**Phytoremediation-Review onBiotechnological Approach forRemediation of**

**Emerging Pollutants**

Lalfelpuii Ruth

Department of Biotechnology

PachhungaUniversity College

Aizawl, India

Email: ruthpuii\_kix@yahoo.co.in

**ABSTRACT**

Exponential growth in human population, urbanization, and industrialization have led to a rise in environmental pollutants globally. These pollutants emerge as a result ofthe increase in human population as well as advancement inthe use and application of agricultural chemical pesticides, medicinal drugs, personal care products (PPCPs), plastic polymers, and heavy metals. Although,the intent of this compound is to improve agricultural yields to ensure food and material supply to satiate the ever-growing need for a growing human population and also human health and better life in general. However, advancement in large-scale production of these compounds results in the generation and release of waste products to terrestrial and aquatic environments as a consequence of which this leads to devastating effects for the entire ecosystems.For addressing the environmental issue environmental-friendly and sustainable means of remediating contaminants is indispensable. To resolve this,biological strategy i.e. bioremediation (plants and microbes) can be utilized for removing this toxic material from the environment.However, extensive release of thesepollutants which may be due to natural processes and human economic activityhas a severe and challenging impact on the environment nowadays where leakage or accidental discharge of these hazardous contaminants are serious problems. The biodegradation capacity of the natural microbiome is insufficient in combating them. In this review, we will be focusing onthe potential of plants and biotechnological exploitation for the improvement ofplant’s ability to tolerate different pollutants and phytoremediation efficiency and highlight future challenges.

**Keywords**—phytoremediation,hyperaccumulator plants, transgenic plants, xenobiotics. oxidative stress

**I. INTRODUCTION**

The term "Phyto-" denotes plants, and "-remediation" signifies the reversal of damage. Therefore, phytoremediation refers to the use of plants for the remediation or cleanup of environmental pollutants. This approach involves the cultivation of plants in contaminated areas to either absorb or break down pollutants (1). It is often hailed as the "Green Revolution" in the realm of innovative cleanup technologies. Although the concept of using metal-accumulating plants to eliminate heavy metals and other compounds was first introduced in 1983, it has actually been practiced for the past 300 years in the treatment of wastewater discharges (69).

Phytoremediation employs various mechanisms to remediate pollutants from the environment. Phytoremediation techniques can be categorized as follows:

(i) Phytostabilization: This involves the use of plants to decrease the mobility of metals in the soil through processes like absorption and precipitation, thus reducing their bioavailability.

(ii) Phytoextraction: This process entails plants extracting metals from the soil and concentrating them within their roots and shoots.

(iii) Phytovolatilization: Contaminants are taken up by plants and subsequently released into the atmosphere through transpiration.

(iv) Phytodegradation: This refers to the degradation of organic pollutants into less toxic forms, either in the soil or within the plant's tissues (2-7).

Phytoremediation, a natural biological process for degrading xenobiotic and recalcitrant compounds that accumulate in the environment is an emerging, eco-friendly green engineering Phyto-technology where hyper-accumulator plants with their natural ability to remediate these pollutants are selected or are genetically engineered to improve their ability to tolerate as well as improve their ability to directly uptake pollutants from surface water, groundwater, soil, and sediments. Phytoremediation has received increased attention for sequestering and mineralizing organic and inorganic compounds present in contaminated soilwhich is of worldwide concern, and is applicable for a wide range of contaminants viz; heavy metals, radionuclides, organic compounds like chlorinated solvents, polycyclic aromatic hydrocarbons, pesticides/insecticides, explosive and surfactants,thus, prove to be an effective, economical and socially accepted technology (8-10).Conventional remediation technologies that use physiochemical and chemical methodsmethods are costly and difficult to implement, slow in the process, and emphasize separation rather than eliminating the hazardous substance from contaminated sites as a result of which causesa buildup of secondary pollutants damaging soil fertility that negatively impacts the agricultural environment(11,12). Because of their metabolic capacities, plants and microbes can both live in contaminated environments and break down contaminants [13, 14].However, the natural processes of microbes and plants are unable to remove contamination caused by heavy metals like mercury. Heavy metals have carcinogenic effects and can cause DNA damage in humans and animals due to their mutagenic ability (15-17). Recalcitrant heavy metals area potential threat as they are nondegradable and stay in the soil for centuries and cleanup of heavy metal contaminated sites is obligatory to abate entry of toxic elements into the food chain. Development of genetically engineered plants by transfer or overexpression of detoxifying genes or metal chelator genes into a candidate plant can improve the phytoremediationtraits of hyperaccumulator plants (18-20), hence, could solve these problems.

