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ORIGINAL PAPER

Pteridophytes in phytoremediation

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Abstract Soil contamination by heavy metals and metalloids is a serious problem which needs to be addressed. There are several methods for removal of contaminants, but they are costly, while the method of phytoremediation is eco-friendly and cost-effective. Pteridophytes have been found to remediate heavy metal-contaminated soil. Pteridophytes are non-flowering plant that reproduces by spores. *Pteris vittata* has been reported as the first fern plant to hyperaccumulate arsenic. The *Pteris* species belongs to the order Pteridales. Other ferns that are known phytoremediators are, for example, *Nephrolepis cordifolia* and *Hypolepis muelleri* (identified as phytostabilisers of Cu, Pb, Zn and Ni); similarly *Pteris umbrosa* and *Pteris cretica* accumulate arsenic in leaves. So, pteridophytes have a number of species that accumulate contaminants. Many of them have been identified, while various other are being explored. The present review article describes the phytoremediation potential of pteridophytes plants and suggests as a potential asset for phytoremediation programs.

Keywords Fern · Heavy metal-contaminated soil · Economic return · Adaptive strategy

Introduction

Background

Environmental pollution has increased to levels that are harmful to all the living beings on this planet Earth. Various health issues have surfaced that were unknown till industrial revolution. Rampant use of resources and negligence for the same has led to various environmental issues such as global warming, heavy metal contamination in soil and water, loss of biodiversity, and increased health-related problems in humans. Although industries are important pillars in the development of society as it gives employment and also products for our use, the way the industrial effluents are released has led to the rise of environment pollution (Mandal and Suzuki 2002). In order to live in a clean environment without compromising comfort, methods of remediation should be promoted and phytoremediation is the one being cheap and eco-

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friendly. The major plant families involved in phytoremediation are from Pteridophyta and Brassicaceae (Prasad and Freitas 2003). Pteridophytes have emerged as a silent kingdom with potential to phytoremediate a number of contaminants, many of which are toxic and carcinogenic. This important feature of pteridophytes is being increasingly considered for clean-up of the hazardous waste from ecosystem. There are 450 varieties of hyperaccumulators for heavy metal, belonging to 45 families with most of them accumulating Nickel (Ni) (Gonzaga et al. 2006; Klopper 2011). The pteridophytes accumulate heavy metals, and most of them are accumulators of arsenic. Currently known ferns that hyperaccumulate arsenic are of the order Pteridales (Table 1), specifically *Pteris vittata* species and *Pityrogramma calomelanos*. *Pteris vittata* was the first plant found to hyperaccumulate arsenic. Other ferns that are known phytoremediators include *Nephrolepis cordifolia* and *Hypolepis muelleri* identified as phytostabilisers of copper (Cu), lead (Pb), zinc (Zn) and nickel (Ni); *Pteris umbrosa* and *Pteris cretica* accumulate arsenic in leaves. Similarly, *Dennstaedtia vallioides* phytostabilises copper (Cu) and zinc (Zn). *Polypodium cambricum* can phytostabilise Zn from soils in temperate regions. *Adiantum capillus veneris* accumulates arsenic in roots, while *Adiantum philippense* and *Adiantum caudatum* are phytoextractors of lead (Pb) and nickel (Ni). *Blechnum orientale* accumulates toxic metals and hazardous PAHs (Zhu et al. 2013). Thus, pteridophytes include species that have proven to be used in phytoremediation of contaminants. In fact it will not be wrong to say that pteridophytes are natural purifiers of contaminants and potential asset for phytoremediation. Thus, division pteridophyta is serving mankind in other ways, with its remediation potential and thus reminding its importance in ecosystem services.

