# Evaluation of the possibility of phytoremediation (using Salix) as a management tool for abandoned sites moderately contaminated with arsenic

– a literature review

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## ABSTRACT

The presence of arsenic in soil and water has become an increasing problem in many countries around the world. The exposure of high concentration of arsenic in its inorganic form in natural environment such as soil and water makes it harmful to both humans, wildlife and plants.

This study considered the possibility of phytoremediation as a management tool for abandoned sites moderately contaminated with arsenic with the aim of reducing its spread and eventual leaching of the contaminant into the groundwater. Focus was placed on Salix tree crops with phytoremediation abilities in relation to arsenic contamination in Sweden. These sites are termed abandoned because they are of less priority for public funding for remediation and total cleanup.

Using a theoretical framework, this study was carried out by searching, screening and reviewing of scientific publications of previous studies and reports. An economic benefit calculation was done using surveys carried out on few Salix plantations in Sweden, where the farmers were asked about the cost of production and how much revenue was generated from the sale of the harvested biomass for energy purposes.

The results showed that Salix has the potential to effectively phytostabilize arsenic in Sweden as the tree crop is known to preferably/actively accumulate arsenic in its roots and belowground biomass which is a key feature of Phytostabilization. In addition to its Phytostabilization capabilities, Salix has a good biomass production ability, producing woody biomass at a range of 7 – 10 tonnes of dry matter/ha/year regardless of the soil condition or quality as Salix has a good physiological adaptation mechanism and ecological resilience which helps them thrive in various climate zones and site conditions coupled with their rapid woody biomass production ability as a short rotation coppice. The economic benefit calculations revealed that private remediation firms can invest in the remediation of these abandoned sites and still generate revenue of as much as 8,000 – 10,000 SEK/ha/year and make a reasonable profit of up to 57% through the sale of the harvested woody biomass to energy producing plants. These woody biomass has little or no arsenic accumulated in them because the accumulation of arsenic is in the root of the Salix tree, thereby meeting the quality requirement for energy production

From the survey used for calculating potential profit generated from the cultivation of Salix, the Salix plantations studied were cultivated on agricultural soils with good soil quality. Therefore they produced woody biomass with an average of 9 tonnes of dry matter/ha/year. Nevertheless, it was feasible to relate the cultivation of Salix and biomass yield produced by Salix on an agricultural soil to those cultivated on brown fields or soils with poor quality as the findings in this study showed that the quality or condition of soils does not significantly affect the biomass production and yield of Salix tree crops.

*Keywords:*

*Phytostabilization, Leaching, solubility and mobility, economic benefits.*

## POPULAR SCIENCE SUMMARY

Arsenic contamination of soil and groundwater has become an increasing problem in many countries of the world because of its harmfulness to humans, plants and wildlife when ingested through drinking water or food consumption. To reduce the risk associated with arsenic contamination, certain guideline values have been set in reference to the land use, which in Sweden can be either sensitive or non-sensitive land use. For a sensitive land use such as farming, the guideline value for arsenic concentration is set at a concentration of 10 mg/kg and for non-sensitive land use such as recreation purposes, the concentration of arsenic can be as high as 25 mg/kg without further actions needed to be taken.

In Sweden, a good number of sites is said to be contaminated with arsenic and these sites needs to be cleaned up to prevent direct or indirect effects on human health since the risk for the contaminant leaching to the groundwater increases as long as the contaminant is left in the soil.

Due to certain reasons, some of these arsenic-contaminated lands are not remediated and are abandoned because they are of less priority for public funding for a total cleanup. Some of these sites can be moderately contaminated in comparison to others with high contaminant concentration. Even if these sites are being moderately contaminated, there might still the risk of arsenic leaching into the groundwater.

In the light of this, this study looks into how these abandoned sites can be managed to prevent the contaminants from contaminating the groundwater through its spread and leaching. This study evaluated the possibility of using phytoremediation as a management tool, which involves the use of plants as annuals, perennials, cash crops or trees to take up contaminants from the soil, or immobilize them, thereby reducing the risk of contaminant spreading and leaching into the groundwater. In addition to this, this study also evaluated the possibility of making profit from this cleanup process, by considering tree crops with phytoremediation abilities for cleanup as harvestable woody parts of the tree crop can be sold to energy producing plants so that they can be burned into energy.

The result of the study showed that;

- Salix trees can be used as the phytoremediation tree crop for arsenic contaminated sites in Sweden as the tree species has the ability to take up arsenic and accumulate it in its root and also thrive well in regions with harsh climatic conditions such as Sweden.
- Salix trees have the ability to produce a good amount of harvestable woody parts which are not affected by the soil quality or condition. With a life cycle of 25 years, the Salix tree can be harvested down to the shoot in a 4 - 6 year harvest cycle without a need for replanting.
- The harvestable woody parts can give a yield of up to 7 – 10 tonnes of dry matter/ha/year and according to certain studies, this is enough to generate a profitable revenue.
- An average of 8,000 – 10,000 SEK/ha/year can be generated from the sales of the harvested woody biomass and when compared to the cost of production, there is a potential of making up to 57% in profits.