**II. TRANSGENIC APPROACH FOR BIOREMEDIATION- USE OF TRANSGENIC PLANTS**

Genetically engineered organisms offer environmentally friendly and cost-effective alternatives for managing and eliminating pollutants in contaminated sites. Within plant cells, there exist cellular and molecular mechanisms with the potential for detoxifying pollutants by either removing or converting them into biologically inactive forms. The concept of using hyper-accumulator plants for removing heavy metals and other compounds was introduced in 1983 (22). Plants possess the ability to uptake pollutants from the soil through their roots and transport them to the above-ground parts (23). Some plants release compounds into their root zones, which can chelate metals, aiding in their solubilization and uptake (24), a process regulated by numerous genes.It is essential to introduce these genes responsible for pollutant mitigation into hyperaccumulator plants. For incorporating hyperaccumulation traits into fast-growing, high-biomass plants, traditional breeding techniques such as plant hybridization are utilized (64). Somatic hybridization allows for the transfer of the metal hyperaccumulation trait to high biomass plants. Notably, somatic hybrids derived from T. caerulescens and B. napus, combining enhanced hyperaccumulation capabilities with increased biomass production (65), have demonstrated the capacity to accumulate substantial levels of Zn and Cd.Compared to traditional breeding, genetic engineering offers advantages in modifying plants with desirable traits for phytoremediation. Moreover, it enables the transfer of desirable genes from hyperaccumulator species to sexually incompatible plant species (66,67), showing promise in the field of phytoremediation. By employing Agrobacterium tumefaciens-mediated plant transformation, these genes can be introduced and expressed in recipient plants (25)Genes responsible for various metal-related processes, including uptake, removal, translocation, and bioaccumulation, have been successfully identified (26-28). Through the transfer or overexpression of these genes in candidate plants, transgenic plants with enhanced abilities to degrade xenobiotics and accumulate metals have been developed (29). Remarkably, transgenic plants have demonstrated the capability to degrade chlorinated solvents, explosives, and phenolic substances (30-32). For instance, transgenic cauliflower that incorporates the Yeast CUP1 gene accumulates cadmium levels 16-fold higher than unmodified cauliflower (33, 34).

In addition to cadmium tolerance, two novel rice genes, HPP (heavy metal-associated plant protein) and HIPP (heavy metal-associated isoprenylated plant protein), have been identified, conferring tolerance to copper, zinc, cadmium, and manganese (33). The co-expression of vacuolar proton pump (V-PPase) with a Na/proton antiporter (NHX1 transporter) enhances copper tolerance and accumulation in transgenic tobacco (34). The expression of Cytochrome P450 genes in transgenic plants has the potential to remove pollutants from soil and water (35). Moreover, various genes, including the bacterial biphenylchlorophenyldioxygenase gene (bphC), CYP71A10, Mn peroxidase gene, pentaerythritoltetranitratereductase (onr) gene in tobacco, basic peroxidase (tpxl) gene in tomato plants, and Cytochrome P450 monoxygenase (XplA and XplB) gene in Arabidopsis thaliana, have been generated as potential tools for phytoremediation of hazardous contaminants (36-41).

Furthermore, the introduction of the bacterial merA gene into the roots of A. thaliana has enabled the absorption of toxic mercury ions and their conversion into less hazardous volatile mercury (42). Transgenic B. juncea, overexpressing c-glutamylcysteinesynthetase, has exhibited greater tolerance and accumulation of cadmium, chromium, copper, lead, and zinc compared to wild-type plants (43).