Phytoremediation action

In simple words, phytoremediation is remediation of contaminants from soil, water and air through the plants. It is the name given to a set of technologies that uses plant to clean contaminated sites (EPA 2000). The term phytoremediation (*phyto* = plant and *remediation* = correct evil) was coined in 1991. The process seems to be quite simple, but it is a complex process where the contaminants go through oxidation and reduction to simpler forms and is either stored in vacuoles within plants or is volatilised in atmosphere. A complex metabolic pathway is involved with the involvement of antioxidants. Phytoremediation includes a variety of techniques for remediation of contaminants (Table 2). The plants that accumulate contaminants are classified in two ways (i.e. accumulators and hyperaccumulators). Accumulator plants

Table 1 List of plants from pteridophytes that accumulate arsenic

As hyperaccumulator	References	As hyperaccumulator	References
Pteris vittata	Ma et al. (2001)	*Pteris biaurita*	Srivastava et al. (2006)
	Chen et al. (2002a, b)	*Pteris quadriaurita*	
Cretan Brake	Wei et al. (2002)	*Pteris ryukyuensis*	
Pityrogramma calomelanos	Francesconi et al. (2002)	*Pteris multifida*	
	Visoottiviseth et al. (2002)	*Pteris oshimensis*	Wang et al. (2006))
Pteris cretica	Sridokchan et al. (2005)	*Pteris aspericaulis*	
Pteris longifolia		*Pteris cretica var. Nervosa*	
		Pteris fauriei	
Pteris umbrosa	Zhao et al. (2002)	*Pteris multifida*	
Pteris multifida	Du et al. (2005)	*Pteris multifida f. serrulata*	
Pteris cretica chilsii			
Pteris cretica crista			
Pteris cretica rowerii		*Pteris oshimensis*	Wang et al. (2007)
Pteris cretica mayii		*Pteris umbrosa*	Koller et al. (2007)
Pteris cretica parkerii	Meharg (2002)		

accumulate contaminants to a level that are not toxic to plants, while hyperaccumulators can accumulate more than 1000 mg/kg dry weight of the contaminants (Reeves 2003). The best example of hyperaccumulator is *Pteris vittata*; it accumulates arsenic up to 7500 mg/kg without any toxic effects (Ma et al. 2001).

In earlier works of phytoremediation, various plants were searched of which some were edible like of Brassicaceae family from which oil is extracted and is used widely in cooking (Riddell-Black et al. 1996; Punshon et al. 1996). Thus, the search was confined only to identify plants that can accumulate contaminants so that the rising problem of contamination can be controlled. Now, we have data of various plants which are edible and non-edible and accumulate contaminants. Thus, with the ample knowledge of the plants for phytoremediation, the ones that are consumed are avoided for the purpose and those that are not consumed are used. Plants that are not consumed and produce valuable end products, such as vetiver oil (perfume, medicine, etc.), are advocated for the purpose of phytoremediation as the end products in most of the cases are safe to use (Zheljazkov et al. 2006). These end products have good market value, so the cultivator can earn from their contaminated land and also side by side it will be remediated. The plants such as Pteris have its application in bouquets and also as ornamental plants. One can question that being an accumulator how its product can be safe? So, one need not worry about it because only those plants can be selected which have accumulated contaminants but have safe limit of accumulation in its product like in the case of vetiver where we obtain essential oil which is of great economic value and it has been observed that its oil does not have contamination (Pandey and Singh 2015; Pandey et al. 2015). Similarly, plants (such as *Miscanthus, Saccharum*) with good biomass have also their use for energy production (bioethanol, bioenergy, etc.) (Pandey et al. 2012, 2016; Meers et al. 2007; Witters et al. 2012). The increasing problem of contamination and pollution of environment has led to the use of methods that are effective and environment-friendly, and one such method, i.e. phytoremediation, has gained immense importance for contaminants remediation. This has also led scientists to search not only plants that accumulate contaminants but also the accumulator plants which have some valuable end product. The concept of using plants for both phytoremediation and economic returns (in terms of phytoproducts of economic value) can be better described with the term "phytomanagement" (Pandey and Bajpai 2019). This concept has revolutionised the phytoremediation method. Generally, phytoremediation is a time-consuming process and this is the only drawback that can also be managed with the concept of "phytomanagement". The term "Phytomanagement" is well described in detail by Pandey and Bajpai (2019). In addition, Pandey and Souza-Alonso (2019) also explored market opportunities in phytoremediation. The companies have successfully employed this concept of extraction of valuable end products from plants in phytoremediation. The essential oil-yielding aromatic plants such as *Vetiver*, *Cymbopogon* and

