and less bioproductivity due to shallow root systems</div> <div>2. Biomass/phytomass must be disposed of cautiously</div>
Phytostabilization	
Cost-effective and less disruptive which enhances the ecosystem restoration/re-vegetation.	<div>1. The requirement of extensive fertilization/soil modification. Proper maintenance is required to prevent leaching</div>
Phytovolatilization	
Contaminants/pollutants are transformed into less toxic forms, for example, volatilization of mercury(Hg) by conversion to the elemental form in transgenic <i>Arabidopsis</i> and yellow poplars which contains bacterial mercuric reductase (<i>merA</i>)	<div>1. Contaminants/hazardous metabolites might accumulate in vegetation viz., fruits/lumber</div> <div>2. Low levels of metabolites can be found in plant tissues</div>
Phytofiltration/rhizofiltration	
<i>In situ</i> (pond floating rafts) or <i>ex-situ</i> (tank system); aquatic Absorption and adsorption play an important role	<div>1. Constant pH monitoring of the medium is required for optimizing the uptake of metals</div> <div>2. Influent chemical speciation and all the species interactions are to be understood</div> <div>3. Intensive maintenance is needed</div> <div>4. Large root surface area is usually required</div>

Table 6.
Advantages and limitations of phytoremediation.

7. Effect of metals on the physiological process

Generally, metals play a significant part in the metabolic pathways in plants during the growth and development in appropriate amounts but lethal in excess. Soil gets contaminated due to several activities such as mining, disposal of solid wastes, automobile exhausts, and engineering activities. Therefore, there is a possibility of augmented uptake of metals by food crops, which cause human health risks, thus affecting food quality and safety. Metals viz., iron (Fe), molybdenum (Mo), copper (Cu), cobalt (Co), manganese (Mn), and zinc (Zn) are crucial for plant growth, categorized as essential micronutrients. The nonessential metals found as pollutants comprise mercury (Hg), chromium (Cr), selenium (Se), uranium (U), nickel (Ni), cadmium (Cd), arsenic (As), lead (Pb), vanadium (V), and wolfram (W). Prior published reports by [74] provided information on the impact of metal on the seed of crops and medicinal plants regarding biochemical and molecular implications, which provide an important role in seed germination. It has been noted that metals applied exogenously in the range of micromolar to milimolar concentrations could affect seed variability. Seeds from metal tolerant plants and hyperaccumulators possess higher threshold toxicity than the seeds of nontolerant plants. Nonetheless, data on their effects on *in situ* seed germination are in the nascent stage, which is required to be investigated. Cd and Cu inhibit water uptake, obligatory for seed germination. One can overcome seed dormancy with metal treatment, although the actual mechanism of action yet to be understood. But the process of deposition and toxicity of metals are unknown in developing seeds, to embryos and cotyledons.

Similarly, few experiments have focused on the detoxification of metals by phytochelatins (PC) and metallothioneins (MT). Similarly, Shanker et al. [75] have studied extensively about the chromium toxicity in plants which predominantly hinge on valence states of chromium ions. Cr has toxic effects on plant development which includes modifications in the germination process, development of roots, leaves, and stems which ultimately affects entire dry mass production and yield. Chromium too has harmful effects on the plant's physiological processes such as photosynthesis, water channeling, and mineral nutrition. Shukla et al. [76] inspected the effects of cadmium in wheat (*Triticum aestivum* L.) plant. Gupta and Gupta [77] reported in their publication that nutrient toxicities in crops due to manganese and boron are more compared with other nutrients. The foremost toxicity symptoms in crops include burning, chlorosis, and yellowing of leaves. The toxicity of metals is influenced by metal concentration, the composition of minerals, and organics in the soil, pH, redox potential, and the existence of other metals in the soil. Metal toxicity is also affected by the association to mineral constituents of the polluted sites. Since, there is a lack of basic understanding of metal behavior for a precise condition a precise protective method toward metal additions to soils is warranted [78].

In addition, the requirement to know the proper metal toxicity in food products and their nutritional intake in evaluating their risk to human well-being is more. However, the problem of metal toxicity persists due to contamination of the environment, which worsens intensively due to negative human activities. Hyperaccumulators grow on metalliferous soils; leaves possess toxic metal accumulation compared with other plant species. Studies aimed regarding these hyperaccumulators to understand their physiological role and molecular mechanisms, and thus, these plants can be used as a tool in removing metals from natural metal-rich soils (ores) and contaminated areas. Metal tolerant species *Hordeum vulgare*, *Brassica juncea*, *Triticum aestivum*, *Brassica napus*, and *Helianthus annuus* accumulates toxic metals in high concentrations in their shoot system.

8. Transgenic plants usage in phytoremediation

Transgenic plants with wide geographic distribution are used owing to their enhanced tolerance and phytoextraction potential. Transgenic plants are fast growing and seem to possess high biomass, much-elongated roots, and greener leaves than unmodified plants. Herbivores are repulsive to transgenic plants, thus making it greatly an encouraging candidate in phytoremediation efforts [79].

