Chapter

Aquatic Plants as Bioremediators in Pollution Abatement of Heavy Metals

Aaltharackal Vikraman Meera, Manorama Thampatti KC, Jacob John, Bhadra Sudha and Abdulmajeed Sajeena

Abstract

Over use of chemical inputs and exploitation of natural resources have degraded our ecosystem to a large extent. Our water bodies are drastically affected, especially due to the impact of heavy metal loading. The biomagnification that results from these difficult to degrade metals is naturally affecting the human health. The physical and chemical methods commonly employed for water purification are not only highly expensive but also further aggravate the pollution problem. Hence, all efforts must be taken to exploit the emerging green technology approach in pollution remediation. Several aquatic plants have specific affinity towards heavy metals and they flourish well in this contaminated environment. The common mechanisms of phytoremediation and varied type of aquatic plants with high remediation potential are reviewed in this chapter.

Keywords: pollution, aquatic macrophytes, phytoremediation, hyperaccumulators

1. Introduction

Industrialization, urbanization and over exploitation of precious natural resources have resulted in much degradation of our environment. The dire need for promotion of intensive cultivation to satisfy primary human needs led to over dependence on chemical resources. This in turn, caused much degradation to our ecosystem mainly through environmental pollution. Among the natural resources, the worst affected are water resources. 97% of hydrosphere is covered by saltwater, leaving only mere 3% fresh water, of which hardly 1.5% is available for ready use [1]. The entire world is relying on this meager resource for daily consumption, irrigation, industrial purposes, power and other diverse uses. Injudicious human activities including disposal of sewage and wastes have caused great impact on water bodies all over the world. Wetlands act as sink for contaminants and thereby reduce the impact of point and non-point sources of pollution [2]. But drastic reduction in water inflow has been resulted due to fragmentation of water bodies and irreversible conversion to satisfy human needs.

Heavy metal pollution in water bodies is a serious environmental problem, threatening not only the aquatic ecosystems, but also human health. Over the years, the main sources of metal pollution have shifted from mining and manufacturing to rock weathering and waste discharge [3]. There are several reports on the deleterious effects of biomagnification of heavy metals within aquatic organisms and its impact on human nervous, reproductive and cardio vascular systems [4]. Disposal of plastic wastes, batteries, fertilizer materials, untreated industrial effluents etc. releases heavy metals including Cd into the aquatic environment which causes several causalities like osteoporosis, kidney failure, infertility and improper brain development. Globally, majority of surface water bodies are highly polluted with heavy metals like As, Co, Cr and Ni, with levels exceeding WHO and USEPA guideines and have evoked much concern among the government agencies and public [5].

As heavy metals are non-biodegradable, removal of these metals from the aquatic system is the only remedy available for decontamination [6]. The conventional methods usually employed to remove the metals from a polluted system like coagulation, flocculation, osmosis, stabilization etc. are highly expensive. In addition, they further aggravate deterioration with the release of chemicals being used and hence these methods are not at all environmentally safe [7, 8]. But, a new method of decontamination employing green plants is fast emerging, referred as phytoremediation, which is specifically suited for wetland restoration. The plants growing in the contaminated areas will absorb the elements from the sediment/soil/water by roots. The absorbed elements travel from root through cell sap and finally get precipitated in vacuole or cell membrane, thereby reduces the level of contaminants in sediment/soil/water [9]. Such aquatic plant species and adsorbents can be included in land management plans to reduce human risks. This method is relatively cheap and very successful over other methods [10].

2. Phytoremediation: a bio-decontamination approach

The concept of extraction of metals by macrophytes was actually given by Chaney [11]. Efficiency of macrophytes to extract metals from contaminated site depends on the metal hyperaccumulation capacity and biomass production. The selection of particular plant species for phytoremediation depends on the following characteristics:

i. native to the particular ecosystem.

ii. well flourishing nature and high biomass yield.

iii. ability to uptake large amount of metals.

iv. transportation of metals to aboveground plant portion.

v. mechanism to tolerate metal toxicity.