Table 2 Phytoremediation process and its characteristics. *Source*: Subhashini and Swamy (2013), Ali et al. (2013), Vamerali et al. (2010), Elekes (2014), Alkorta et al. (2004), USPA (2000, 2001), Dushenkov et al. (1995), Tangahu et al. (2011), Vangronsveld et al. (2009), Raskin and Ensley (2000), Kumar et al. (1995), Horne (2000), Mendez and Maier (2008)

Process	Definition	Goal	Selection criteria for plant species
Phytoextraction	Uptake of contaminants from root and translocation to shoots	Extraction of contaminant and its capture	Tolerance, high accumulation capability, rapid growth rate, easy to harvest, high translocation factor
Phytostabilisation	Reduction in mobility and bioavailability of pollutants	Containment of contaminants	Abundant root system, low translocation factor
Phytovolatilisation	Absorption of pollutants and its volatilisation to the atmosphere by foliar system	Containment, extraction and finally release to atmosphere	Tolerance, high translocation factor, rapid growth rate
Rhizofiltration	Plant roots adsorb or absorb contaminants surrounding the root zone	Containment, extraction and capture	Tolerance, high adsorption surface, low translocation factor

Lavandula can be employed in phytoremediation programs to utilise its oil in cosmetics or perfumery (Pandey et al. 2019). Moreover, energy crop-based phytoremediation is beneficial to generate biofuels (Pandey and Bajpai 2019). Thus, there are several types of plants such as energy plants, aromatic plants, fibre plants, ornamental plants, etc., and must exploit in phytoremediation programs to generate economic returns (Pandey and Bajpai 2019). Currently, such economically valuable plants are now being suggested to be used for phytoremediation so that both environmental cleaning and earning can be achieved. Thus, this new way of phytoremediation with economic returns will make it a more popular, significant, effective, sustainable, easily and widely acceptable method for remediation of contaminants from environment (Pandey and Souza-Alonso 2019). All over the world, thousand hectares of agricultural land have been contaminated with heavy metals. This type of contaminated agricultural land must remediate with the help of economically valuable plants to generate economic returns in terms of some valuable end products. The owners of agricultural land generally hesitate in applying phytoremediation, as during this period the land is left fallow and it incurs loss. But with the concept of commercial phytoremediation, this problem can be reduced. One way can be of growing essential oil-yielding aromatic plants in agricultural land for phytoremediation or intercropping of accumulator plants (*Vetiver, Phragmites*) along with crop. The method of growing crops with accumulators (*Pteris, Vetiver* and *Phragmites*) has been applied by Praveen et al. (2017, 2019), where they found reduction in uptake of arsenic in crop thus having safe grain. In addition, the accumulators such as Vetiver contain essential oil in their roots as economic return. Thus, phytoremediation can be made more effective and sustainable via phytomanagement.

Benefits and limiting factors in phytoremediation

Although phytoremediation is a very cost-effective and environment-friendly process, it has its own advantages and limitations (Table 3). However, some of its limitation such as long time can be mitigated with novel methods of plantation. Praveen et al. (2017) and several authors in their experiment have planted *Pteris vittata* along with crop plants to reduce uptake of contaminants in crop, thus delimiting one of the limitations of phytoremediation method. The other problem of disposal of biomass of accumulator can also be managed by using it for energy generation, successfully done in *Vetiver* (Rao et al. 2015, Wongwatanapaiboon et al. 2012a, b), *Miscanthus* (Hoogwijk et al. 2003), etc. or phytomining like the one done for nickel. The cost–benefit analysis of phytoremediation has been clearly explained by Wan et al. (2016) in his 2-year phytoremediation work, where he worked on remediation of As, Cd and Pb. They calculated that the costs of running this project can be recovered in less than seven years. So, there are always two sides, one counts and other regrets, but with some novel methods some of the regrets can be made to count in usefulness.