With the above findings, private individuals/firms can be encouraged to invest in the remediation of these moderately contaminated sites using phytoremediation and can be sure of making a substantial profit in the process.

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# 1. INTRODUCTION

The presence of arsenic (As) in soil and water has become an increasing problem in many countries around the world. Exposure to sufficiently high concentrations of arsenic in its inorganic form in natural environments such as water, sediments and soils has proven to be very harmful to organisms. The main pathway of arsenic exposure to organisms, especially humans, includes the ingestion of drinking water and food consumption. Arsenic is a contaminant that is toxic to a broad range of organisms (Bhattacharya et al., 2007). It belongs to the top class of human carcinogenic substances (Ravi Naidu, 2006). Unlike organic contaminants, As cannot be decomposed chemically or biologically (Bisone et al., 2016). Fine-textured soils often contain higher concentration of potentially toxic elements than coarse-textured soils due to the higher clay content in the former, thereby making them have more binding sites (Collins, 2013). However in recent studies carried out in Australia, it was revealed that even in strongly sorbing soils such as Oxisols, the mobility of As may be increased under certain soil and environmental conditions.

Different factors that increase the release of As into the soil solution also increase the potential for As leaching from the soil. Soil properties such as pH, CEC, the nature of clay, organic matter and soil solution composition influence the As retention capacity of soils (Naidu et al 2006).

Although arsenic occurs naturally in the soil, human activities also lead to the deposition of As due to pesticides use, mining and ore processing operations, operation of coal-burning power plants, wood treatment and preservation, and waste treatment. This has led to extensive contamination of soils throughout the world (Naidu et al., 2006). The concentration of As in a non-contaminated soil is usually in the range of 5 to 10 mg/kg of soil and when the concentration exceeds this range, the soil is said to be As-contaminated. (Smith et al., 1998). In Sweden, the guideline value for a soil to be considered As-contaminated is between 10 mg/kg and 25 mg/kg of soil depending on the land use. The health limit of As in drinking water is set to 10 µg/L by the World Health Organization due to its toxicity (Bhattacharya et al., 2010, WHO Edition, 2008).

There are several methods of removing arsenic from the soil or to reduce the concentration and spread of arsenic. These methods can either be physical, chemical or biological. Each of these methods have their advantages and disadvantages. Some of these methods are: washing with sulfuric acid, nitric acid, phosphoric acid and hydrogen bromide, immobilization of soluble arsenic using cements, soil flushing using aqueous solutions such as surfactants and co-solvents, stabilization using nanosized oxides and Fe(0) (particle size of 1 to 100 nm), immobilization of As in the solid phase through microbial oxidation, reduction of arsenic using phytoremediation (Lim et al., 2014).

Phytoremediation consists of the use of plants and associated microorganisms to remove, contain, inactivate or degrade harmful environmental contaminants in order to revitalize contaminated sites. The performance of phytoremediation as an environmental remediation technology depends on several factors including: the availability and accessibility of contaminants for rhizosphere microorganisms and uptake into roots and also the ability of the plant and its associated microorganisms to intercept, absorb, accumulate and/or degrade the contaminants (Vangronsveld et al., 2009). As an emerging technology, phytoremediation requires the use of specific and efficient plants to clean up contaminated sites (Lasat, 2000). Remediation in general, whether in-situ or ex-situ, has the goal of either removing the contaminants from the contaminated site (site decomposition or clean-up techniques) or reducing the risk posed by the contaminants by reducing exposure (site stabilization techniques) (Vangronsveld et al 2009).

### 1.1. Aim of the study

The aim of this study is to;

1. Evaluate (by reviewing previous research on the phytoremediation of arsenic using tree crops) if it is possible to use phytoremediation as a management tool in the remediation of abandoned sites contaminated with arsenic in order to reduce its spread in the soil and eventual leaching to the groundwater.
2. Carry out economic benefit calculations to see how profitable the whole process will be if the remediation process is done with an intention of profit making.

The focus is on abandoned contaminated sites because they are of less priority for public funding for a total clean up.

## 2. LITERATURE REVIEW

### 2.1. Arsenic contamination in Sweden

One of the main quality objectives of the Swedish environmental protection agency is to have a non-toxic environment with a high concern on remediation of contaminated sites (Swedish EPA 2019). When remediating contaminated sites, a high priority is given to sites posing high risks to human health and the environment (Forslund et al., 2010). The focus on a limited number of high-priority sites will cause other sites to be abandoned. Although the abandoned sites may currently have a low effect on human health, concerns are that they could affect the wildlife and have long-lasting effects due to the spread and release of arsenic into the biosphere.