In addition, factors like pH, light intensity and nutrient availability influences the plant growth and thus, phytoremediation potential [12–16]. Agronomic practices for soil and crop management and improved genetic engineering technologies to enhance metal tolerance and translocation can affect the remediation mechanism. Exsituas well asinsitu methods of phytoremediation are there:*exsitu method* involves excavation of contaminated soil followed by its treatment and also shifting the soil for land filling;*insitu method* is less laborious and more cost effective and commonly employs mechanisms like phytoextraction and phytostabilization [17].

3. Mechanisms of phytoremediation

Depending upon the process by which plants/microbes are removing or reducing the toxic effect of contaminants from the soil and water, phytoremediation technology can be broadly classified as follows:

a. Phytoextraction or phytoaccumulation –This refers to the uptake and translocation of metal contaminants in the soil by plant roots with subsequent transport to the aerial plant organs. Certain plants called hyperaccumulators absorb unusually large amounts of metals in comparison to other plants and concentrate them in the aerial portions [11, 18–20].

b. Phytosequestration–The phytochemicals that are released into the rhizosphere may form complex association with the contaminants, sequestering them in the root zone and thus reducing their mobility This prevents further transport to soil, water and air. The complexation can also occur with the aid of transport proteins on root surface or through sequestration in the vacuoles of root cells [21].

c. Rhizofiltration - It is the adsorption or precipitation of contaminants onto plant roots or absorption into the roots that are in solution surrounding the root zone. The acclimatized plants against contamination are planted in the contaminated area and the roots extract the contaminants along with water. As the roots become saturated with contaminants, they are harvested and incinerated [22–25].

d. Phytodegradation or phytotransformation– Here, organic pollutants are converted by internal or secreted enzymes into compounds with reduced toxicity. The metabolic processes, with the aid of enzymes within the plant or secreted externally, result in the degradation of pollutants and may be incorporated into the plant tissues or used as nutrients [20, 26, 27].

e. Rhizodegradation–Microbial activity in the rhizosphere results in the breakdown of contaminants, leading to their phytoremediation. Compared to phytodegradation it is a much slower process. Microflora (yeast, fungi, or bacteria) utilize the organic substrates for nutrition and energy [28, 29].

f. Phytostabilization–The particular plant species involved helps in the immobilization of contaminants through absorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone. This results in reduction in mobility of contaminants and migration to ground water or air is blocked, which in turn hinders their bioavailability [30, 31].

g. Phytovolatalization –It is the uptake and transpiration of contaminant by a plant, with the release of that contaminant or its modified form to the atmosphere. In this process, the soluble contaminants are taken up along with water by the roots, transported to the leaves, and volatized into the atmosphere through the stomata. For *eg*., volatilization of mercury (Hg) by conversion to the elemental form in transgenic *Arabidopsis* and yellow poplars containing modified bacterial mercuric reductase (*merA*) [32–34].

Among the different methods of phytoremediation, phytoextraction by hyperaccumulators is the most efficient one as it helps in removal of the phytoextracted biomass from contaminated sites. But phytoremediation cannot be used as a primary treatment method for highly contaminated areas with heavy metals like Cd, Zn, Cr and Pb, because of the prolonged time taken for the complete clean up. The dominant families that include hyperaccumulators are Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, Cunouniaceae, Fabaceae, Flacourtiaceae, Lamiaceae, Poaceae, Violaceae, and Euphobiaceae. Brassicaceae has the largest number of taxa *viz*. 11 genera and 87 species. *Thlaspi* species are known to hyperaccumulate more than one metal *viz.,T. caerulescence* - Cd, Ni, Pb, and Zn; *T. goesingense* - Ni and Zn and *T. ochroleucum* - Ni and Zn and *T. rotundifolium* - Ni, Pb and Zn. Aquatic plants in freshwater, marine and estuarine systems act as receptacle for several metals. Several aquatic macrophyteslike*Eichhorneacrassipes, Hydrillaverticillata, Typhaangustata,* etc. can remove Zn, Cu, Pb, Ni and Cd from lakes and maintain water quality.