Transgenic plants, when grown in Cu-contaminated soil, and leaves contain two to three times more Cu compared to other plants [80]. *Arabidopsis thaliana* also possess greater Cu accumulation as reported by overexpression of a pea MTgene [81]. PsMTA from *Pisum sativum*, when overexpressed in *A. thaliana*, accumulated eight times more Cu in roots [82]. *Nicotiana glauca* (shrub tobacco) has a high tolerance toward Pb and Cd when grown in a metal-contaminated soil; the transgenic plants accumulated higher Pb concentrations in the shoot system (50% more) and in the root system (85% more).

An attempt was made toward transferring and expression of genes from bacteria, yeast, animals, or other plants and improvised for potentially high yield. One of the encouraging advances in transgenic technology is the use of multiple genes (cytochrome P450s, GSH, GT, etc.) for thorough degradation of xenobiotics within the plant system that was involved in metabolism, uptake, and transport of specific pollutants in transgenic plants [1, 83, 84]. A published review focused on the development of transgenic plants for remediation of 2,4,6-trinitrotoluene, hexahydro-1,3,5-trinitro-1,3,5-triazine, and glycerol trinitrate [85] by introducing and expressing bacterial nitro-reductases and cytochrome p450s.

As hyperaccumulators have a high metal tolerant trait, probable detoxification capacity is maximum thus efficiently used in phytoremediation. But there is an alternative to hyperaccumulators due to sluggish growth and condensed biomass production; hence, it requires numerous years for sanitization of contaminated sites. Thus, to facilitate faster decontamination, the remedial property can be extensively improvised by genetic manipulation, plant tissue culture, imbursement of transgenic approaches viz., genes, traits can be manipulated and thus the production of transgenic plants, mainly industrialized for remediating heavy metal contaminated soil sites. Examples include *Nicotiana tabacum* expressing a yeast metallothionein gene for higher cadmium tolerance or *Arabidopsis thaliana* overexpressing a mercuric ion reductase gene for higher mercury tolerance [86]. Dhankher et al. [87] stated about arsenic sequestration which happens largely in vacuoles by complexation with glutathione (-GSH) and phytochelatins (PCs).

In another example, the arsenic fall was seen in the transgenic plant developed by using bacterial genes ArsC from *E. coli* with co-expression of γ -glutamylcysteine synthetase to provide sufficient -GSH for subsequent conjugation [88]. By the expression of bacterial genes merA gene encoding organo-mercurial lyase, transgenic plants show better resistance against the toxic effects of mercury [89]. When merB was expressed in endoplasmic reticulum, resistance was further improved. Therefore, findings on chloroplast are the primary target for mercury poisoning and are leading the ongoing research in chloroplast genome engineering. Further, the expression of bacterial genes atrazine chlorohydrolase (atzZ) and 1-aminocyclopropane-1-carboxylate deaminase has shown a promising result in the remediation of atrazine and alachlor [90]. Transgenic plants expressing these genes show significantly increased tolerance, uptake, and detoxification of targeted explosives. Expression of cytochrome p450 as in CYP2E1 in tobacco and poplar plants have not only increased TCE metabolism but also is metabolizing vinyl chloride, benzene, toluene, and chloroform [84]. Also, trace element detoxification

systems have been implemented at the molecular level in yeast and bacteria. A vivid study and approaches by manipulation of molecular genetic techniques to regulate the discharge of metals as contaminants can be controlled through the use of the transgenic plant.

9. Metal homeostasis in plants

Metal homeostasis is defined as the metal uptake, trafficking, efflux, and sensing pathways, which allows organisms to maintain a narrow intracellular concentration range of essential transition metals. The molecular and genetic basis for these mechanisms will be vital in the development of plants that can be agents for phytoremediation of contaminated sites. One among the recurrent general mechanism requires metal homeostasis, chelation of the metal by a ligand, and subsequent compartmentalization of ligand-metal complex. Plants evolved a variety of mechanisms managing heavy metal stress, which include the synthesis of the sulfur-rich metal chelators, glutathione (GSH), phytochelatins (PCs), and metallothioneins (MTs) [91, 92]. Organic acids such as citrate and maleate which chelate extracellularly have significant tolerance to aluminum. Peptide ligands comprise metallothioneins (MTs) and small gene-encoded, Cys-rich polypeptides. GSH, abundantly the low-weight molecular SH-compound in plants, is synthesized through ATP-dependent enzymatic pathway. GSH protects plants from environmental and oxidative stresses, xenobiotics, and heavy metals. Glutathione acts as a precursor of phytochelatins (PCs) during excessive mental stress [93, 94]. The SH-peptide GSH (γ -Glu-Cys-Gly) and its variation homo-glutathione (h-GSH, γ -Glu-Cys- α -Ala) has a stimulus in the form and toxicity to heavy metals such as Cu, Cd, As, Hg, and Zn in different ways. Inventive measures of remediation technologies are of paramount importance; thus, plants can be an introduced as supplementary alternative renewable source and thus used in situ remediations.

9.1 Metallothioneins

Metallothioneins (MT) are cytoplasmic proteins [95], a family of small, vastly conserved, cysteine-rich metal-binding proteins (M.W. $\sim$ 7000), that are rich in sulfhydryl groups (thiols, make them bind to a number of trace metals) that are significant small proteins that bind toward Zn and Cu homeostasis, small amounts of Fe, Hg and perhaps other heavy metals [96], safeguard against oxidative stress, and buffering against toxic heavy metals. MTs were recognized firstly as Cd-binding proteins in mammalian tissues. Comparably, proteins are recognized in large numbers of animal species [97]. Cysteine-rich proteins are known for their high affinity toward cations Cd, Cu, Zn, etc. and also known for deliberating heavy-metal tolerance and accumulation in yeast and plants.