An average of 85,000 sites in Sweden are contaminated and over a thousand of these sites have been classified as sites with very high risk to human health and the environment (Swedish_EPA, 2019). Of the contaminated sites with very high risk, about 30% are contaminated with metals (Forslund and Barregård, 2008). Of these sites, 26% were contaminated with As and it appears that As is the most common primary metal contaminat. Most arsenic emissions into the Swedish soils are from the use of wood impregnating substance/chemicals, which are used to preserve wood and to improve its characteristics (Forslund et al., 2010).

### 2.2. Remediation of arsenic contaminated sites

Removal of As from contaminated sites is necessary to reduce its toxic effects on humans and the environment (Pandey et al., 2018). Soils contaminated with As can be remediated using different approaches and methods. These approaches can be physical, chemical or biological (Wang and Mulligan, 2006).

Forslund et al. (2010) carried out an assessment on a few contaminated sites in Sweden with As contamination giving records of the concentration of As before and after remediation procedures had taken place. The concentration of arsenic on the sites before the remediation action was taken from site-specification investigation reports and from consultants involved in the remediation of these sites. The concentration of arsenic on the sites after the remediation has been completed was taken from the Swedish EPA quarterly report of quarter 4 of 2007 (Swedish EPA 2007; Forslund et al 2010). All site where the remediation is finalized have As concentration below 25 mg/kg (Table 1) which is in agreement with the guideline value for non-sensitive land-use with concentration less than 25 mg/kg for the site to be termed uncontaminated. These sites went through different forms of remediation which were not documented.

Table 1: Site-specific characteristics of selected sites in Sweden contaminated with arsenic, from Forslund et al. (2010)

| | Arsenic concentration (mg/kg) | | No. of exposed individuals | Accessibility | Land-use (non-sensitive) |
|---|---|---|---|---|---|
| | Pre | Post | | | |
| Akterspegeln | 163 | 15 | 100-1000 | Open | Recreation |
| Robertsfors | 250 | 15 | 10-100 | Enclosed | Recreation |
| Burträskbygden | 260 | 40 | 1-10 | Open | Industry |
| Tvärån | 608 | 17 | 10-100 | Open | Industry |
| Svartbyn | 80 | 15 | 1-10 | Open | Housing |
| Sjösa | 30 | 6 | 10-100 | Enclosed | Industry |
| Lyshälla | 170 | 15 | 1-10 | Open | Housing |
| Mjölby | 46 | 40 | 1-10 | Enclosed | Industry |
| Rimforsa | 49 | 15 | 1-10 | Open | Industry |
| Hjulsbro | 87 | 15 | 10-100 | Open | Recreation |
| Glasbrukstomten | 102 | 20 | 100-1000 | Open | Industry |
| Grimstorp | 424 | 10 | 1-10 | Open | Industry |
| Elnaryd | 130 | 40 | 1-10 | Enclosed | Industry |
| Högsby-Ruda | 55 | 5 | 10-100 | Open | Housing |
| Tröingeberg | 23 | 15 | 10-100 | Open | Housing |
| Oxhultc | 94 | 15 | 1-10 | Open | Housing |
| Gudarp | 119 | 80 | 10-100 | Enclosed | Recreation |
| Konsterud | 119 | 15 | 10-100 | Open | Housing |
| Kramfors | 500 | 15 | 1-10 | Open | Industry |
| Svanö | 418 | 100 | 10-100 | Open | Recreation |
| Svartvik | 150 | 40 | 1-10 | Open | Recreation |
| Forsmo | 1128 | 10 | 1-10 | Enclosed | Recreation |
| Fagervik | 65 | 40 | 10-100 | Open | Recreation |

Pre: Arsenic concentration (mg/kg) before remediation actions are carried out.

Post: Arsenic concentration (mg/kg) after remediation activities are finalized

### 2.3. **Phytoremediation approach**

From Figure 1, we see that the main biological method for remediation is the phytoremediation process. Phytoremediation can take place in the form of extraction, stabilization and volatilization. These procedures are usually carried out in-situ. Phytostabilization involves the cultivation of plants on contaminated soils with the aim of reducing the mobility or spread of the contaminant through accumulation by the plant root or immobilization of the contaminant by the rhizosphere (Bolan et al., 2011). Phytoextraction is the most commonly used phytoremediation technique and it involves the use of plant-hyper accumulators for the absorption of contaminants mostly heavy metals from the soil. These contaminants are accumulated in the harvestable biomass of the plants such as the shoot and/or leaves (Pajevic et al 2016). Phytovolatilization is a process in which plants take up contaminants from the soil and release them as volatile forms into the atmosphere through transpiration (Biotechnology, 2011)