4. Phytoremediation by aquatic macrophytes

Aquatic macrophytes constitute a group of taxonomically diverse macroscopic plants whose life cycle takes place completely or periodically in the aquatic environment. They play a dominant role in maintaining the ecosystem biodiversity, represented by 33 orders and 88 families, numbering about 2614 species in 412 plant genera. The wide adaptation in their growing habits help them to classify as emergent, floating-leaved, free-floating, submerged and marginal plants [35, 36].

i. *Emergent*macrophytes: They grow in shallow littoral waters and form aerial leaves, suited for life in environments where the soil is saturated with water (wetlands, marshes, swamps, flooded areas), and their root and rhizome systems are often adapted for constantly anaerobic sediments, rooted in the lake bottom, but their leaves and stems extend out of water.

ii. eg. *Phragmitesaustralis, Typhaaugustifolia, Limnocharisflava.*

iii. *Floating-leaved*macrophytes: Their roots are attached to the ground and possess floating or aerial reproductive organs eg. *Nymphaea* sp., *Nupharlutea*, *Potamogetonnatans.*

iv. *Free floating*macrophytes:They float on the surface of pond with roots hanging in water and possess well developed root system or very short roots. The reproductive organs of these plants are floating and aerial. Eg. *L. minor*, *Eich horneacrassipes*,*Salviniamolesta.*

v. *Submerged*macrophytes: Such plants complete their life cycle fully under the water surface. Some are rooted plants with most of their vegetative portion below the water surface. eg. *Vallisneria* sp., *Myriophyllum* sp.

vi. *Marginal*macrophytes:They grow around the margins where the water is shallow. Eg. *Rhizophora*sp., *Cyperus* sp.

In the given **Table 1**, some common aquatic macrophytesand their specificity for particular elements are detailed.

These macrophytes have the ability to concentrate metals both in the root and aerial parts, without causing any toxic symptoms on plant growth. In general,

Macrophyte group	Plant species	Heavy/toxic metal	References
Emergent	*L. flava*	Pb	[37]
		Pb, Cd	[38–40]
		Fe	[41]
	Typha sp.	Al	[42, 43]
	R. fluitans	Pb, Mn and Zn	[44]
	Scirpus sp	Pb	[45, 46]
	C. esculenta	Pb, Cd	[40, 47]
Floating-leaved	*N. nucifera*	Cd	[48, 49]
	Nymphaea sp.	Pb, Cd	[50, 51]
Free floating	*Eichhornea crassipes*	Al,Pb, Cd, Fe, S	[49, 52–61]
	P. stratiotes	Al, Fe	[52, 62]
	Salvinia polyrrhiza	Fe	[53, 62]
	Azollapinnata	Cd	[63]
Submerged	*C. demersum*	Pb	[64]
	Potamogeton scrispus	Pb, Cd	[65]
	V. spiralis	Al, Fe, Si, Mn, Pb	[66, 67]
	H. verticillata	Al, Fe, Si, Mn	[66]
	A. pinnata	Al, Fe, Si, Mn	[66]
	R. rotundifolia	Pb	[46]
	Myriophyllum intermedium	Pb	[46]
Marginal	*Cynadon*sp.	Al, Pb, Cd, Fe	[68–72]
	Commolina bengalensis	Fe, Al	[68]
	A. philoxeroides	Pb	[56, 73]
	S. trilobata	Pb	[40, 74]

Table 1.
Common aquatic macrophytes and their phytoremediation potential.

the submerged and floating macrophytes have the potential to accumulate more metals than emergent ones. Rhizofiltration offers much scope in the purification of heavily contaminated precious water resources, a big boon for eco restoration of aquatic systems.

5. Indices to estimate hyperaccumulation potential

The hyperaccumulation potential of macrophytesare determined primarily based on two indices *viz.*,bio concentration factor (BCF) and translocation factor (TF). BCF is defined as the ability of a plant to accumulate a particular metal in its plant part with respect to its concentration in the soil substrate while TF is the ratio of metal concentration in shoot to that in the root. BCF more than oneindicates that the plant is an accumulator while less than one, means the plant is an excluder. Hyperaccumulators are plants that contain more than 10,000 mg kg^{-1} of Zn and Mn; 1000 $mgkg^{-1}$ of Cu, Cr, Pb, Ni, Co and 100 mg kg^{-1} of Cd and other rare metals, in the dry matter [75].