To mention,

- a. Enhanced Cd tolerance is a result of overexpression of MT genes in tobacco and oilseeds.
- b. A 16-fold greater Cd tolerance was observed by MT yeast gene (CUP 1) overexpression in cauliflower.
- c. The yeast metallothionein (CUP1) encourages Cu uptake in tobacco—seven times more in older leaves than fresh leaves, during Cu stress.

- d. Likewise, high accumulation of Cu was found in *Arabidopsis thaliana* by overexpression of a pea MT gene.

9.2 Phytochelatins

Phytochelatins (PC) are oligomers of glutathione [98] produced by the enzyme phytochelatin synthase from GSH, seen in plants, fungi, nematodes, and all the algal groups including cyanobacteria. Phytochelatins are central for heavy metal detoxification and act as chelators [99], Cysteine-rich metal-chelating (post-translationally synthesized) peptides which suggestively show heavy-metal tolerance in plants and fungi by chelation and thus decrease their unrestricted availability. It is projected that PCs are the functionally alike MTs [100].

PCs are not reported in animal species, which supports that MTs performs normal functions well in animals, as a contribution by PCs in plants. Heavy-metal toxicity in plants is seen in diverse ways; these include chelation, exclusion, compartmentalization of the metal ions, immobilization, and the expression of more stress response mechanisms in general such as ethylene and other stress proteins [11].

To mention,

- a. In the *Agrobacterium*-mediated transformation, the induction and overexpression of phytochelatin synthase (PCS1) in *Nicotiana glauca* bring about high concentrations of Pb and Cd.
- b. Accumulation of high Pb concentrations in aerial parts and roots were also observed in transgenic plants.
- c. Longer roots, greener higher leaves than unmodified plants were seen in transgenic seedlings.
- d. Overexpression of an Arabidopsis PC synthase (AtPCS1) in transgenic which increases PC synthesis thus accumulating and tolerating metals.

As PCs are found in tissues of the plants and cell cultures upon open to trace levels of crucial metals and the level of PCs were seen in cell cultures is correlated with the medium by reduction of metal ions. These remarks are inferred to designate the role of PCs in the crucial metal ion metabolism homeostasis [94, 101].

10. Conclusion

Among several regions of the world, cultivation of plants is significant in the maintenance of the ecosystem. Environmental contamination occurs due to geogenic and anthropogenic activities as discussed in the review paper. Although a few metals are true bio elements at normal concentration, they can cause a potentially hazardous impact on excessive usage causing environmental contamination. There are a variety of measured steps taken through the different aspects of phytoremediation to curb the menace of contaminants and pollution, but there is always a step of further progress which can be implemented in this scenario.

Plants are naturally found to synthesize nanoparticles. Nanophytoremediation is an innovative and encouraging technology which has gathered a wider reception due to its current area of research in plants. As in the review paper, there are several plant families which act in the biosynthesis of nanoparticles. It is significant to

study on metal nanoparticles formation, types of nanoparticles, and derivatives of these nanoparticles, and their action on the physiological process will further eliminate the bioaccumulation of toxic nanoparticles in the plants. Numerous countries globally use plants as a primary source of energy for food; fodder; thus, toxicity and contamination of metals in crops and medical plants may have a huge impact. In our review paper, we have made a significant effort to understand the phytoremediation processes, in general, the nanoparticles occurrence, the need to biomonitor the trace elements in the environment, the physiological effects of the bioelements, transgenic plants which can be used effectively in nanophytoremediation. Thus, in conclusion, nanophytoremediation can be a complementary biological clean-up technique, thus maintaining the sustainability of the environment.

Conflicts of interest

The authors declare no conflict of interest.

Author Contributions

Silpi Sarkar, Manoj Kumar Enamala, and Murthy Chavali wrote the chapter; Mannam Krishnamurthy contributed to the scope of the manuscript; Enamala Manoj Kumar planned the review of the literature and reorganized the chapter; verification was done by Subbaroy Sarma and Murthy Chavali critically reviewed the manuscript. All the authors contributed to this book chapter.