Transgenic Arabidopsis plants were able to transport oxyanion arsenate to above ground levels, where it was subsequently reduced to arsenite and sequestered into thiol peptide complexes. This was achieved through the introduction of E. coli ArsC and γ-ECS genes (21). Heavy metal tolerance in plants is closely linked to the strength of their oxidative stress defense systems. Heavy metals can trigger the excessive production of reactive oxygen species (ROS), leading to oxidative stress. To bolster antioxidant activity, a common approach is to overexpress genes involved in the antioxidant machinery (68). Modifying oxidative stress-related enzymes can result in enhanced metal tolerance (44).The insertion of xenobiotic degradation genes into the root system of transgenic plants facilitates the degradation of pollutants in contaminated sites (45-46). By expressing ACC in transgenic plants, it was observed that ethylene levels were reduced (47). Phytotoxic nitroaromatic explosives, which are challenging for non-transgenic plants to deal with, can be more effectively remediated using transgenic plants when bacterial genes involved in their degradation are expressed (48).Reports indicate that metal transporter genes like ZAT and CAX-2 genes in transgenic plants enhance the accumulation of zinc, calcium, cadmium, and manganese (49,50). Altering oxidative stress-related enzymes can also lead to improved metal tolerance (51). Aluminium (Al) toxicity can inhibit root elongation (52-56). The introduction of the AtGR1 gene in transgenic plants resulted in more rapid root elongation, even under various concentrations of Al treatment. This suggests that AtGR1 gene expression alleviated Al-induced root growth inhibition by mitigating Al-induced oxidative stress, offering an effective approach to enhance Al tolerance (57).

Identifying and introducing metal transporter genes that encode transporter molecules capable of enhancing the plant's capacity to absorb metal ions represent a promising approach in phytoremediation. Several plant metal transporters have been identified, including the Arabidopsis IRT1 gene, which encodes a protein regulating the uptake of iron and other metals (58), and the MRP1 gene, which encodes the Mg-ATPase transporter (59). Co-expressing two bacterial genes, arsenatereductase (ArsC) and γ-glutamylcysteinesynthetase (γ-ECS), in Arabidopsis plants significantly increased arsenic tolerance compared to wild-type plants or plants expressing γ-ECS or ArsC alone (60). Additionally, the overexpression of the YCF1 yeast protein in Arabidopsis thaliana enhanced tolerance and increased the accumulation of Cd and Pb (61).

Top of Form

**III. Perspective**

The existence of hazardous toxic substances in the environment hasan excessive negative impact on the overall health of living organisms. The persistentnonbiodegradable nature of heavy metals could enter the food chain which might result inthe rapid accumulation of these pollutants in living organisms through biomagnification (63). It also decreases soil richness altering nutrient cycling. Thus, efficient, environmental friendly and economical technologies are indispensible to promote detoxification in the recovery of affected biomes and for mitigation of pollutants from contaminated sites. Identification of promising plant species and specific gene for detoxification and then transferring those genes to other species using genetic engineering tool can significantly enhanced the detoxification capabilities of hyperaccumulator plants as a result of which it can lead to more effective contaminated sites reclamation.Already existing scientific studies of several genes and the use of techniques for pollutant degradation provide hope for developing novel transgenic plants with improved tolerance to heavy metals and for detoxification or degradation of toxic substances into recipients with increasedadaptability.Discovering novel genes that can break down new contaminants is an urgency to create new transgenic organisms that can remediate pollutants in a proficient manner as the industry continues to grow and there is an exponential increase in the amount of toxic material generated from these industries on a consistent basis.For the eco-rehabilitation of toxic recalcitrant substances, phytoremediation proves to be a promising technique. Further investigations must be carried out in this area to enhance our knowledge to identify genes and clarify metabolites and their mechanisms and their capacity to combat pollutants using modern scientific technologywhich can aid in discovering novel genes and metabolites for efficient phytoremediationof pollutants by transgenic hyper-accumulator plants (62).Understanding the underlying mechanism of the intrinsic detoxification methods,phytoremediation using transgenic plants will provide environmental friendly alternative to conventional remediation methods.