A high value for TF indicate the efficiency of the plant to translocate metals from the root to shoot and such plants (TF > 1) are referred as hyperaccumulators. They possess the phytoextraction ability to remove contaminants from the growth medium to the above ground portions and the biomass can be uprooted and removed. Aquaticmacrophytes, especially floating macrophytes, have the potential to concentrate metals more in the roots. Based on BCF and TF, the hyperaccumulation potential of *E. crassipes*and *A. philorexoides*for Cd has been proved beyond doubt, whereas higher BCF and lower TF is an indication of phytostabilisation effect eg. *L. flava* and *C. dactylon*.

6. Mechanisms of heavy metal tolerance by macrophytes

Accumulation of heavy metals inside the plant body results in certain physiological changes and synthesis of certain enzymes to tolerate the metal stress. Major changes that occur inside the plant cell to activate metal absorption include enhancement in the bioavailability of metal in the rhizosphere region leading to an increased uptake of metal towards the plasma membrane. Inside the cell wall, chelation of metal may occur by binding with various proteins like phytochelatin or, metallothionein or form a bond with the cell wall or get sequestered into the cell vacuole [76, 77].

Acidification of rhizosphere by the action of plasma membrane proton pumps and secretion of ligands capable of chelating the metal helps in desorption of metals from the soil matrix. Soluble metals can enter into the root symplast by crossing the plasma membrane of the root endodermal cells or they can enter the root apoplast through the space between cells. Excluder plants survive by enhancing specificity for the essential element or pumping the toxic metal back out of the plant. On reaching the xylem, the metal will get transported alongwith xylem sap towards the leaves and get deposited there. The cell tissue where the metal get deposited, vary with the hyperaccumulator species as shown by *T. caerulescens* and *Arabidopses halleri - T. caerulescens* has preferential adsorption for Zn in the epidermis over mesophyll cells while the reverse for *Arabidopses halleri* [78].

At any point along the pathway, the metal could be converted to a less toxic form by chemical conversion or complexation. Various oxidation states of toxic elements have very different uptake, transport, and sequestration or toxicity characteristics in plants. Two major chelating peptides present in plants include metallothioneins and phytochelatins. Sequestration of metals in sites away from where the cellular processes are likely to be get disrupted will result in their deposition. The most prominent site is cell vacuole, for that metal or metal- ligand complex must cross the vacuolar membrane. Metal ions may also get bonded with negative charges on cell wall leading to their sequestration in the cell wall.

7. Conclusions

It is high time that the water bodies be conserved for ecological sustenance and well-being of the future generation. Aquatic plants can play a vital role in the purification of contaminated lakes, rivers and ponds, which make them fit for human consumption and irrigation purposes. The nature and extent of amelioration varies with particular plant species. They are specifically adapted to tolerate heavy/ toxic metal concentration in their ecosystems.

Author details

Aaltharackal Vikraman Meera[1]*, Manorama Thampatti KC[2], Jacob John[1], Bhadra Sudha[1] and Abdulmajeed Sajeena[1]

1 Integrated Farming System Research Station, Kerala Agricultural University, Karamana, India

2 Department of Soil Science and Agricultural Chemistry, College of Agriculture, Kerala Agricultural University, Vellayani, India

*Address all correspondence to: meera.av@kau.in

References

[1] https://earthdata.nasa.gov/learn/toolkits/freshwater-availability

[2] Bystorm O, Andersson H, and Gren I. Economic criteria for using wetlands as nitrogen sinks under uncertainty. Ecol. Econ. 2000;35 (1): 35-45

[3] Zhou Q, Yang N, Li, Y, Ren B, Ding X, Bian H, Yao X. Total concentrations and sources of heavy metal pollution in global river and lake water bodies from 1972 to 2017. Global Ecol. Conservation. 2020;22: 1-11.

[4] Mishra S, Srivastava S, Tripathi RD, Kumar R, Seth CS, Gupta DK. Lead detoxification by coontail (Ceratophylumdemersum L.) involves indication of phytochelatins and antioxidant systemin response to its accumulation. Chemosphere 2006;65 (6): 1027-1039.

[5] Kumar V, Parihar RD, Sharma A, Bakshi P, Sidhu GPS, Bali AS, Karaouzas I, Bhardwaj R, and Thukral AK. Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. 2019.124364,ISSN 0045-6535. https://doi.org/10.1016/j.chemosphere.2019.124364.