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References

- [1] Van Aken B. Transgenic plants for phytoremediation: Helping nature to clean up the environmental pollution. *Trends in Biotechnology*. 2008;**26**(5):225-227. DOI: 10.1016/j.tibtech.2008.02.001
- [2] Warriar RR. Phytoremediation for environmental clean-up. *Forestry Bulletin*. 2012;**12**(2):1-7. Available from: <https://pdfs.semanticscholar.org/a855/2eb54d818442b99072f5c39676278d9feff.pdf>
- [3] Sinha R, Valani D, Sinha SS, Herat S. Bioremediation of contaminated sites: A low-cost Nature's biotechnology for environmental clean-up by versatile microbes, plants and earthworms. In: Faerber T, Herzog J, editors. *Solid Waste Management and Environmental Remediation*. NY, USA: Nova Science Publisher; 2010. pp. 1-73
- [4] Masarovicova E, Králova K. Plant-heavy metal interaction: Phytoremediation, biofortification and nanoparticles. In: Monatanaro G, Dichio B, editors. *Advances in Selected Plant Physiology Aspects*. Croatia: InTech; 2012. pp. 75-102
- [5] Gajewska E, Skłodowska M, Słaba M, Mazur J. Effect of nickel on antioxidative enzyme activities, proline and chlorophyll contents in wheat shoots. *Biologia Plantarum*. 2006;**50**(4):653-659. DOI: 10.1007/s10535-006-0102-5
- [6] Lytle CM, Lytle PW, Yang N, Qian JH, Hansen D, Zayed A, et al. Reduction of Cr(VI) to Cr(III) by wetland plants: Potential for in situ heavy metal detoxification. *Environmental Science & Technology*. 1998;**32**(20):3087-3093. DOI: 10.1021/es980089x
- [7] Weis JS, Weis P. Metal uptake, transport and release by wetland plants: Implications for phytoremediation and restoration. *Environment International*. 2004;**30**(5):685-700. DOI: 10.1016/j.envint.2003.11.002
- [8] Nzengung VA, McCutcheon SC. Phytoremediation of perchlorate. In: McCutcheon SC, Schnoor JL, editors. *Phytoremediation: Transformation and Control of Contaminants*. New Jersey: John Wiley and Sons, Inc.; 2003. pp. 863-885
- [9] Susarla S, Medina VF, McCutcheon SC. Phytoremediation: An ecological solution to organic chemical contamination. *Ecological Engineering*. 2002;**18**(2):647-658. DOI: 10.1016/S0925-8574(02)00026-5
- [10] Krämer U. Metal hyperaccumulation in plants. *Annual Review of Plant Biology*. 2010;**6**(1):517-534. DOI: 10.1146/annurev-arplant-042809-112156
- [11] Sanità Di Toppi L, Gabbriellini R. Response to cadmium in higher plants. *Environmental and Experimental Botany*. 1999;**42**(2):105-130. DOI: 10.1016/S0098-8472(98)00058-6
- [12] Gupta A, Joia J, Sood A, Sood R, Sidhu C, Kaur G. Microbes as potential tool for remediation of heavy metals: A review. *Journal of Microbial and Biochemical Technology*. 2016;**8**:364-372
- [13] Mandal A, Purakayastha T, Ramana S, Neenu S, Bhaduri D, Chakraborty K, et al. Status on phytoremediation of heavy metals in India- a review. *International Journal of Stress Management*. 2014;**5**(4):553-560. DOI: 10.5958/0976-4038.2014.00609.5
- [14] Mahimairaja S, Bolan NS, Adriano DC, Robinson B. Arsenic contamination and its risk management in complex environmental settings.

- Advances in Agronomy. 2005;**86**:1-82. DOI: 10.1016/S0065-2113(05)86001-8
- [15] McGrath SP, Zhao FJ, Lombi E. Plant and rhizosphere processes involved in phytoremediation of metal-contaminated soils. Plant and Soil. 2001;**232**(1):207-214
- [16] Dotaniya ML, Thakur JK, Meena VD, Jajoria DK, Rathor G. Chromium pollution: A threat to environment-a review. Agricultural Reviews. 2014;**35**(2):153-157. DOI: 10.5958/0976-0741.2014.00094.4
- [17] Wu J, Overton C. Asian ecology: Pressing problems and research challenges. Bulletin of Ecological Society of America. 2002;**83**(3):189-194
- [18] Yadav KK, Singh JK, Gupta N, Kumar V. A review of nanobioremediation technologies for environmental clean-up: A novel biological approach. Journal of Materials and Environmental Science. 2017;**8**(2):740-757
- [19] Handy RD, Owen R, Valsami-Jones E. The ecotoxicology of nanoparticles and nanomaterials: Current status, knowledge gaps, challenges, and future needs. Ecotoxicology. 2008;**17**(5):315-325. DOI: 10.1007/s10646-008-0206-0
- [20] Stampoulis D, Sinha SK, White JC. Assay-dependent phytotoxicity of nanoparticles to plants. Environmental Science & Technology. 2009;**43**(24):9473-9479
- [21] Shekhawat GS, Arya V. Biological synthesis of Ag nanoparticles through in vitro cultures of *Brassica juncea* C. zern. Advances in Materials Research. 2009;**67**:295-299. DOI: 10.4028/www.scientific.net/AMR.67.295
- [22] Ankamwar B. Biosynthesis of gold nanoparticles (green-gold) using leaf extract of *Terminalia catappa*. E-Journal of Chemistry. 2010;**7**(4):1334-1339. DOI: 10.1155/2010/745120
- [23] Beattie IR, Haverkamp RG. Silver and gold nanoparticles in plants: Sites for the reduction of the metal. Metallomics. 2011;**3**(6):628-632. DOI: 10.1039/c1mt00044f
- [24] Watlington K. Emerging nanotechnologies for site remediation and wastewater treatment. Report prepared for National Network of Environmental Management (NNEM) studies the grantee under a fellowship from the U.S. Environmental Protection Agency (US-EPA). 2005
- [25] Saif S, Tahir A, Chen Y. Green synthesis of iron nanoparticles and their environmental applications and implications. Nanomaterials. 2016;**6**(11):1-26. DOI: 10.3390/nano6110209
- [26] Ponder SM, Darab JG, Mallouk TE. Remediation of Cr (VI) and Pb (II) aqueous solutions using supported, nanoscale zero-valent iron remediation of Cr (VI) and Pb (II) aqueous solutions using supported, nanoscale zero-valent iron. Environmental Science & Technology. 2000;**34**(12):2564-2569. DOI: 10.1021/es9911420
- [27] Schrick B, Hydutsky BW, Blough JL, Mallouk TE. Delivery vehicles for zerovalent metal nanoparticles in soil and groundwater. Chemistry of Materials. 2004;**16**(11):2187-2193. DOI: 10.1021/cm0218108
- [28] Schrick B, Blough JL, Jones AD, Mallouk TE. Hydrodechlorination of trichloroethylene to hydrocarbons using bimetallic nickel-iron nanoparticles. Chemistry of Materials. 2002;**14**(12):5140-5147
- [29] Li C, Zhou L, Yang H, Lv R, Tian P, Li X, et al. Self-assembled exopolysaccharide nanoparticles for bioremediation and green synthesis