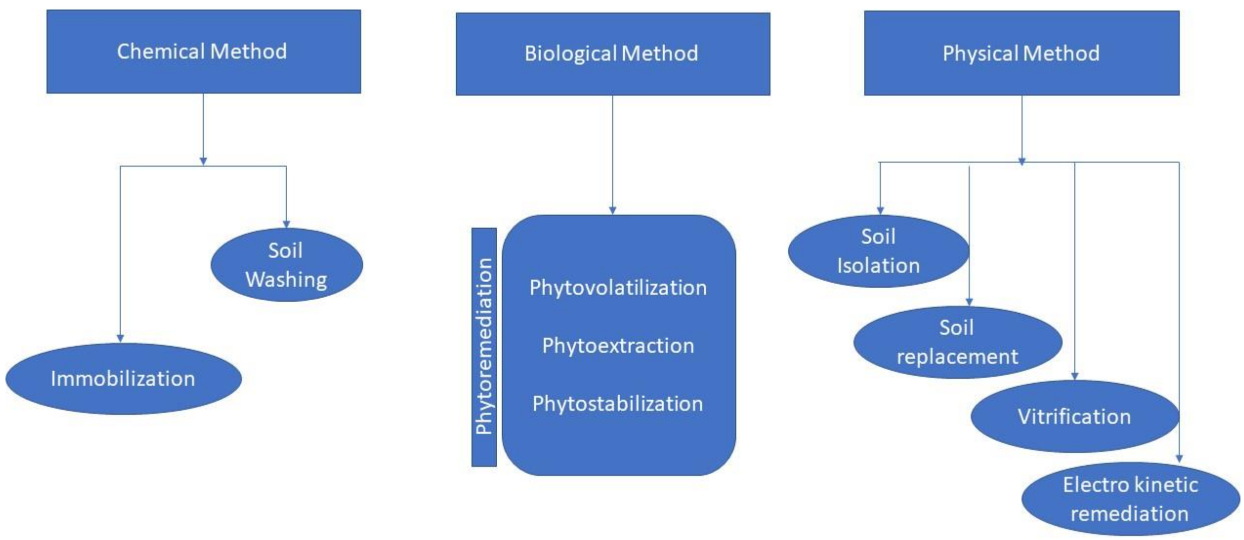


Figure 1: Comparison of different soil clean-up methods (Khalid et al., 2017), permission to reproduce image obtained from RightsLink copyright clearance center, Aug. 11, 2020, order number: 4885930074215.

For the successful implementation of phytoremediation, the main prerequisite is to identify native plants that are able to take up, extract or degrade hazardous contaminants from the soil/environment (Pajević et al., 2016).

## 2.4. Plant for phytoremediation

Plants have been able to evolve with effective strategies and mechanisms to survive environments that have highly contaminated sites (Gawronski and Gawronska, 2007). The interaction between soils, contaminants, microbes and plants has an important role to play in the use of plants for remediation (Lasat, 2000). Plants can survive environments with concentrations of contaminants that are hardly tolerated by humans. For contaminants such as metals, plants overcome their toxicity in various ways such as detoxification or degradation of contaminant, ability to store this contaminant or toxic metals in specialized cells or cell compartments and also exclusion (Gawronski and Gawronska, 2007). Plants that exhibit these survival mechanisms are referred to as hyper-accumulators (Vatamaniuk et al., 2001). One of the reasons why these plants can detoxify or carry out detoxification of heavy metals is due to the presence of phytochelatins in the plant (Vatamaniuk et al., 2000). The phytochelatin is produced by the enzyme called phytochelatin synthase (Gawronski and Gawronska, 2007, Vatamaniuk et al., 2001).

Hyperaccumulator plants are plants that are capable of accumulating metals in quantities greater than the ones non-accumulator plants would take up (Lasat, 2000). Hyperaccumulators mostly belong to the botanic families of the *Brassicaceae, Poaceae, Papilionaceae, Caryophyllaceae* and *Asteraceae*. These families provide most of the plants that can remediate heavy metals (Gawronski and Gawronska, 2007). Some plants that belong to the family of *Salicaceae* can also be used in the phytoremediation of heavy metals due to their effectiveness against a range of pollutants (Marmiroli et al., 2011).

The use of tree crops for phytoremediation is favored over other plant species due to their long term growth and high biomass of tissue that helps with the accumulation of much more contaminants in the plant parts (Marmiroli et al., 2011) coupled with their economic value (Gansauer, 2012). Trees have strong tendencies of growing and thriving in areas with not so good soil quality for other plants due to their large, microbially diverse rhizosphere. Thereby they are of great help for the ecological restoration of contaminated areas (Gansauer, 2012). Trees such as willows (*Salix*), mulberry (*Morus*), eucalyptus and poplar trees have been used for phytoremediation to stabilize, volatilize, extract and degrade chemical contaminants in the soil. Among all the tree species used for phytoremediation, the Salicaceae have the capability of manifesting fast growth with a deep root possibility which is a positive trait for phytoremediation (ITRC, 2009).