[6] Cheng S, Grosse W, Karrenbrock F, Thoennessen M. Efficiency of constructed wetlands in decontamination of water polluted by heavy metals. Ecol. Eng. 2002;8:317-325

[7] Rai PK. Heavy metal phytoremediation from aquatic ecosystems with special reference to macrophyte. Crit. Rev. Environ. Sci. Technol. 2009; 39: 118-125.

[8] Tangahu, BV, Abdullah SRS, Basri H, Idris M, Anuar N, Mukhlisin M. A Review on Heavy Metals (As, Pb, and Hg) Uptake by Plants through Phytoremediation. *Int. J. Chem. Eng.* 2011;20(11): 31-41.

[9] Cunningham,S.D. and Ow, D.W. Promises and prospects of phytoremediation. *Plant Physiol.* 1996;110: 715-719

[10] Yan A, Wang Y, Tan SN, MohdYusof ML, Ghosh S and Chen Z . Phytoremediation: A Promising Approach for Revegetation of Heavy Metal-Polluted Land. Front. Plant Sci. 2020;11:359. doi: 10.3389/fpls.2020.00359.

[11] Chaney, R.L. Plant uptake of inorganic waste constituents. In: Parr, J. F., Marsh, P. B. and Kla, J. M. (eds), Land Treatment of Hazardous Wastes. Noyes Data Corp., Park Ridge, New Jersey, 1983. pp 50-76.

[12] Ali H, Khan E, Sajad MA. Phytoremediation of heavy metals—Concepts and applications. Chemosphere. 2013;91: 869-881.

[13] Liu J, Wen Z, Penghang QU, Mingxin and Wang. Cadmium tolerance and accumulation in fifteen wetland plant species from cadmium-polluted water in constructed wetlands. *Front. Environ. Sci. Eng.* 2014: 1 -7.

[14] Zhang X, Zhang X, Gao B, Li Z, Xia H, Li H, Li J. Effect of cadmium on growth, photosynthesis, mineral nutrition and metal accumulation of an energy crop, king grass (*Pennisetumamericanum* and *P. purpureum*). *Biomass Bioenergy* 2014;67: 179-187.

[15] Reeves RD, Baker AJ, Ja_ré, T, Erskine PD, Echevarria G, van der Ent A. A global database for plantsthathyperaccumulate metal and metalloid trace elements. New Phytol. 2018.218: 407-411.

[16] Neina D. The role of soil pH in plant nutrition and soil remediation. *Applied Environ. Soil Sci*. 2019 Article ID 5794869 https://doi.org/10.1155/2019/5794869

[17] Sheoran V, Sheoran, A. Poonia, P. Factors affecting Phytoextraction: A Review. Pedosphere. 2016; 26: 148-166.

[18] Baker AJM, McGrath SP, Sidoli CMD, Reeves RD. The possibility of in-situ heavy-metal decontaminationof polluted soils using crops of metal-accumulating plants. *Res. Conserve. Recycl*. 1994;11: 41-49.

[19] Brooks RR, Chambers MF, Nicks LJ, Robinson BH. Phytomining. *Trends Plant Sci*. 1998;1: 359-362.

[20] Salt DE, Smith RD, Ruskin I. Phytoremediation. *Annu. Rev. Plant Physiol. Plant Mol. Biol*. 1998;49: 643-668.

[21] Cunningham SD, Shann JR, Crowley DE, Anderson TA. Phytoremediation of contaminated water and soil. In: Kruger EL, Anderson TA, Coats JR. (eds), *Phytoremediation of Soil and Water Contaminants.* American Chemical Society, Washington, D.C. pp. 1997;133-151.

[22] Dushenkov V, Kumar PBAN, Motto H, Raskin I. 1995. Rhizofiltration: the use of plants to remove heavy metals from aqueous streams. *Environ. Sci. Technol*. 29:1239-1245

[23] Zhu YL, Zayed AM, Quian JH, DeSouza M, Terry N. Phytoaccumulation of trace elements by wetland plants: II. water hyacinth. J. Environ. Qual. 1999;28: 339-344.