of noble metal nanoparticles. *ACS Applied Materials & Interfaces*. 2017;**9**(27):22808-22818. DOI: 10.1021/acsami.7b02908

[30] Tan J, Liu R, Wang W, Liu W, Tian Y, Wu M, et al. Controllable aggregation and reversible pH sensitivity of AuNPs regulated by carboxymethyl cellulose. *Langmuir*. 2010;**26**(3):2093-2098. DOI: 10.1021/la902593e

[31] Yin Y, Hu Y, Xiong F. Sorption of Cu (II) and Cd(II) by extracellular polymeric substances (EPS) from *Aspergillus fumigatus*. *International Biodeterioration and Biodegradation*. 2011;**65**(7):1012-1018. DOI: 10.1016/j.ibiod.2011.08.001

[32] Feng M, Chen X, Li C, Nurgul R, Dong M. Isolation and identification of an exopolysaccharide-producing lactic acid bacterium strain from Chinese Paocai and biosorption of Pb(II) by its exopolysaccharide. *Journal of Food Science*. 2012;**77**(6):T111-T117. DOI: 10.1111/j.1750-3841.2012.02734.x

[33] Salehizadeh H, Shojaosadati SA. Removal of metal ions from aqueous solution by polysaccharide produced from *Bacillus firmus*. *Water Research*. 2003;**37**(17):4231-4235. DOI: 10.1016/S0043-1354(03)00418-4

[34] Baig T, Nayak J, Dwivedi V, Singh A, Tripathi PK. A review about dendrimers: Synthesis, types, characterization and applications. *International Journal of Advances in Pharmacy, Biology and Chemistry*. 2015;**4**(1):44-59

[35] Mauter MSC, Elimlech M. Environmental applications of carbon-based Nanomaterials. *Environmental Science & Technology*. 2008;**42**(16):5843-5859. DOI: 10.1021/es8006904

[36] Kandah MI, Meunier J-L. Removal of nickel ions from water

by multi-walled carbon nanotubes. *Journal of Hazardous Materials*. 2007;**146**(1-2):283-288

[37] Li Y, Liu F, Xia B, Du Q, Zhang P, Wang D, et al. Removal of copper from aqueous solution by carbon nanotube/calcium alginate composites. *Journal of Hazardous Materials*. 2010;**177**(1-3):876-880. DOI: 10.1016/j.jhazmat.2009.12.114

[38] Gong J-L, Wang B, Zeng G-M, et al. Removal of cationic dyes from aqueous solution using magnetic multi-wall carbon nanotube nanocomposite as adsorbent. *Journal of Hazardous Materials*. 2009;**164**(2-3):1517-1522

[39] Mackay DM, Cherry JA. Groundwater contamination: Pump-and-treat remediation. *Environmental Science & Technology*. 1989;**23**(6):630-636. DOI: 10.1021/es00064a001

[40] Tungittiplakorn W. Engineered polymeric nanoparticles for bioremediation of hydrophobic contaminants. *Environmental Science & Technology*. 2005;**39**(5):1354-1358

[41] Liao C, Xu W, Lu G, Liang X, Guo C, Yang C, et al. Accumulation of hydrocarbons by maize (*Zea mays* L.) in remediation of soils contaminated with crude oil. *International Journal of Phytoremediation*. 2015;**17**(7):693-700. DOI: 10.1080/15226514.2014.964840

[42] Mojiri A. The potential of corn (*Zea mays*) for phytoremediation of soil contaminated with cadmium and Lead. *Journal of Biological and Environmental Sciences*. 2011;**5**(13):17-22

[43] Bargar JR, Bernier-Latmani R, Giammar DE, Tebo BM. Biogenic uraninite nanoparticles and their importance for uranium remediation. *Elements*. 2008;**4**(6):407-412. DOI: 10.2113/gselements.4.6.407