Pteridophytes and its role in phytoremediation

General introduction of Pteridophytes

Pteridophytes have a significant place in plant kingdom on the basis of its evolutionary development. These are considered the first true land plants. The origin of pteridophytes dates back to 400 million years. These are known as seedless vascular plants for the presence of vascular system and the absence of seeds. The pteridophytes reproduce through spores. The spores are formed at the margins of fronds (*Pteris, Adiantum*, *Nephrolepis,* etc.), in axils of leaf (Lycopodiophyta) or strobilus (Equisetum). The pteridophytes are homosporous as well as heterosporous. In homosporous, only one type of spore is produced, while in heterosporous forms two types of spores are produced (microspores and megaspores). Microspores are minute and numerous and form male gamete, while megaspores are large and few and form female gametophyte. The largest diversity of pteridophytes is in tropics (Kreft et al. 2010). There is a rich fossil record of pteridophytes, where they were long trees, but now there are only herbaceous plants with a few woody ones. The pteridophytes have alternation of generation with dominant sporophytic generation and a brief gametophytic generation, thus evolving to dominant diploid phase, whereas in bryophytes and algae the dominant phase is haploid.

Table 3 Benefits and limitation of phytoremediation. *Source*: Ghosh and Singh (2005), Moosavi and Seghatoleslami (2013), Ali et al. (2013), Elekes (2014), Paz-Ferreiro et al. (2014), Hegedus et al. (2009), Mudgal et al. (2010)

	Benefits	Limitations
1	Cost-effective	It is a lengthy process and takes a long time to clean
2	Environment-friendly	It is applicable to the length of roots and is limited to surface soils
3	Applicability to a wide range of toxic metals	Restricted to sites with low contaminant concentration
4	Aesthetic and pleasing	High contaminant concentration may be toxic to plants
5	Permanent treatment solution	Most of the hyperaccumulators are slow growers
6	Potential to treat sites contaminated with more than one pollutant	Climate and other factors are limiting
7	High skilled persons not required as one has to plant the accumulators recommended	Seasonally dependent
8	In situ application avoids excavation and transport	The problem of accumulated biomass disposal

Potential features of pteridophytes and its adaptive strategy in phytoremediation

Despite the division pteridophytes comprising of mainly herbaceous and shrubby plants and no consumables (as food) are obtained, it is considered the most important for its role in phytoremediation. Most of the arsenic and other heavy metal-accumulating plants belong to this division. The success of pteridophytes in phytoremediation can be linked to its features and adaptive strategies (Fig. 1), which are discussed under two headings as: (1) potential features and (2) adaptive strategies.

Potential features

The plants in pteridophytes have good biomass, require less time to grow, mostly perennials, no extra effort required to maintain and have phytoremediation potential. These are some of the properties which make pteridophytes special in remediation roles. Some of the properties are detailed as follows.

Biomass Biomass in plant means the weight of the whole plant (all parts). This is of significance in phytoremediation as plants with well biomass will remediate more contaminants from the site. *Pteris vittata* is a hyperaccumulator of arsenic (Ma et al. 2001); similarly some small aquatic pteridophytes

