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Arsenic hyperaccumulating fern: Implications for remediation of arsenic contaminated soils

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ABSTRACT

The ability of hyperaccumulating plants to tolerate, translocate and accumulate very high concentrations of toxic contaminants makes them suitable candidates for phytoremediation of contaminated soils and water. Though there are several arsenic tolerant plants, Chinese brake fern (*Pteris vittata* L.) is the first arsenic hyper-accumulator and the most widely studied. A lot of work has been done to understand the detoxification mechanisms of arsenic hyperaccumulation in this fern. It has been suggested that vacuolar sequestration of arsenite in the fronds may be responsible for the high tolerance of *P. vittata* to arsenic. Studies on phytoextraction and rhizofiltration of arsenic contaminated soils and groundwater have been very successful in reducing contaminant levels. Numerous studies have shown that arsenic uptake by *P. vittata* depends majorly on soil and plant factors. Soil properties like soil arsenic concentrations, bioavailability of arsenic, partitioning of soil arsenic, redox potential, phosphate concentration and presence of co-contaminants may limit or enhance arsenic uptake by *P. vittata*. Plant characteristics like plant age, nutrition, root exudation and biological associations also influence greatly arsenic accumulation by *P. vittata*. An integration of these factors can be used to increase the efficiency of As hyperaccumulators in phytoremediation of arsenic contaminated soils and groundwater. Phytoremediation of arsenic contaminated soils is best in soils with low Fe/Al oxides, low redox potential, and low available P though addition of phosphates increases arsenic extraction.

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1. Introduction

Hyper-accumulating plants are plants that are able to accumulate metals above standard levels in their aboveground biomass while growing or thriving in contaminated soils (Kabata-Pendias and Pendias, 2001). Earlier studies have reported discoveries of hyperaccumulators for nickel (Ni), copper (Cu), cobalt (Co), zinc (Zn), selenium (Se) and lead (Pb) (Harris and Oparka, 1994; Salt and Kramer, 2000). Though, Chinese brake fern (*Pteris vittata*, Linnaeus, L.) is not the first arsenic (As) tolerant plant, it's the first As hyperaccumulator discovered (Komar et al., 1998; Ma et al., 2001). Since then, several studies have reported the discovery of other As hyperaccumulators (Francesconi et al., 2002; Luongo and Ma, 2005; Srivastava et al., 2006). Extensive research has been carried out to understand the mechanisms behind the high tolerance of these hyperaccumulating plants to As. Arsenic is toxic, hence, the ability of a plant to survive and thrive in a soil contaminated with arsenic shows remarkable tolerance.

Despite its toxicity, As is ubiquitous in the environment with origins from both anthropogenic and geogenic sources (Kumar et al., 2015). Arsenic contaminated soil and groundwater has been reported in several countries worldwide (Smedley and Kinniburgh, 2002; Singh et al., 2015). About 10% of the groundwater analyzed in the United States had As concentrations exceeding the maximum contaminant limit (MCL) of 10 μg L^{-1} showing low As exposure in the region (Welch et al., 2000). High As concentrations in groundwater from natural origin in the United States are due to volcanic activities, while human activities such as mining and smelting of ores containing As can also lead to contamination (Camacho et al., 2011).

The most severe As contamination was reported in Bangladesh more than a decade ago with 84% of groundwater having As concentration above 10 μg L^{-1}, which put 75 million people at risk (Safiuddin and Karim, 2001). Natural sources such as arsenic rich sulfide minerals are responsible for the contamination in Bangladesh. Two mechanisms proposed for mobilization of As into groundwater in Bangladesh are arsenopyrite oxidation and hydroxide reduction processes (Safiuddin et al., 2011). In Bolivia, 90% of wells sampled had As concentrations greater than the regulatory limit of 10 μg L^{-1} showing severe exposure of the general public to As (Muñoz et al., 2016).