**REFERENCES**

[1] R. Kane, “The green fuse: Using plants to provide ecosystem services. Sustainable Plant Research and Outreach, Silverton, OR, USA,

 pp.27, 2004.

[2] I. Hussain, M. Puschenreiter, S. Gerhard, P. Schofter, S. Yousaf, A. Wang, J.H. Syed, T.G. Reichenauer, “Rhizoremediation of

 Petroleum hydrocarbon-contaminated soil: improvement opportunities and field applications,” Environmental and Experimental

 Botany, vol.147, pp.202- 219, 2018.

[3] R. Kamusoko, R. Jingura, “Utility of Jatropha for phytoremediation of heavy metals and emerging contaminants of water resources: a

 review,” CLEAN Soil Air Water, vol.45, pp.1-8, 2017.

[4] I. Khan, J.K. Rono, B.Q. Zhang, X.S. Liu, M.Q. Wang, L.L. Wang, X.C. Wu, X. Chen, H.W. Cao, Z.M. Yang, “Identification of novel

 rice (Oryza sativa) HPP and HIPP genes tolerant to heavy metal toxicity,” Ecotoxicology and Environmental Safety, vol.175,pp.8-18,

 2019.

[5] Z. Li, M. Jia, L. Wu, P. Christie, Y. Luo, “Changes in metal availability, desorption kinetics and speciation in contaminated soils during

 repeated phytoextraction with the Zn/Cd hyperaccumulator Sedum plumbizincicola,” Environmental Pollution, vol.209, pp.123-131,

 2016.

[6] S. Muthusaravanan, N. Sivarajasekar, J.S. Vivek, T. Paramasivan, M. Naushad, J. Prakashmaran, V. Gayathri, O.K. Al-Duaij,

 “Phytoremediation of heavy metals: mechanism, method and enhancements,” Environmental Chemistry Letters, vol.16, pp.1339-1359,

 2018.

[7] W. Wang, E.G. Dudel, “Fe plaque-related aquatic uranium retention via rhizofiltration along a redox-state gradient in a natural

 Phrahmites australis Trin ex Steud.wetland,” Environmental Science and Pollution Research, vol.24, pp.12185-12194,2017.

[8] T. Macek, M. Mackov, J. Kas, “Exploitation of plants for the removal of organics in environmental remediation,” Biotechnology

 Advances, vol.18, pp. 23-34, 2000.

[9] X. J. Wang, F. Y. Li, M. Okazaki, and M. Sugisaki, “Phytoremediation of contaminated soil”, Annual Report CESS, vol. 3, pp. 114-123,

 2003.

[10] K. Oh, T. Li, H.Y. Cheng, Y. Xie, and S. Yonemochi, “ Development of Profitable Phytoremediation of Contaminated Soils with

 Biofuel Crops,” Journal of Environmental Protection, vol.4, pp. 58-64, 2013.

[11] H. Zhan, Y. Feng, X. Fan, S. Chen, “Recent advances in glyphosate biodegradation,” Applied Microbiology and

 Biotechnology, vol.102, pp. 5033-5043, 2018.

[12] B.V. Chang, S.N. Fan, Y.C. Tsai, Y.L. Chung, P.X. Tu, C.W. Yang, “Removal of emerging contaminants using spent mushroom compost,” Science of the Total Environment, vol.634, pp. 922-933, 2018.

[13] A.R. Autry, G.M. Ellis, “Bioremediation: an effective remedial alternative for petroleum hydrocarbon contaminated soil,”

 Environmental Progress and Sustainable Energy, vol.11, pp.318–323, 1992.

[14] S. Saval, “La biorremediacio´n como alternative para la limpieza de suelos y acuı´feros,” Ingeniería y ciencias ambientales, vol.34,

 pp.6–9, 1998.