[24] Raskin I, Ensley BD. *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment* John Wiley and Sons,Inc., New York, 2000;pp 53-70.

[25] Gardea-Torresdey JL, de la Rosa G, Peralta-Videa JR. X. Use of phytofiltration technologies in the removal of heavy metals: a review. *Pure Appl. Chem*. 2004;76(4): 801-803.

[26] Black H. Absorbing possibilities: Phytoremediation. *Environ. Health Prespect* 1995; 103(12): 1106-1108.

[27] Suresh B, Ravishankar G. Phytoremediation - A novel and promising approach for environmental clean-up. *Crit. Rev. Biotech*. 2004;24: 97-124.

[28] Kuiper I, Lagendijk EL, Bloemberg GV, Lugtenberg BJJ. Rhizoremediation: a beneficial plant-microbe interaction. *Mol. Plant-Microbe Interact.* 2004;17: 6-15.

[29] Yadav SK. Heavy metals toxicity in plants: an overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. S. *Afr. J. Bot.* 2010;76: 167-179.

[30] Berti WR, Cunningham SD Phytostabilization of metals. In: Raskin, I. and Ensley, B. (eds), *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment*. Wiley Interscience, New York, 2000;pp. 71-88.

[31] Stoltz E, Greger M. Accumulation properties of As, Cd, Cu, Pb and Zn by four wetland plant species growing on submerged mine tailings. *Environ. Exp. Bot.* 2002;47(3), 271-280.

[32] Heaton ACP, Rugh CL, Wang N, Meagher RB. Phytoremediation of mercury- and methyl mercury polluted soils using genetically engineered plants. *J. Soil Contam*. 1998;74: 497-510.

[33] Rugh CL, Senecoff JF, Meagher RB, Merkle SA. Development of transgenic yellow poplar for mercury phytoremediation. *Nat. Biotechnol.* 1998;16: 925-928.

[34] Dushenkov D. Trends in phytoremediation of radionuclides. *Plant and Soil* 2003.;249: 167-175.

[35] Chambers PA, Lacoul P, Murphy KJ, Thomaz SM. Global diversity of aquatic macrophytes in freshwater. Hydrobiologia, 2008; 198: 9-26.

[36] Lesiv MS, Polishchuk AI, Antonyak HL. Aquatic macrophytes: Ecological features and functions. Biol. Stud. 2020;14(2): 79-94.

[37] RachmadiartiF, Soehono LA, Utomo WH, Yanuwiyadi B, Fallowfield H. Resistance of yellow velvetleaf (*Limnocharisflava*(L.) Buch.) exposed to lead. *J. Appl. Environ. Biol. Sci*. 2012;2(6): 210-215.

[38] Bindhu T, Sumi MM, Ramasamy, EV. Decontamination of water polluted by heavy metals with taro (*Colocasiaesculenta*) cultured in a hydroponic NFT system. *Environ*. 2010;30: 35-44.

[39] Anning AK, Percy E, Korsah, Addo-Fordjour P. Phytoremediation of waste water with *Limnocharisflava, Thaliageniculata*and *Typhalatifolia* in constructed wetlands. *Int. J. Phytoremediation* 2013;15(5): 452-464.

[40] Meera AV. Phytoremediation of inorganic contaminants in Vellayani wetland ecosystem. Ph.d Thesis, Kerala Agricultural University; 2017

[41] Kamrudzaman AN, Zakariaa MH, Aziza RA, Faizal MA, Jalil. Removal of iron (Fe) from landfill leachate using horizontal and vertical subsurface flow constructed wetland system planted with *Limnocharisflava*. *Int. J . Chem. Environ. Eng.* 2012;3(2): 15 – 20.

[42] Hegazy AK, Abdel-Ghani NT, El-Chaghaby A. Phytoremediation of industrial wastewater potentiality by *Typhadomingensis. Int. J. Environ. Sci. Tech*. 2011;8 (3): 639-648.

[43] Kumari A, Lala B, Rai UN. Assessment of native plant species for phytoremediation of heavy metals growing in the vicinity of NTPC sites, Kahalgaon, India. *Int. J. Phytoremediation* 2016;18 (6): 592-597.