## 2.5. Arsenic accumulation in plants

Arsenic is considered a non-essential element for plants, animals and microbes. The uptake of arsenic by different plant species depends on the total concentration of arsenic and its speciation in the soil (Abbas et al., 2018). Arsenic enters the plant in an inorganic form as either arsenite or arsenate through proteins that work as transporters. The uptake is usually controlled by the As gradient between growth media and plant cells (Lundh et al., 2010, Gulz et al., 2005, Bergqvist, 2011, Bergqvist, 2013, Bergqvist and Greger, 2012).

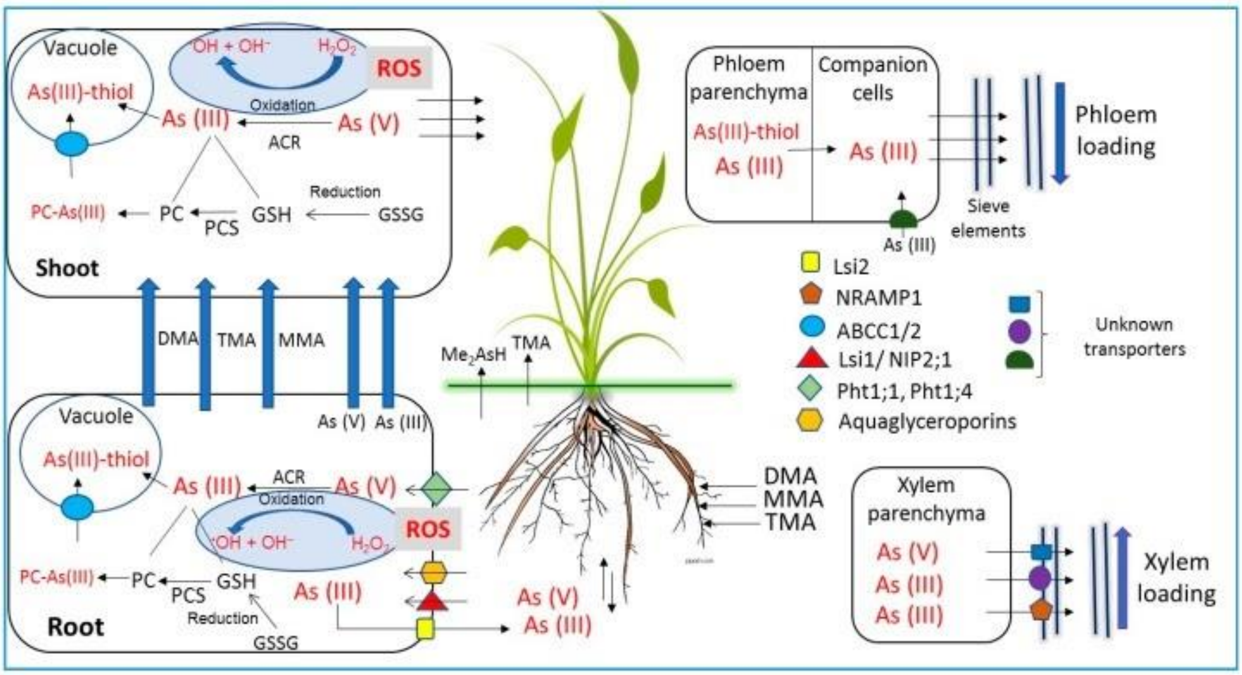


Figure 2: The different components involved in As uptake, transportation and detoxification in the plant. (Abbas et al., 2018). Right to reuse under open access creative common CC by license (https://www.mdpi.com/openaccess).

The main driving force for the uptake of the two species of arsenic (arsenite and arsenate) is a concentration gradient between the source and the sink. Arsenate uses various P-channels to enter into the plant cell due to its similar chemical characteristics with P, while arsenite enters the plant cell using various protein channels. The movement of arsenite is bi-directional resulting to a to and fro movement between the plant cell and the growth medium (Abbas et al., 2018).

Taking up arsenic could have a dangerous biochemical effect on the plant at the subcellular level which is the production of the reactive oxygen species (ROS). These ROS are dangerous to the plants metabolism as they can cause irreversible damages to important macromolecules such as lipids, proteins, carbohydrates and DNA (Abbas et al 2018).

The composition of the soil has a strong influence on the availability of arsenic for plant uptake. Factors such as pH, redox potential influencing the availability, solubility and mobility of arsenic in the soil are important (Masscheleyn et al 1991). When the soil contains a higher amount of other elements like iron, calcium and aluminum, the availability of As is usually very low as arsenic may be sorbed to compounds that these elements form (Bergqvist, 2013). There is a growing interest in the use of phosphate fertilizers to aid the uptake of arsenic by plant (Tu and Ma, 2003). Accumulation of arsenic in terrestrial and emergent plants generally occurs via the roots and on very few occasions via the shoot in areas with atmospheric deposition of As (De Temmerman et al., 2012).