[15] S. Knasmuller, E. Gottmann, H. Steinkellner, A. Fomin, C. Pickl, A. Paschke, R. God, M. Kundi, “Detection of genotoxic effects of

 heavy metal contaminated soils with plant bioassays,” Mutation Research, vol.420, pp. 37-48, 1998.

[16] C. Baudouin, M. Charveron, R. Tarrouse, Y. Gall, “Environmental pollutants and skin cancer,” Cell Biology and Toxicology, vol.18,

 pp.341- 348, 2002.

[17] V. Hooda, “Phytoremediation of toxic metals from soil and wastewater,” Journal of Environmental Biology, vol.28, pp.367-376, 2007.

[18] S. Karenlampi, H. Schat, J. Vangronsveld, J.A.C. Verkleiji, D.L Van der, M. Mergeay, A.L. Tervahauta, “Genetic engineering in the

 improvement of plants for phytoremediation of metal polluted soils,” Environmental Pollution, vol.107, pp.225-231, 2000.

[19] E.S. Pilon, M. Pilon, “Phytoremediation of metals using transgenic plants,” Critical Reviews in Plant Science, vol.21, pp.439-456,

 2002.

[20] S. Clemens, M.G. Palmgren, U. Kramer, “A long way ahead: understanding and engineering plant metal accumulation,” Trends in Plant

 Science, vol.7, pp.309-314, 2002.

[21] S. Eapen, S.D. Souza, “Prospects of genetic engineering of plants for phytoremediation of toxic metals,” Biotechnology Advances,

 vol.23, pp.97-114, 2005.

[22] R.L. Chaney, M. Malix, Y.M. Li, S.L. Brown, E.P. Brewer, J.s. Angle, A.J. Baker, “Phytoremediation of soil metals,” Current Opinion

 In Biotechnology, vol.8, pp. 279-284, 1997.

[23] J.F. Ma, K. Nomoto, “Effective regulation of iron acquisition in graminaceous plants the role of mugineic acids as phytosiderophores,”

 Plant Physiology,vol.97, pp.609-617, 1996.

[24] L.Q. Ma, K.M. Komar, C. Tu, W. Zhang, Y. Cai, E.D. Kennelley, “A fern that hyperacuumulates arsenic,” Nature, vol.409, pp.579,

 2001.

[25] K.H. Han, R. Meilan, C. Ma, S.H. Strauss, “An Agrobacterium transformation protocol effective in a variety of cottonwood hybrids

 (genus Populus),” Plant Cell Reports, vol.19, pp.315-320, 2000.

[26] P.C. Abhilash, S. Jamil, N. Singh, “Transgenic plants for enhanced biodegradation and phytoremediation of organic xenobiotics,”

 Biotechnology Advances, vol.27, pp.478-488, 2009.

[27] S.P. Bizily, C.L. Rugh, R.B. Meagher, “Phytodetoxification of hazardous organomercurials by genetically engineered plants,” Nature

 Biotechnology, vol.18, pp. 213-217, 2000.

[28] X. Pan, B. Zhang, G.P. Cobb, “Transgenic plants: environmental benefits and risks,” Physiology and Molecular Biology of Plants,

 vol.11, pp.13-32, 2005.

[29] S. Karenlampi, H. Schat, J. Vangronsveld, J.A.C. Verkleiji, D.L Van der, M. Mergeay, A.L. Tervahauta, “Genetic engineering in the

 improvement of plants for phytoremediation of metal polluted soils,” Environmental Pollution, vol.107, pp.225-231, 2000.

[30] S. Eapen, S. Singh, S.D. Souza, “Advances in the development of transgenic plants for remediation of xenobiotic pollutants,”

 Biotechnology Advances, vol.25, pp.442-451, 2007.

[31] C.J. French, S.J. Rosser, G.J. Davies, S. Nicklin, N.C. Bruce, “Biodegradation of explosives by transgenic plants expressing

 pentaerythritoltetranitratereductase,” Nature Biotechnology, vol.17, pp.491-494, 1999.