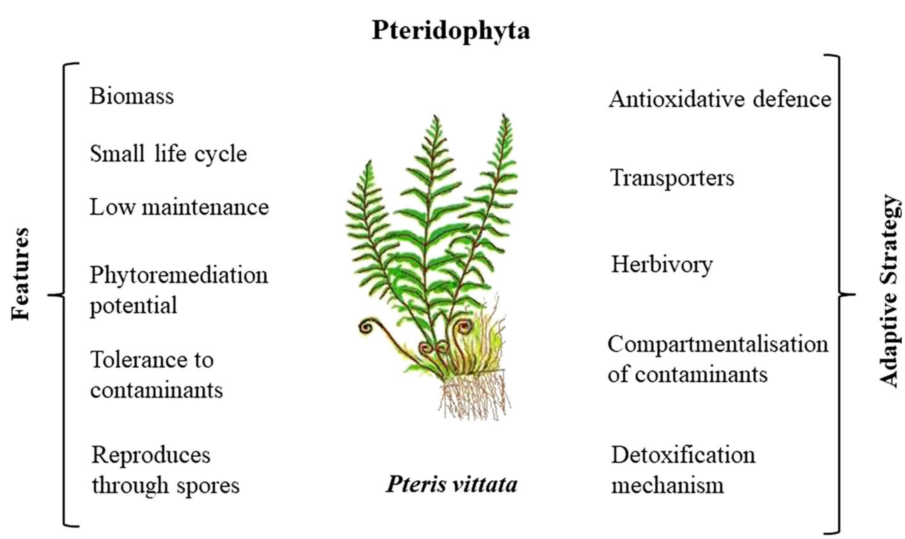

Fig. 1 Depicting the potential features of pteridophytes and its adaptive strategy in phytoremediation

(*Salvinia, Azolla*) are also known to accumulate heavy metals. *Salvinia* sp. accumulates copper better as compared to other weeds (Sukumaran 2013), and it also accumulates iron (Fe), copper (Cu), chromium (Cr), cadmium (Cd), lead (Pb) (Dhir et al. 2011). *Azolla caroliniana* accumulates chromium (960 mg/dm^3 approx.) and mercury (560 mg/dm^3 approx.), which is quite high and thus most efficient in remediating these heavy metal contaminants (Bennicilli et al. 2003). *A. filiculoides* accumulates Pb and zinc (Zn). The aquatic pteridophytes despite having less biomass as compared to the terrestrial pteridophytes are faster in multiplying and increasing its number making them comparable with the terrestrial plants. The aquatic pteridophytes multiply fast, thus there are more plants for accumulation.

Short life cycle The division pteridophytes are generally herbaceous or shrubby and perennial which is an important feature required for phytoremediation. The importance of short life cycle can be understood with the fact that after the harvest, a new plant can again be used for remediation. This is a benefit in phytoremediation as in the plants with long life cycles, the accumulation slows down as it grows old while every time a new plant is planted, then it will remove contaminants faster and also in less time.

Maintenance The plants in division pteridophytes grow easily and also do not require extra effort to grow. Maintenance is the fact of daily needs; even we human beings require it, animals, ornamental plants, insects, etc. Thus, a plant that grows on its own without any additional care and also it is cleaning the environment by accumulating it is a bonus. Thus, nature itself has found solution to the problem of rising pollutants in environment.

Phytoremediation potential Phytoremediation is the term used to define plants that uptake contaminants thus cleaning the environment. Plants in pteridophytes are known for phytoremediation of contaminants. This kingdom harbours many hyperaccumulators that remove contaminants faster. The pteridophytic plants perform all sorts of phytoremediation, viz. phytoextraction, phytostabilisation, phytoaccumulation and phytovolatilisation. Thus, pteridophytes have proved to be an important keystone in phytoremediation.

Adaptive strategies

Pteridophytes grow in the contaminated places and also accumulate contaminants, so how do they survive? The plants of this division have developed mechanisms to reduce the effects of toxicity due to contaminants with efficient antioxidative system, presence of transporters, sequestering the contaminants in vacuoles. All these adaptive mechanisms are discussed in separate headings as follows:

Antioxidative defence There are several enzymatic and non-enzymatic antioxidants that are produced in plants. These antioxidants are formed in plants at the basal level, but the formation increases with the oxidative stress to reduce the toxicity caused by accumulation of contaminants. The important antioxidants are SOD, CAT, APX, GPX that reduces the toxicity in plants; the mechanism has been discussed in detail in "Mechanism to reduce metal toxicity in plants" section.

Transporters The transporters are the paths through which the heavy metals are taken up and further accumulated in different parts of the plant. The various transporters have been identified that take up the contaminants based on the concentration of the contaminants like phosphate transporters that take up phosphate, but at high concentrations of arsenate (a phosphate analogue) these transporters take up arsenate. The uptake of contaminants through the transporters has been discussed in detail in "Transport and metabolism of contaminants in plants" section.