For most terrestrial and emergent plants, arsenic is usually accumulated in the root (Di Lonardo et al., 2011), but can be higher in the shoot for some species that has the ability to hyperaccumulate (Smith et al., 2008). For an arsenic hyperaccumulating plant, the concentration of arsenic in the plant biomass can exceed 1 g/kg (Branquinho et al., 2007).

## 2.6. **Salix for phytoremediation and biomass for energy.**

Sweden is a country with temperate climate and the choice of plants to be used for remediation is streamlined to plants that can only thrive in cold regions. Most phytoremediation with tree crops carried out in the past has been done with use of the Salix species and this is because of its ability to thrive across Sweden. The Salix species are known to have good physiological adaptation mechanism and ecological resilience, which help them thrive in various climate zone and also at adverse micro sites (Wani et al., 2011). In addition, Salix species also have a rapid production ability of shoots and roots making them suitable for both phytoextraction and phytostabilization (Meers et al., 2007). The Salix is a genus of about 500 species distributed mainly in the northern parts of America, Europe and mountains of China and peculiar to these regions is their cold climate (Argus, 1986). The growth habit of Salix varies from species with height of about 20 m to those with height of about 6 m which are usually referred to as shrubs (Argus 1965).

Salix has been cultivated on approximately 10,500 ha of land across Sweden (Jordbruksverket, 2017) and is also known as a short rotation coppice (SRC). As a short rotation coppice, it is an energy crop that is densely planted for high yielding biomass used for renewable energy (Commission, 2006) and the renewable energy can be used to replace fossil fuels (WMO 2016). Salix are planted as stem cuttings with lengths of 18-20 cm. A Salix plantation is expected to remain productive for at least 25-30 years and during this time the biomass can be harvested between 6 and 10 times in a growing and re-sprouting cycle of 3 to 5 years and after each harvest, new shoots sprout from the cut stumps producing a dense coppice (Larsson et al., 2003).

Mola-Yudego et al. (2015) reviewed several academic publications concerning the commercial cultivation of Salix across Sweden. The average yield recorded for biomass production was between 4.6 odt $ha^{-1}year^{-1}$ to 7.7 odt $ha^{-1}year^{-1}$ (odt = oven dried tonnes for biomass measurement)

In a study carried out by Tlustoš et al. (2007) on the variation in the uptake of arsenic, cadmium, lead and zinc by different species of Salix growing in contaminated soils, it was found that the ability to accumulate lead and arsenic in the aboveground biomass and harvestable part by Salix was found to be negligible. Instead arsenic was retained in the roots.

Since plant species with an ability to hyperaccumulate arsenic into the harvestable biomass of the plant are rare, as for Salix, it can be said that for phytoremediation of arsenic using Salix phytoextraction cannot be possible, but phytostabilization is. For phytostabilization, the spread of the contaminant within the soil and the leaching of the contaminant to the groundwater is reduced as the contaminant is been held up in the root and as the root grows bigger and longer it continues to take up the contaminant.

# 3. METHODS

## 3.1. Literature search

This study was based on searching, screening and review of literature, articles, scientific papers and previous studies using keywords such as phytoremediation, arsenic, Salix, leaching, fertilization, phytostabilization etc. These searches were done online from different academic website such as Google Scholar (scholar.google.com), CLU-in (clu-in.org), Web of Science (www.webofknowledge.com), Researchgate (www.researchgate.net) and Science direct (www.science-direct.com) to list a few.

## 3.2. Data extraction and analysis

Data that are relevant to this study were extracted through the review of different experimental studies and used to theoretically analyze the potential of the processes considered in this study.

## 3.3. Economic benefit calculations

Economic benefit calculation was made to analyze the benefit of the action by comparing the cost of production to the revenue generated from the production process to see if there was any potential for profit making. With this we can determine if the action of using phytoremediation as a management tool to remediate abandoned sites contaminated with arsenic is feasible and viable for investment.

With the intention to focus on tree crops as the remediating plants, the cost of cutting harvested trees into wood chips was be inquired for from accessible wood chip makers. The cost of purchasing wood chips for energy production by energy producing plants was also inquired from relevant sources. Revenue generated from the sales of wood chips are then compared to the cost of production to see if cultivation of Salix for both phytoremediation and biomass production has a profit making potential for investment.