[32] R.B. Meagher, “Phytoremediation of toxic elemental and organic pollutants,” Current Opinion in Plant Biology, vol.3, pp.153-162,

 2000.

[31] M. Chatthai, K.H. Kaukinen, T.J. Tranbarger, P.K. Gupta, S. Misra, “The isolation of a novel metallothionein related cDNA expressed

 in somatic and zygotic embryos of Douglas fir: regulation of ABA, osmoticum and metal ions,” Plant Molecular Biology, vol.34, pp.

 243-254, 1997.

[32] R. Sriprang, Y. Murooka, “Accumulation and detoxification of metals by plants and microbes,” In: S.N. Singh, R.D. Tripathi (eds),

 “Environmental bioremediation technologies,” Springer, New York, pp.77-100, 2006.

[33] I. Khan, J.K. Rono, B.Q. Zhang, X.S. Liu, M.Q. Wang, L.L. Wang, X.C. Wu, X. Chen, H.W. Cao, Z.M. Yang, “Identification of novel

 rice (Oryza sativa) HPP and HIPP genes tolerant to heavy metal toxicity,” Ecotoxicology and Environmental Safety, vol.175,pp.8-18,

 2019.

[34] S. Gouiaa, H. Khoudi, “Expression of V-PPase proton pump, singly or in combination with a NHX1 transporter, in transgenic tobacco

 improves copper tolerance and accumulation,” Environmental Science and Pollution Research, vol.26, pp.37037-37045, 2019.

[35] S. Kumar, “Phytoremediation of explosives using transgenic plants,” Journal of Petroleum and Environmental Biotechnology,” vol.4,

 pp.1-2, 2012.

[36] M. Mohammadi, V. Chalavi, M. Novakova-Sura, L.F. Jean, S. Michel, “Expression of bacterial biphenylchlorophenyl dioxygenase

 genes in tobacco plants,” Biotechnology Bioengineering, vol.97, pp. 496–505, 2007.

[37] K. Francova, M. Sura, T. Macek, M. Szekeres, S. Bancos, K. Demnerova, M. Sylvestre, M. Mackova, “Preparation of plants containing

 bacterial enzyme for degradation of polychlorinated biphenyls,” Fresenius Environmental Bulletin, vol.12, pp.309–313, 2003.

[38] B. Siminszky, F.T. Corbin, E.R. Ward, J.F. Thomas, ED Ralph, “Expression of a soybean cytochrome P450 monooxygenase cDNA in

 yeast and tobacco enhances the metabolism of phenylurea herbicides,” Proceedings of the National Academy of Sciences, USA, vol.96,

 pp.1750– 1755, 1999.

[39] Y. Limura, S. Ikeda, T. Sonoki, T. Hayakawa, S. Kajita, K. Kimbara, K. Tatsumi, K. Katayama, “Expression of a gene for Mn-

 peroxidase from Coriolus versicolor in transgenic tobacco generates potential tools for phytoremediation,” Applied Microbiology and

 Biotechnology, vol.59, pp.246–251, 2002.

[40] A.L.W. Oller, E. Agostini, M.A. Talano, C. Capozucca, “Overexpression of a basic peroxidase in transgenic tomato (Lycopersicon

 esculentum Mill. cv. Pera) hairy roots increases phytoremediation of phenol,” Plant Science, vol.169, pp.1102–1111, 2005.

[41] E.L. Rylott, R.G. Jackson, J. Edwards, G.L. Womack, H.M. Seth-Smith, D.A. Rathbone, S.E. Strand, N.C. Bruce, “An explosive

 degradingcytochrome P450 activity and its targeted application for the phytoremediation of RDX,” Nature Biotechnology, vol.24, pp.

 216-219, 2006.

[42] C.L. Rugh, H.D. Wilde, N.M. Stack, D.M. Thompson, A.O. Summers, R.B. Meagher,“Mercuric ion reduction and resistance in

 Transgenic Arabidopsis thaliana plants expressing a modified bacterial merA gene,” Proceedings of the National Academy of

 Sciences, vol.93, pp.3182- 3187, 1996.