Herbivory Herbivory is defined as the defensive mechanism acquired in some plants to avoid grazing by herbivores. The pteridophytes by accumulating contaminants render it unsuitable for grazers thus preventing grazing by herbivores. This is advantageous also in terms of phytoremediation as the plant remains undisturbed and continuously performs the function of environment cleaning.

Plants in pteridophytes that accumulate heavy metals

The plants of pteridophytes are known to accumulate various environmental contaminants. A list (Table 4) of some plants in pteridophytes has been made that

Table 4 Some identified plants of the pteridophytes for phytoremediation of heavy metals and metalloids

Plants	Contaminants	References
Pityrogramma calomelanos	Arsenic	Francesconi et al. (2002)
Pteris vittata	Arsenic	Ma et al. (2001)
Salvinia natans	Boron, nickel, arsenic, copper	Holtra et al. (2010), Dhir (2009)
S. molesta	Copper, iron, lead	Preetha and Kaladevi (2014)
S. minima	Arsenic, nickel, lead, chromium, cadmium	Fuentes et al. (2014), Dhir (2009)
S. herzogii	Cadmium, chromium	Dhir (2009)
Asplenium australasicum	Arsenic	Draghiceanu et al. (2014), Kachenko et al. (2007)
A. bulbiferum	Arsenic	
Adiantum capillus veneris	Arsenic	
Pteris cretica	Arsenic	
Pteris umbrosa	Arsenic	
Dennstaedtia davallioides	Cadmium, copper	
Pellaea falcate	Cadmium, lead, nickel, chromium, zinc	
Nephrolepis cordifolia	Cadmium, chromium	
Blechnum cartilagineum	Nickel, zinc	
Azolla filiculoides	Lead, zinc, copper, cadmium, nickel	Ganji et al. (2005), Asbchin et al. (2012)
Adiantum philippense	Lead, nickel	Pongthornpruek et al. (2008)
Adiantum caudatum	Lead, nickel	
Hypolepis muelleri	Copper, lead, zinc, nickel	Kachenko et al. (2007)
Polypodiumcambricum	Zinc	Roccotiello et al. (2010)
Actiniopteris radiata	Selenium	Srivastava et al. (2005)

accumulates different contaminants. There are a number of plants in pteridophyta that accumulate contaminants and still various others are to be explored. From the various works and on-going researches, it has been established that pteridophytes through evolution or the extremities of environment have made itself to survive. The plants accumulate the contaminants and sequester it in vacuoles thus rendering it harmless to plants.

Transport and metabolism of contaminants in plant

The contaminant present in soil must be mobilised or made available to plants. The availability of metals to plant is made through several ways. The plants release exudates from root that attract micro-organisms, and the micro-organisms through the release of side-rophores stabilise the metals. In some cases, the addition of amendments to soil of nutrients such as N, P, K and Ca can either reduce or enhance the metal uptake by plants. Plants also release phytosiderophores that solubilise metals bound to soil. The metals are than taken up through roots. The entry of metals into roots is made through transporters, like in the case of arsenic the phosphate transporters take up arsenate (AsV), while the arsenite (AsIII) enters plant through the nodulin 26-like intrinsic proteins [NIPs (OsACR2:1 in rice and PsPvH in *Pteris vittata*)]. The mechanism and uptake of heavy metal contaminants, especially of arsenic (As), have been widely studied in pteridophytes. *Pteris vittata* a fern is a known hyperaccumulator of arsenic (Ma et al. 2001). Besides *Pteris vittata*, *P. Cretica*, *P. longifolia* and various others are known to accumulate arsenic (Table). The arsenic has two common forms, arsenate (AsV) and arsenite (AsIII). The AsV is a phosphate analogue, i.e. it resembles phosphate in structure, while AsIII has a similarity with silicon (Si) in size. The resemblance of AsV with phosphate enables its uptake through phosphate transporters in plants. This has a damaging effect in plant with damage to proteins and amino acids. The AsIII enters plant through silicon transporters and is absorbed by roots through the nodulin 26-like intrinsic proteins (NIPs) (Meharg and Jardine 2003; Ma et al. 2008). These belong to the aquaporins family of intrinsic proteins. In Pteris, the NIPs identified are PvPht 1:3 (Ma et al. 2008). The *Pteris vittata* which is a hyperaccumulator of arsenic has a high affinity for arsenate (AsV) than other non-hyperaccumulating plants (Wang et al. 2002).