The use of contaminated groundwater to irrigate farmlands in the affected areas has led to contamination of farmland soils. Other agricultural activities such as applications of agrochemicals have also resulted in soil contamination. Disposal of waste generated during mining processes have also contributed to elevated As concentrations in the soil. As concentrations above regulatory limit have been reported in soils close to wood treated with chromate copper arsenate (CCA), golf course soils treated with herbicides, cattle dip vat soil where animals were treated with pesticides and mining soils (Fayiga and Ma, 2005a).

Arsenic is a known carcinogen which can cause cancer, a deadly health problem. The remediation of As contaminated water and soil is the most effective option to reduce the health effects of As (Singh et al., 2015). Remediation techniques for As contaminated soils can be classified into physical, chemical and biological methods. Physical methods include soil excavation/replacement and thermal desorption; chemical methods include chemical leaching/washing, chemical fixation/stabilization, electrokinetics and vitrification; while biological methods include phytoremediation and bioremediation (Yao et al., 2012). Though there are many technologies for remediation of arsenic contaminated soils and groundwater, most are impracticable in the field due to financial implications. The physical methods tend to be disruptive to the ecosystem while the chemical methods may adversely affect soil fertility due to removal of basic cations.

Phytoremediation, a cost effective and environmental friendly option, makes use of plants in the remediation of contaminated soils and water. Arsenic hyperaccumulating plants such as *Pteris vittata* L. are good candidates for phytoremediation because of their ability to translocate and bioaccumulate As in their above ground biomass. *P. vittata* is the most widely studied arsenic hyperaccumulator reported in literature probably because it's been found in several countries. Numerous studies conducted on *P. vittata* have helped to understand the factors that can enhance As uptake and increase its efficiency to remediate contaminated soils and water. There have been several reviews on *P. vittata* but they have all focused on the detoxification mechanisms while little has been mentioned about its practical use in remediation of arsenic contaminated soils and groundwater.

This paper is a review of already published literature which summarizes the extensive research on *P. vittata* since its discovery, discusses its potential use in phytoremediation of arsenic contaminated soils and identifies areas that need to be further studied. The goal of this paper is to discuss the implications of arsenic hyperaccumulating plants for remediation of arsenic contaminated soils, present the successes and challenges faced with phytoremediation of arsenic contaminated soils and groundwater, identify factors which strongly influence phytoremediation by *P. vittata* and compare the efficiency of *P. vittata* with other hyperaccumulators.

2. Speciation, sources and effects of arsenic

The speciation of arsenic is very important because it determines its mobility in the soil and translocation within the plant. Speciation of arsenic is dependent on source of arsenic and environmental conditions such as redox potential, aeration of the soil, moisture content, and time. Speciation and sources of arsenic also determine the effects it has on the environment and public health. Most of the uses of arsenic are based on its toxicity and potential to kill living organisms. On the other hand, the toxicity of arsenic is what makes it a public health concern and the subject of several investigations.

Arsenic is a metalloid in group V of the periodic table of elements that exists in several forms and oxidation states (Table 1). Arsenic can be found in both inorganic and organic compounds. In the inorganic forms, it exists as arsenate (As V), the stable oxidation state in aerobic conditions while it exists as arsenite (As III) in anaerobic conditions. Arsenite is more toxic than As (V) and is one of the most toxic arsenic compounds. Methanogenic bacteria converts As from the inorganic forms to the organic forms by reducing As (V) to As (III) and methylating it either to monomethylarsonic acid (MMA) or dimethylarsinic acid (DMA) (Smith et al., 1998). This conversion is believed to reduce the toxicity of As because the inorganic forms are more toxic than the organic forms. However, recently, it has been reported that organic forms of As with oxidation number 3 are more toxic than the inorganic forms (Cullen, 2014).

Table 1
Speciation of arsenic.[a]

Name	Type	Chemical formula
Arsenite As (III)	Inorganic	$H_2AsO_3^-$, $HAsO_3^{2-}$, AsO_3^{3-}
Arsenate As (V)	Inorganic	$H_2AsO_4^-$, $HAsO_4^{2-}$, AsO_4^{3-}
Monomethylarsonic acid (MMA)	Organic	$CH_3AsO(OH)_2$
Dimethylarsinic acid (DMA)	Organic	$(CH_3)_2AsO(OH)$

[a] Smith et al. (1998).