[44] Cherian S, Oliveira MM. Transgenic plants in phytoremediation: Recent

- advances and new possibilities. *Environmental Science & Technology*. 2005;**39**(24):9377-9390. DOI: 10.1021/es051134l
- [45] Čechmánková J, Vácha R, Skála J, Havelková M. Heavy metals phytoextraction from heavily and moderately contaminated soil by field crops grown in monoculture and crop rotation. *Soil and Water Research*. 2011;**6**(3):120-130
- [46] Baldantoni D, Maisto G, Bartoli G, Alfani A. Analyses of three native aquatic plant species to assess spatial gradients of lake trace element contamination. *Aquatic Botany*. 2005;**83**(1):48-60. DOI: 10.1016/j.aquabot.2005.05.006
- [47] Rizwan M, Singh M, Mitra CK, Morve RK. Ecofriendly application of nanomaterials: Nanobioremediation. *Journal of Nanoparticle Research*. 2014;**2014**:431787 8, 1-7. DOI: 10.1155/2014/431787
- [48] Bharti S, Banerjee TK. Phytoremediation of the coal mine effluent. *Ecotoxicology and Environmental Safety*. 2012;**81**:36-42. DOI: 10.1016/j.ecoenv.2012.04.009
- [49] Chen JC, Wang KS, Chen H, Lu CY, Huang LC, Li HC, et al. Phytoremediation of Cr(III) by *Ipomoea aquatica* (water spinach) from water in the presence of EDTA and chloride: Effects of Cr speciation. *Bioresource Technology*. 2010;**101**(9):3033-3039. DOI: 10.1016/j.biortech.2009.12.041
- [50] Marín CMD, Oron G. Boron removal by the duckweed *Lemna gibba*: A potential method for the remediation of boron-polluted waters. *Water Research*. 2007;**41**(20):4579-4584. DOI: 10.1016/j.watres.2007.06.051
- [51] El-Khaiary MI. Kinetics and mechanism of adsorption of methylene blue from aqueous solution by nitric-acid treated water-hyacinth. *Journal of Hazardous Materials*. 2007;**147**(1-2):28-36. DOI: 10.1016/j.jhazmat.2006.12.058
- [52] Hasan SH, Talat M, Rai S. Sorption of cadmium and zinc from aqueous solutions by water hyacinth (*Eichhornia crassipes*). *Bioresource Technology*. 2007;**98**(4):918-928. DOI: 10.1016/j.biortech.2006.02.042
- [53] Khataee AR, Movafeghi A, Torbati S, Salehi Lisar SY, Zarei M. Phytoremediation potential of duckweed (*Lemna minor* L.) in the degradation of C.I. acid blue 92: Artificial neural network modelling. *Ecotoxicology and Environmental Safety*. 2012;**80**(1):291-298. DOI: 10.1016/j.ecoenv.2012.03.021
- [54] Pandey VC. Phytoremediation of heavy metals from fly ash pond by *Azolla caroliniana*. *Ecotoxicology and Environmental Safety*. 2012;**82**:8-12. DOI: 10.1016/j.ecoenv.2012.05.002
- [55] Srivastava S, Bhainsa KC, D'Souza SF. Bioresource technology investigation of uranium accumulation potential and biochemical responses of an aquatic weed *Hydrilla verticillata* (L.f.) Royle. *Bioresource Technology*. 2010;**101**(8):2573-2579. DOI: 10.1016/j.biortech.2009.10.054
- [56] Islam MS, Saito T, Kurasaki M. Phytofiltration of arsenic and cadmium by using an aquatic plant, *Micranthemum umbrosum*: Phytotoxicity, uptake kinetics, and mechanism. *Ecotoxicology and Environmental Safety*. 2015;**112**:193-200. DOI: 10.1016/j.ecoenv.2014.11.006
- [57] González I, Neaman A, Cortés A, Rubio P. Effect of compost and biodegradable chelate addition on phytoextraction of copper by *Oenothera picensis* grown in Cu-contaminated acid soils. *Chemosphere*. 2014;**95**:111-115. DOI: 10.1016/j.chemosphere.2013.08.046