# 4. RESULTS AND DISCUSSION

## 4.1. Potential of Salix for phytostabilization of arsenic and biomass production

Phytostabilization of arsenic should include low accumulation of arsenic in the shoot of the plant species used and a higher accumulation of arsenic in the root (Bergqvist and Greger, 2012, Butcher, 2009). Tree plants are mostly preferred for phytostabilization due to their high evapotranspiration ability (Pulford and Watson, 2003). These abilities help to retain arsenic and to reduce the flow of water down the soil profile resulting in the reduction of leaching of pollutants to the groundwater table. The elongated roots of trees helps them take up contaminants from deeper soil depth compared to other plant types (Negri et al., 2003). When phytostabilizing with trees, priority is usually placed on the use of native tree species in order to prevent introducing invasive plant species to remediation sites (Mench et al., 2010). Salix species are native to Sweden and most cold regions of the world. Its high biomass producing abilities made it the plant in focus of this study for the remediation of abandoned contaminated sites in Sweden, with a joint aim of producing as much biomass as possible for conversion into wood chips for energy production by energy plants. Several experiments have been carried out to investigate the phytostabilization capacity of different tree species.

The experiments summarized in Table 2 were carried out on contaminated sites to see the how much arsenic is accumulated in different part of a Salix plant. From the results obtained from all the experiments it was confirmed that arsenic accumulated more in the root of Salix and very little in the shoot and leaves.

The experimentnof Sylvain et al. (2016) was able to deduce that Salix has a good phytostabilizing ability as it accumulated a very high amount of arsenic in its root compared to its aboveground biomass. Moreover, the cultivation of Salix on contaminated sites did not affect the growth of the tree crop. Salix is known for its preference in accumulating Zn, Cd, Cu etc. in its aboveground biomass and its capacity to accumulate arsenic in its belowground biomass (Keller et al., 2003, Rosselli et al., 2003). This accumulating preference was further verified in an experiment conducted by Vamerali et al. (2009) where the result showed the accumulation of arsenic and zinc in the above-ground biomass of *Salix alba*. The concentration of arsenic accumulated in the above-ground biomass was as low as 5 mg/kg in comparsion to that of zinc that was as high as 509.6 mg/kg.

Table 2: Different experiment on the phytostabilization abilities of Salix spp

| **Reference** | **Soil Condition** | **Aim of study** | **Period/Duration** | **Plant Species used** | **Amount of Arsenic accumulated in plant biomass (mg/kg)** |
| --- | --- | --- | --- | --- | --- |
| Sylvain et al. (2016) | Gold mine area | Stabilization potential of 2 different Salix species on As, Pb and Sb | 45 days | *Salix viminalis* (S1) and *Salix purpurea* (S2) | S1: Root (2000 mg/kg), Shoot (225 mg/kg), leaves (100 mg/kg)<br><br>S2: Root (3500 mg/kg), Shoot (150 mg/kg), leaves (50 mg/kg) |
| Vamerali et al. (2009) | Contaminated waste derived from mineral roasting for Sulphur extraction | Comparing the growth and uptake of trace element of populus and salix in a pot and field trial | 2 years | *Populus alba* (Pa), *Populus nigra* (Pn), *Populus tremula* (Pt), *Salix alba* (Sa) | Pa: Leaves (2.4 ± 0.39), Fine roots (779±8.5)<br>Pn: Leaves (2.0 ± 0.28), Fine roots (144.5±77.08)<br>Pt: Leaves (2.3 ± 0.63), Fine roots (62.0±13.08)<br>Sa: Leaves (5.0 ± 0.54), Fine roots (59.2±14.76) |
| Otones et al. (2011a) | Mining area affected by the abandoned exploitation of an arsenical tungsten deposit | To assess its arsenic pollution level and the feasibility of native plants for being used in phytoremediation approach on two different sites named B1 and B2 | | Several plants were used including *Salix atrocinerea* | Accumulation of arsenic in the below ground biomass of Salix was of a moderate amount with up to 119 mg/kg accumulated and a very low accumulation in the aboveground biomass as low as 18.4 mg/kg |
| Sandhi and Greger (2012) | Mine area | Screen the possibility of locally grown Salix spp for phytostabilization of arsenic. | | *Salix alba* 1 (Sa1)<br>*Salix caprea* (Sc)<br>*Salix alba* 2 (Sa2) | Arsenate:<br>Sa1: Root (116.0±13.5), Stem (1.36±1.03), Leaves (0.57±0.3)<br>Sc: Root (103.7±18.0), Stem (0.15±1.00), Leaves (2.94±0.4)<br>Sa2: Root (228.0±109.6), Stem (3.64±1.8), Leaves (0.36±0.4)<br>Arsenite:<br>Sa1: Root (136.7±37.6), Stem (0.91±0.57), Leaves (1.73±1.1)<br>Sc: Root (78.3±19.5), Stem (1.26±0.92), Leaves (5.98±0.5)<br>Sa2: Root (109.04±41.8), Stem (3.30±0.74), Leaves (0.75±1.2) |
| Navazas et al. (2019) | Arsenic contaminated brownfield | To further verify the ability of certain plants to tolerate and accumulate arsenic using Salix spp | | *Salix atrocinerea* | Root: 2400 mgAs/kg<br><br>Leaves: 25 mgAs/kg |
| Malik and Qayyum (2018) | Arsenic affected soil | Assess the potential of three tree seedlings to reclaim an arsenic affected soil | 24 months | *Eucalyptus camadulensis* (Ec)<br>*Terminalia arjuna* (Ta)<br>*Salix tetrasperma* (St) | Ec: Aboveground biomass (37.25), Belowground biomass (6.55).<br>Ta: Aboveground biomass (24.13), Belowground biomass (4.22)<br>St: Aboveground biomass (35.76), Belowground biomass (6.03) |