[44] Othman R, Hanifah NA, Ramya R, BtMohdHatta FA, Sulaiman WS, Yaman M, Baharuddin ZMB. Sequestration rate of heavy metal contaminants using *Ricciafluitans*as potential phytoremediation agent in polluted aquatic ecosystem. Int. J. Sustain. Energy Environ. Res. 2014;3(4): 185-192.

[45] Tangahu BV, Rozaimah SA, Basri SRS, Idris HM, Anuar N, Mukhlisin M. Phytotoxicity of wastewater containing lead (Pb) effects *Scirpusgrossus. Int. J. Phytoremediation*. 2013; 15(8): 814-826.

[46] Marbaniang D, Chaturvedi SS. A study on lead uptake and phytoremediation potential of three aquatic macrophytes of Meghalaya, India. Int. J. Sci. Res. Publ. 2014;4(6): 224-241.

[47] Madera-Parra CA, Peña-Salamanca EJ, Peña MR, Rousseau DPL, Lens PNL. Phytoremediation of landfill leachate with *Colocasiaesculenta*, *Gynerumsagittatum* and *Heliconiapsittacorum* in constructed wetlands. *Int. J. Phytoremediation*. 2015;17 (1-6): 16-24.

[48] Mishra V, Pathak V, Tripathi B. Accumulation of cadmium and copper from aqueous solutions using Indian lotus (*Nelumbonucifera*). *AmbioJ. Human Environ*. 2009;38(2): 110-115.

[49] Kamal K. Evaluation of aquatic pollution and identification of phytoremediators in Vellayani lake. M.Sc.(Ag) thesis, Kerala Agricultural University, Thrissur; 2011.

[50] Schor-Fumbarov T, Keilin Z, Tel-Or E. Characterization of cadmium uptake by the water lily *Nymphaea aurora*. *Int. J. Phytoremediation* 2003;5(2): 169-179.

[51] Shuaibu UOA, Nasiru A. Phytoremediation of trace metals in Shadawanka stream of Bauchi Metropolis, Nigeria. *Universal J. Environ. Res. Technol.* 2011;1(2): 176 – 181.

[52] Klumpp A, Bauer K, Franz-Gerstein C, Max de Menezes. Variation of nutrient and metal concentrations in aquatic macrophytes along the Rio Cachoeira in Bahia (Brazil). *Environ. Int.* 2002;28: 165– 171.

[53] Mishra VK, Tripathi BD. Concurrent removal and accumulation of heavy metals by the three aquatic macrophytes. *Biores. Technol*. 2008;99:7091-7097.

[54] KAU [Kerala Agricultural University]. Bioremediation of inorganic contaminants of rice based wetland ecosystems of Kuttanad, Kerala. *Final Report of ICAR Adhoc Project.* Kerala Agricultural University, Thrissur, Kerala; 2009.

[55] Narain S, Ojha CSP, Mishra SK, Chaube UC, Sharma PK. Cadmium and chromium removal by aquatic plant. *Int. J. Environ. Sci*. 2011;1(6): 1297-1304.

[56] Nan H, Zheng J, Ding D, Li G, Yin J, Chen X, Yu J. Screening of native hyperaccumulators at the Huayuan river contaminated by heavy metals. *Bioremediation. J*. 2013;17(1): 21-29.

[57] Sukumaran D. Phytoremediation of heavy metals from industrial effluent using constructed wetland technology. *Appl. Ecol. Environ. Sci*. 2013;1 (5): 92-97.

[58] Khankhane PJ, Sushilkumar, H.S. Bisen. Heavy metal extracting potential of common aquatic weeds. *Ind. J. Weed Sci*. 2014;46(4): 361-363.

[59] Das S, Goswami S, Talukda, AD. Physiological responses of water hyacinth, *Eichhorniacrassipes* (Mart.) Solms, to cadmium and its phytoremediation potential. *Turkish. J. Biol.* 2016;40: 84-94.

[60] Meera AV, Thampatti MKC. *Nelumbonucifera* as an ideal macrophyte for phytoremediation of toxic metals in contaminated wetland. *Adv. Life Sci*. 2016;5(9): 3562 -3565.