- [58] Sooksawat N, Meetam M, Kruatrachue M, Pokethitiyook P, Nathalang K. Phytoremediation potential of charophytes: Bioaccumulation and toxicity studies of cadmium, lead and zinc. *Journal of Environmental Sciences*. 2013;**25**(3):596-604. DOI: 10.1016/S1001-0742(12)60036-9
- [59] Siva Kiran RR, Madhu GM, Satyanarayana SV, Bindiya P. Bioaccumulation of cadmium in blue-green algae *Spirulina* (*Arthrospira*) *Indica*. *Journal of Bioremediation & Biodegradation*. 2012;**3**(3):1-4. DOI: 10.4172/2155-6199.1000141
- [60] Favas PJC, Pratas J, Prasad MNV. Accumulation of arsenic by aquatic plants in large-scale field conditions: Opportunities for phytoremediation and bioindication. *Science of the Total Environment*. 2012;**433**:390-397. DOI: 10.1016/j.scitotenv.2012.06.091
- [61] Tuzen M, Sari A, Mendil D, Uluozlu OD, Soylak M, Dogan M. Characterization of the biosorption process of As(III) on green algae *Ulothrix cylindricum*. *Journal of Hazardous Materials*. 2009;**165**(1-3):566-572. DOI: 10.1016/j.jhazmat.2008.10.020
- [62] Hua J, Zhang C, Yin Y, Chen R, Wang X. Phytoremediation potential of three aquatic macrophytes in manganese-contaminated water. *Water and Environment Journal*. 2012;**26**(3):335-342. DOI: 10.1111/j.1747-6593.2011.00293.x
- [63] Maine MA, Duarte MV, Suñé NL. Cadmium uptake by floating macrophytes. *Water Research*. 2001;**35**(11):2629-2634. DOI: 10.1016/S0043-1354(00)00557-1
- [64] Mishra VK, Upadhyay AR, Pandey SK, Tripathi BD. Concentrations of heavy metals and aquatic macrophytes of Govind Ballabh Pant Sagar an anthropogenic lake affected by coal mining effluent. *Environmental Monitoring and Assessment*. 2008;**141**(1-3):49-58. DOI: 10.1007/s10661-007-9877-x
- [65] Ha NTH, Sakakibara M, Sano S. Accumulation of indium and other heavy metals by *Eleocharis acicularis* an option for phytoremediation and phytomining. *Bioresource Technology*. 2011;**102**(3):2228-2234. DOI: 10.1016/j.biortech.2010.10.014
- [66] Sakakibara M. Phytoremediation of toxic elements-polluted water and soils by aquatic macrophyte *Eleocharis acicularis*. *AIP Conference Proceedings*. 2016;**1744**:1-6. DOI: 10.1063/1.4953512
- [67] Sarma H. Metal hyperaccumulation in plants: A review focusing on phytoremediation technology. *Journal of Environmental Science and Technology*. 2011;**4**(2):118-138. DOI: 10.3923/jest.2011.118.138
- [68] Ladislav S, El-Mufleh A, Gérente C, Chazarenc F, Andrès Y, Béchet B. Potential of aquatic macrophytes as bioindicators of heavy metal pollution in urban stormwater runoff. *Water, Air, and Soil Pollution*. 2012;**223**(2):877-888. DOI: 10.1007/s11270-011-0909-3
- [69] Landberg T, Greger M. Differences in uptake and tolerance to heavy metals in *Salix* from unpolluted and polluted areas. *Applied Geochemistry*. 1996;**11**(1):175-180. DOI: 10.1016/0883-2927(95)00082-8
- [70] Ariyakanon N, Winaipanich B. Phytoremediation of copper contaminated soil by *Brassica juncea* (L.) Czern and *Bidens alba* (L.) DC. var. *radiata*. *Journal of Scientific Research, Chulalongkorn University*. 2006;**31**(1):49-56
- [71] Das S, Goswami S, Talukdar AD. A study on cadmium phytoremediation potential of water lettuce, *Pistia*

- stratiotes* L. Bulletin of Environmental Contamination and Toxicology. 2014;**92**(2):169-174. DOI: 10.1007/s00128-013-1152-y
- [72] Amin H, Arain BA, Amin F, Surhio MA. Analysis of growth response and tolerance index of *Glycine max* (L.) Merr. under hexavalent chromium stress. Advances in Life Sciences. 2014;**1**(4):231-241
- [73] Imtiyaz S, Agnihotri RK, Ganie SA, Sharma R. Biochemical response of glycine max(L.) Merr to cobalt and lead stress. Journal of Stress Physiology and Biochemistry. 2014;**10**(3):259-272
- [74] Kranner I, Colville L. Metals and seeds: Biochemical and molecular implications and their significance for seed germination. Environmental and Experimental Botany. 2011;**72**(1):93-105. DOI: 10.1016/j.envexpbot.2010.05.005
- [75] Shanker AK, Cervantes C, Loza-Tavera H, Avudainayagam S. Chromium toxicity in plants. Environment International. 2005;**31**(5):739-753. DOI: 10.1016/j.envint.2005.02.003
- [76] Shukla UC, Singh J, Joshi PC, Kakkar P. Effect of bioaccumulation of cadmium on biomass productivity, essential trace elements, chlorophyll biosynthesis, and macromolecules of wheat seedlings. Biological Trace Element Research. 2003;**92**(3):257-273. DOI: 10.1385/BTER:92:3:257
- [77] Gupta UC, Gupta SC. Trace element toxicity relationships to crop production and livestock and human health: Implications for management. Communications in Soil Science and Plant Analysis. 1998;**29**(11-14):1491-1522. DOI: 10.1080/00103629809370045
- [78] McBride MB, Sauve S, Hendershot WH. Solubility control of Cu, Zn, Cd and Pb in contaminated soils. European Journal of Soil Science. 1997;**48**(2):337-346
- [79] Gisbert C, Ros R, Haro AD, Walker DJ, Bernal MP, Serrano R, et al. A plant genetically modified that accumulates Pb is especially promising for phytoremediation. Biochemical and Biophysical Research Communications. 2003;**303**:440-445
- [80] Thomas JC, Davies EC, Malick FK, Endreszl C, Williams CR, Abbas M, et al. Yeast metallothionein in transgenic tobacco promotes copper uptake from contaminated soils. Biotechnology Progress. 2003;**19**(2):273-280
- [81] Pan A, Yang M, Tie F, Li L, Chen Z, Ru B. Expression of mouse metallothionein-I gene confers cadmium resistance in transgenic tobacco plants. Plant Molecular Biology. 1994;**24**:341-351
- [82] Evans KM, Gatehouse JA, Lindsay WP, Shi J, Tommey AM, Robinson NJ. Expression of pea metallothionein-like gene PsMTA function. Plant Molecular Biology. 1992;**20**:1019-1028
- [83] Abhilash PC, Jamil S, Singh N. Transgenic plants for enhanced biodegradation and phytoremediation of organic xenobiotics. Biotechnology Advances. 2009;**27**(4):474-488. DOI: 10.1016/j.biotechadv.2009.04.002
- [84] Doty SL. Enhancing phytoremediation through the use of transgenics and endophytes. The New Phytologist. 2008;**179**(2):318-333. DOI: 10.1111/j.1469-8137.2008.02446.x
- [85] Van Aken B. Transgenic plants for enhanced phytoremediation of toxic explosives. Current Opinion in Biotechnology. 2009;**20**(2):231-236. DOI: 10.1016/j.copbio.2009.01.011
- [86] Rugh CL, Senecoff JF, Meagher RB, Merkle SA. Development