Toxicity due to uptake in plant

The contaminants such as arsenic (As), mercury (Hg) and cadmium (Cd) are not essential to plants and cause toxic symptoms in plants which are mirrored in its growth, yield and development. Even though nitrogen (N), phosphorus (P) and potassium (K) are important nutrients for plants, but at high concentrations they have their negative impact on plants. Although metals are important, at higher concentration, these are toxic to plants and interfere in the metabolic process (Kumar et al. 2015). In general, the toxicity may lead to the death of plant, but in the case of accumulators/hyperaccumulators this does not happen. The contaminants are sequestered in vacuoles in roots or shoots of plant. There are also enhanced detoxification mechanism and chelating agents that sequester the contaminants and reduces the toxicity.

Mechanism to reduce metal toxicity in plants

The plants that grow in contaminated areas have developed mechanism for their survival. Some of the important mechanisms are discussed as follows.

Removal through senescence

Pteris vittata which is a hyperaccumulator of arsenic accumulates it in its shoot (fronds). It has been observed that as the fronds have accumulated arsenic to its capacity, it undergoes senescence and fall (Tu and Ma 2002).

Stabilising contaminants through binding

The contaminant enters the root and is bound by the polysaccharides in cell wall and hence remains there, also it binds to the carboxylic or aldehydic group of cellulose and thus in a way reduces its further transport to the cytoplasm (Nishizono et al. 1987).

Compartmentalisation of heavy metals

The heavy metals that surpass the two check points pass in to the cytoplasm. In the cytoplasm, it is bound to the organic acids, phytochelatins or metallothioneins and is sequestered into the vacuoles, thus inhibiting the toxicity nearby (Webb et al. 2003; Chen et al. 2002a, b).

Detoxification through antioxidants

The uptake of contaminants in plant causes the production of reactive oxygen species (ROS). However, the formation of ROS and its removal occur normally in plants but the formation of ROS increases with the stress and this causes imbalance in the removal mechanism resulting in cell death (Alscher and Hess 1993). The plants have mechanisms to reduce the stress through enzymatic and non-enzymatic antioxidants (Gratao et al. 2005). The enzymatic antioxidants are superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidise (APX), guaiacol peroxidase (GPX), while non-enzymatic antioxidants are glutathione (GSH, GSSG), phytochelatins (PC), Ascorbate, Carotenoids and Anthocyanins. The SOD acts as a first line of defence (Alscher et al. 2002) in quenching the superoxide ($O^{2\cdot-}$) and forms hydrogen peroxide (H_2O_2). The H_2O_2 formed is toxic, and it is reduced to water (H_2O) and oxygen (O_2) by CAT and APX, respectively (Asada 1992; Lin and Kao 2000). The enhanced activity of SOD and CAT in all the studied cultivars infers that the plant responded to stress in a positive manner by controlling the level of ROS and thus decreasing oxidative damage (Miller et al. 2008).

Action of micro-organisms

The part of the plant that first encounters contaminants are roots, and if at this rhizospheric zone contaminants can be degraded, it would be of great importance. There are microbes that in interaction with plant roots degrade the contaminants, and the method is known as rhizoremediation (Schwab and Banks 1994). Plant microbe interaction plays an important role in facilitating plant growth. The rhizoremediation of through the microbial interaction can raise the availability of compounds and will help the plants in extraction and removal of the compounds (Chaudhry et al. 2005).