[61] Thampatti KCM, Beena VI, Usha PB. Aquatic macrophytes for phytomining of iron from rice based acid sulphate wetland ecosystems of Kuttanad. *J. Indian Soc. Coastal Agric. Res*. 2016;34(2):1-6.

[62] Preetha SS, Kaladevi V. Phytoremediation of heavy metals using aquatic macrophytes. *World J. Environ. Biosci*. 2014;3 (1): 34-41.

[63] Rai PK. Phytoremediation of Hg and Cd from industrial effluents using an aquatic free floating macrophyte. *Azollapinnata. Int. J. Phytoremediation*. 2008;10: 430-439.

[64] Keskinkan O, Goksu MZL, Basibuyuk M, Forster CF. Heavy metal adsorption properties of a submerged aquatic plant (*Ceratophyllumdemersum*). *Biores. Technol*. 2004;92:197-200.

[65] Norouznia H, Hamidian AM. Phytoremediation efficiency of pondweed (*Potamogetoncrispus*) in removing heavy metals (Cu, Cr, Pb, As and Cd) from water of Anzali wetland. *Int. J. Aquat.Biol*. 2014;2(4): 206-214.

[66] Kumar NJI, Sreenivas S, Rana BC. EDAX- analysis of mud of four ponds from central Gujarat. *Indian Bot. Cont*. 1989;1: 75-76.

[67] Kumar NJI, Soni H, Kumar RN, Bhatt I. Macrophytes in phytoremediation of heavy metal contaminated water and sediments in Pariyej community reserve, Gujarat, India. *Turkish J. fish. Aquat. Sci.* 2008;8: 193-200.

[68] KAU [Kerala Agricultural University]. Bioremediation of inorganic contaminants of rice based wetland ecosystems of Kuttanad, Kerala. *Annual Report of ICAR Adhoc Project.* Kerala Agricultural University, Thrissur, Kerala;2008.

[69] Soleimani M, Hajabbasi MA, Afyuni M, Charkhabi AH, Shariatmadari, H. Bioaccumulation of nickel and lead by bermuda grass (*Cynodondactylon*) and tall fescue (*Festucaarundinacea*) from two contaminated soils. Caspian J. Environ. Sci. 2009;7 (2): 59-70.

[70] Yetneberk A, KassayeSalbu B, Skipperud L, Einset J. High tolerance of aluminum in the grass species *Cynodonaethiopicus*. *Acta Physiol. Plant*2013;35:1749-1761.

[71] Kumar A, Maiti AJ, Das, R. An assessment of metals in fly ash and their translocation and bioaccumulation in perennial grass growing at the reclaimed open cast mine. *Int. J. Environ. Res.* 2015;9 (3): 1089-1096.

[72] Mahmoud E, Ghoneim AM. Effect of polluted water on soil, sediments and plant contamination by heavy metals in El-Mahla El-Kobra, Egypt. *Solid Earth* 2016;34: 1-23.

[73] Bingzhong, Shi G, Yexu, Jinzhao H.U., Quinsong, XU. Physiological response of *Alternantherap hiloxeroides* (Mart) Griseb leaves to cadmium stress. *Environ. Pollut.* 2007;147(3): 800-803.

[74] Patel M, Nerkar B, Baghel PS, Pandey, B. Phytoremediation of chemicals by *Wedeliatrilobata, Tecomastans* and *Tageteserecta*. *Indian J. Sci. Res*. 2014;4(1): 165-169.

[75] Baker AJM. Brooks R R. Terrestrial higher plants which hyperaccumulate metallic elements- a review of their distribution, ecology and phytochemistry. *Biorecovery* 1989.1: 81-126.

[76] Hall JL. Cellular mechanism for heavy metal detoxification and tolerance. *J. Exp. Bot.* 2002;53(366): 1 – 11.

[77] Yadav R, Arora P, Kumar S, Chaudhury A. Perspectives for genetic engineering of poplars for enhanced phytoremediation abilities. *Ecotoxicol.* 2010. 19: 1574-1588.

[78] Kupper H, Zhao F, McGrath SP. Cellular compartmentation of zinc in leaves of the hyperaccumulator *Thlaspicaerulescens*. *Plant Physiol.* 1999; 119:305-311.