[43] Y.L. Zhu, E.A.H. Pilon-Smits, L. Jouanin, N. Terry, “Overexpression of glutathione synthetase in Indian mustard enhances cadmium

 accumulation and tolerance,” Plant Physiology, vol.119, pp.73-79, 1999.

[44] B. Ezaki, R.C. Gardner, Y. Ezaki, H. Matsumoto, “Expression of aluminium induced genes in transgenic Arabidopsis plants can

 Emelioratealuminium stress and/or oxidative stress,” Plant Physiology, vol.122. pp. 657-665, 2000.

[45] K.E. Gerhardt, X.D. Huang, B.R. Glick, B.M. Greenberg, “ Phytoremediation and rhizoremediation of organic soil contaminants:

 potential and challenges,” Plant Science, vol.176, pp.20-30, 2009.

[46] H. Kawahigashi, “Transgenic plants for phytoremediation of herbicides,” Current Opinion in Biotechnology, vol.20, pp.225-230,

 2009.

[47] M. Arshad, M. Saleem, S. Hussain, “Perspectives of bacterial ACC deaminase in phytoremediation,” Trends in Biotechnology, vol.25,

 pp. 356-362, 2007.

[48] C.J. French, S.J. Rosser, G.J. Davies, S. Nicklin, N.C. Bruce, “Biodegradation of explosives by transgenic plants expressing

 pentaerythritoltetranitratereductase,” Nature Biotechnology, vol.17, pp.491-494, 1999.

[49] B.J. Van der Zaal, L.W. Neuteboom, J.E. Pinas, A.N. Chardonnens, H. Schat, J.A. Verkleij, P.J. Hooykaas, “Overexpression of a

 novel Arabidopsis gene related to putative zinc transporter genes from animals can lead to enhanced zinc resistance and

 accumulation,” Plant Physiology, vol.119, pp.1047-1055, 1999.

[50] K.D. Hirschi, V.D. Korenkov, N.L. Wilganowski, G.J. Wagner, “Expression of Arabidopsis CAX2 in tobacco altered metal

 accumulation and increased manganese tolerance,” Plant Physiology, vol.124, pp.125-133, 2000.

[51] B. Ezaki, R.C. Gardner, Y. Ezaki, H. Matsumoto, “Expression of aluminium induced genes in transgenic Arabidopsis plants can

 emelioratealuminium stress and/or oxidative stress,” Plant Physiology, vol.122. pp. 657-665, 2000.

[52] E. Delhaize, P.R. Ryan, “Aluminum toxicity and tolerance in plants,” Plant Physiology, vol.107, pp.315–321, 1995.

[53] Y. Yamamoto, Y. Kobayashi, S.R. Devi, S. Rikiishi, H. Matsumoto, “Oxidative stress triggered by aluminum in plant roots,” Plant

 Soil, vol.255, pp.239–243, 2003.

[54] K. Tahara, T. Yamanoshita, M. Norisada, I. Hasegawa, H. Kashima, S. Sasaki, K. Kojima, “Aluminum distribution and reactive

 Oxygen species accumulation in root rips of two Melaleuca trees differing in aluminum resistance,” Plant Soil, vol.307, pp167–178,

 2008.

[55] G.F. Zhou, J.F. Pereira, E. Dehaize, M.X. Zhou, J.V. Magalhase, P.R. Ryan, “Enhancing the aluminium tolerance of barley by

 expressing the citrate transporter genes SbMATE and FRD3,” Journal of Experimental Botany, vol. 65, pp. 2381–2390, 2014.

[56] M.J. Zhang, X.P. Deng, L.N. Yin, L.Y. Qi, X.Y. Wang, S.W. Wang, H.B. Li, “Regulation of galactolipid biosynthesis by

 overexpression of the rice MGD gene contributes to enhanced aluminum tolerance in tobacco,” Frontiers in Plant Science, vol.7,

 pp.337, 2016.