There are bacteria that are capable of degrading some organic compounds (PCBs) in association with roots of plants (Saleh et al. 2004). Micro-organisms also facilitate metal uptake by plants (Zhuang et al. 2007: Glick 2010). Besides bacteria, fungi are also used in phytoremediation (Huang et al. 2004, Khan 2006). The use of micro-organisms in association with the root of plants to degrade the contaminants is known as rhizoremediation.

How pteridophytes evolved with the uptake of contaminants

Pteridophytes are ancient plants colonising the Earth 400 million years ago (Li et al. 1981). The long-time stay has an effect on evolution and selection which has worked in the plants in developing mechanisms that increased its survivorship under stress conditions. Maybe it could be a strategy against herbivory and pathogenicity as heavy metal-accumulating plants are seldom eaten by herbivores (Rathinasabapathi et al. 2007). There could also be another theory that plants that grew in contaminated sites took up the contaminants and compartmentalised it in shoots or root to reduce toxicity, and later on due to the presence of contaminants, the herbivores avoided it as feed. The *Pteris vittata* has a gene ACR3 that codes for the arsenous acid transfer protein. This gene is found in the membranes of vacuoles in *Pteris vittata*, while this gene is absent in angiosperms (Indriolo et al. 2010). So, the accumulation and compartmentalisation could have evolved to reduce the toxicity.

Commercial uses of pteridophytes

In the above discussions, we have talked about the phytoremediation potential of pteridophytes and strategies developed to mitigate the toxicity. However, in addition to phytoremediation, the plants of this division have also various uses in food, medicine, fertilizers, ornamental purposes, etc. (Thomas 1999; Baskaran et al. 2018). If we use pteridophytes for commercial phytoremediation, then these uses are subject to safety check. Nowadays, the plants in pteridophytes (*Pteris*, *Adiantum*, *Nephrolepis*, etc.) are extensively used for ornamental purposes (bouquets, marriages, home gardening, etc.) in metro cities (Fig. 2). This is very significant as the land under remediation is giving returns to the grower so they do not have to bother for money during remediation. Generally, this is also one of the drawbacks of phytoremediation as one has to wait for long duration until the contaminants are remediated and this incurs loss to the land owner. Use of plants that have accumulated contaminants will spread it to other areas, but with proper check of toxicity (i.e. safe limit as recommended by the WHO), these can be used. Therefore, pteridophytes have potential for phytoremediation with economic returns, and will help in solving the economic problem faced by land owner/ practitioners during the remediation of contaminated areas.

Conclusion

The contamination of heavy metals in soil and water is of major concern, and efforts are needed to remediate it as these have a direct impact on human health and livestock. There is a dire need for a successful and cost-effective method to remove the contaminants from soil and water. Various plants have been identified that accumulate heavy metals, and most of them belong to pteridophytes and Brassicaceae family of Angiosperms. Compared to Brassicaceae where most of the plants are of economic importance and edible, pteridophytes are non-edible and thus suitable for phytoremediation. The innate ability of pteridophytes to accumulate metals is a boon to the environment and mankind. The antioxidative defence in the pteridophytes also has an impact in reducing the reactive oxygen species and maintaining equilibrium which finally has an impact on plant health. The most notable character of pteridophytes is that these are herbaceous and require less time to grow. In addition, most of the identified accumulators are not edible for both humans and the livestock, thus are suitable in phytoremediation. Various works have been done to increase the accumulating capabilities of plants through genetic engineering and also through organic amendments, but in spite of these the problem still remains unsolved. The best way to reduce the problem will be to identify more plants for the purpose and also limiting the release of contaminants in soil and water.

Fig. 2 Ornamental use of Pteridophytic plants (bouquet, marriage decoration, etc.)

Future prospects

Phytoremediation is a cost-effective, eco-friendly and sustainable approach, but it takes a long time to remediate. So, plants should be identified that are fast growing and have good root and shoot biomass. In addition to identification, plants could also be engineered to increase their capability of accumulating heavy metal contaminants and also the plant microbe interaction should further be explored in pteridophytes. Further the problem of biomass disposal needs to be addressed properly as this is the only question that remains for critics. The problem has been addressed in the sections of this review, and still works are in progress to solve it.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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