of transgenic yellow poplar for mercury phytoremediation. *Nature Biotechnology*. 1998;**16**(10):925-928. DOI: 10.1038/nbt1098-925

[87] Dhankher OP, Li Y, Rosen BP, Shi J, Salt D, Senecoff JF, et al. Engineering tolerance and hyperaccumulation of arsenic in plants by combining arsenate reductase and γ -glutamylcysteine synthetase expression. *Nature Biotechnology*. 2002;**20**(11):1140-1145. DOI: 10.1038/nbt747

[88] Assunção AGL, Da Costa Martins P, De Folter S, Vooijs R, Schat H, Aarts MGM. Elevated expression of metal transporter genes in three accessions of the metal hyperaccumulator *Thlaspi caerulescens*. *Plant, Cell and Environment*. 2001;**24**:217-226. DOI: 10.1046/j.1365-3040.2001.00666.x

[89] Bizily SP, Rugh CL, Meagher RB. Phytodetoxification of hazardous organomercurials by genetically engineered plants. *Nature Biotechnology*. 2000;**18**:213-217. DOI: 10.1038/72678

[90] Wang X, Wu N, Guo J, Chu X, Tian J, Yao B, et al. Phytodegradation of organophosphorus compounds by transgenic plants expressing a bacterial organophosphorus hydrolase. *Biochemical and Biophysical Research Communications*. 2008;**365**(3):453-458. DOI: 10.1016/j.bbrc.2007.10.193

[91] Gasic K, Korban SS. Transgenic Indian mustard (*Brassica juncea*) plants expressing an *Arabidopsis* phytochelatin synthase (AtPCS1) exhibit enhanced As and Cd tolerance. *Plant Molecular Biology*. 2007;**64**(4):361-369. DOI: 10.1007/s11103-007-9158-7

[92] Hall JL. Cellular mechanisms for heavy metal detoxification and tolerance. *Journal of Experimental Botany*. 2002;**53**(366):1-11. DOI: 10.1093/jxb/53.366.1

[93] Cobbett C, Goldsbrough P. Phytochelatins and metallothioneins: Roles in heavy metal detoxification and homeostasis. *Annual Review of Plant Biology*. 2002;**53**(1):159-182. DOI: 10.1146/annurev.arplant.53.100301.135154

[94] Rauser WE. Phytochelatins and related peptides (structure, biosynthesis and function). *Plant Physiology*. 1995;**109**(4):1141-1149. DOI: 10.1104/pp.109.4.1141

[95] Sigel H, Sigel A, editors. *Metallothioneins and Related Chelators (Metal Ions in Life Sciences)*. Vol. 5. Cambridge, England: Royal Society of Chemistry; 2009. ISBN: 1-84755-899-2

[96] Margoshes M, Vallee BL. A cadmium protein from equine kidney cortex. *Journal of the American Chemical Society*. 1957;**79**(17):4813-4814. DOI: 10.1021/ja01574a064

[97] Kagi JHR, Schaffer A. Biochemistry of metallothionein. *The Biochemist*. 1998;**27**(23):8509-8515

[98] Ha S-B, Smith AP, Howden R, Dietrich WM, Bugg S, O'Connell MJ, et al. Phytochelatin synthase genes from *Arabidopsis* and the yeast *Schizosaccharomyces pombe*. *The Plant Cell*. 1999;**11**(6):1153-1164. DOI: 10.1105/tpc.11.6.1153. PMC 144235. PMID: 10368185. Retrieved: January 13, 2014

[99] Olena KV, Elizabeth AB, James TW, Philip AR. A new pathway for heavy metal detoxification in animals: Phytochelatin synthase is required for cadmium tolerance in *Caenorhabditis elegans*. *The Journal of Biological Chemistry*. 2001;**276**(24):20817-20820. DOI: 10.1074/jbc.C100152200. PMID 11313333

[100] Grill E, Winnacker E-L, Zenk MH. Phytochelatins, a class of heavy-metal-binding peptides from

plants, are functionally analogous to metallothioneins. Proceedings of the National Academy of Sciences. 1987;**84**(2):439-443. DOI: 10.1073/pnas.84.2.439

[101] Zenk M. Heavy metal detoxification in higher plants—A review. Gene. 1996;**179**(1):21-30. DOI: 10.1016/S0378-1119(96)00422-2