[57] Y. Lina, M. Junichi, T. Kiyoshi, W. Shiwen, Z. Meijuan, D. Xiping, and Z. Suiqi, “High level of reduced glutathione contributes to

 detoxification of lipid peroxide-derived reactive carbonyl species in transgenic Arabidopsis overexpressing glutathione reductase

 under aluminum stress,” Physiologia Plantarum, vol.161, pp.211–223, 2017.

[58] D. Eide, M. Broderius, J.M. Fett, M.L. Guerinot, “A Novel Iron-Regulated Metal Transporter from Plants Identified by

 Functional Expression in Yeast, Proceedings of National Academy of Sciences, vol.93, pp. 5624-5628, 1996.

[59] Y.P. Lu, Z.S. Li, P.A. Rea, “AtMRP1 gene of Arabidopsis encodes a glutathione S-conjugate pump: isolation and functional

 definition of a plant ATP-binding cassette transporter gene,” Proceedings of the National Academy of Sciences, USA, vol.94,pp.

 8243-8248, 1997.

[60] O.P. Dhankher, Y. Li, B.P. Rosen, J. Shi, D. Salt, J.F. Senecoff, N.A. Sashti, R.B. Meagher, “Engineering tolerance and

 hyperaccumulation of arsenic in plants by combining arsenate reductase and y-glutamylcysteine synthetase expression,” Nature

 Biotechnology, vol.20, pp. 1140-1145, 2002.

[61] I. Alkorta, J.A. Hernandez, J.M. Becerril, I. Amezaga, I. Albizu, I. Garbisu, “Recent findings on the phytoremediation of soils

 contaminated with environmentally toxic heavy metals and metalloids such as zinc, cadmium, lead and arsenic,” Environmental

 Science and Biotechnology,” vol.3, pp.71-90, 2004.

[62] I. Mishra, N.K. Arora,“Rhizoremediation: A Sustainable approach to improve the quality and productivity of polluted soils. In:

 Arora NK, Kumar N (eds) Phyto and Rhizo remediation, microorganisms for sustainability,” Springer, Berlin, pp.33–66, 2019.

[63] Y. An, W. Yamin, N.T. Swee, L.M.Y. Mohamed, G. Subhadip, C. Zhong, “Phytoremediation: A promising approach for revegetation of heavy metal-polluted land,” Frontiers in Plant Science, vol.11, pp.1-15, 2020.

[64] G. DalCorso, E. Fasani, A. Manara, G. Visioli, A. Furini, “Heavy metal pollutions: state of the art and innovation in phytoremediation”

 International Journal of Molecular Science, vol.20, pp.3412, 2019.

[65] E.P. Brewer, J.A. Saunders, J.S. Angle, R.L. Chaney, M.S. Mcintosh, “Somatic hybridization between the zinc accumulator Thlaspi

 caerulescens and Brassica napus” Theoritical and Applied Genetics, vol.99, pp.761–771, 1999.

[66] A. Berken, M.M. Mulholland, D.L. Leduc, N. Terry, “Genetic engineering of plants to enhance selenium phytoremediation,” Critical

 Reviews in Plant Science, vol.21, pp.567–582, 2002.

[67] A.P. Marques, A.O. Rangel, P.M. Castro, “Remediation of heavy metal contaminated soils: phytoremediation as a potentially

 promising clean-up technology,” Critical Reviews in Environmental Science and Technology, vol.39, pp.622–654, 2009.

[68] A. Kozminska,A. Wiszniewska, E. Hanus-Fajerska,E. Muszynska, “Recent strategies of increasing metal tolerance and

 phytoremediation potential using genetic transformation of plants,” Plant Biotechnology, vol.12, pp.1–14, 2018.

[69] R.L. Chaney, M. Malik, Y.M. Li, S. Brown, E.P. Brewer, J.S. Angle, A.J.M. Baker, “Phytoremediation of Soil Metals,” Current Opinion

 in Biotechnology, vol.8, pp.279-284, 1997.