This conclusion was also supported by Otones et al. (2011a) after their experiment showed arsenic been much accumulated in the root of Salix species compared to other part of the tree with as much as 119 mg/kg of arsenic accumulated in the root and as low as 18 mg/kg accumulated in the shoot Navazas et al. (2019) also documented that despite arsenic being very toxic with deleterious effects, it can be tolerated and accumulated by Salix and some other plant species due to their arsenic tolerant mechanism. This is was further verified through an experiment in a controlled condition where a Salix clone (*Salix atrocinerea*) was planted in an arsenic contaminated medium for 30days and at different points after short and long time exposure, with several data taken such as As accumulation in different plant parts. The results showed that the Salix clone had a high tolerance for arsenic as it did not affect the growth and also accumulated arsenic as much as 2400 mg As/kg in the root and around 25 mg As/kg in the leaves. This result further emphasizes the fact that arsenic can be phytostablised with Salix but not phytoextracted.

Malik and Qayyum (2018) designed a study to assess the potential of tree seedlings in restoring an arsenic contaminated site by studying their accumulation of arsenic. The tree seedlings were of different tree types and species namely *Eucalyptus camaldulensis, Terminalia arjuna* and *Salix tetrasperma* and were all 6 months old at the time of use. The experiment was carried out in four treatments with arsenic applied to each treatment in different concentrations of 0.5, 1, 2.0 and 4.0 mg/L at different intervals for 18 months and after which the vegetative part of the trees are harvested and analysed for arsenic concentration. The result of the analysis showed the highest accumulation of arsenic in the root of the trees. From the fourth treatment in which 4.0 mg/L As was applied at several interval over 18 months, the As concentration accumulated in the roots of the trees were 37 mg/kg (*Eucalyptus camaldulensis*), 36 mg/kg (*Salix tetrasperma*) and 24 mg/kg (*Terminalia arjuna*), which was significantly higher than the amount of arsenic accumulated in the leaves of the trees: 6.5 mg/kg, 6.0 mg/kg and 4.2 mg/kg respectively.

In as much as Salix is not a good phytoextractor of arsenic due to the fact that it does not have a good transporter for arsenic and arsenic cannot be transported from the belowground biomass to the aboveground biomass, it still keeps arsenic accumulated in its belowground biomass (root) which causes stabilization as the element is held up in the root and prevented from spreading through the soil and also leaching down the soil profile to the groundwater.

Salix is good for biomass production and also stabilization of arsenic makes it a good tree crop for the simultaneous purpose to carry out remediation and biomass production, as the aboveground biomass is not contaminated with arsenic.

The presence of heavy metals in the biomass of energy trees reduces its worth as most energy plants that uses the wood chips made from it have to spend more funding in disposing its metal-containing ashes. Therefore they prefer wood chips made from tree biomass that are free of heavy metal contaminants. Since Salix accumulates arsenic in its roots, Salix grown for biomass production can be grown on sites with high arsenic contamination to help reduce the spread of the contaminants and also its leaching to groundwater with the assurance that the aboveground biomass will still be profitable as its heavy metal content is quite low.

## 4.2. **Influence of plant on the solubility and leaching of arsenic**

Unlike organic contaminants, metal(loids) like arsenic do not undergo microbial or chemical degradation and persist for a long time after they have been introduced into the environment or soil.(Bolan et al., 2014). The solubility of arsenic is influenced by several factors of which the most important ones are redox potential and pH (Sadiq, 1997). Arsenic usually forms inorganic and organic complexes but the two biologically important species are the inorganic arsenate [As(V)] and arsenite [As (III)]. The redox potential and pH of the soil determine which one of the species of aresnic predominates. (Bergqvist and Greger, 2012, Tripathi et al., 2007). Masscheleyn et al (1991) in an experiment on the effect of redox potential and pH on arsenic species, arsenate [As(V)] and arsenite [As(III)] in a controlled Eh-pH condition found that both redox status and pH had an effect on the solubility of the arsenic species. At an increasing pH and decreasing Eh, the solubility of arsenite increases while the solubility of arsenate decreases. This is shown in Table 3

Table 3: Concentration of As as affected by increasing pH and reducing Eh (Masscheleyn et al., 1991)

| | | Concentration of Arsenic (mg/kg) | |
|---|---|---|---|
| pH | Eh (Mv) | As (III) | As (V) |
| 5.6 | 340 | 1.4 | 5.6 |
| 6.7 | 100 | 46.8 | 3.1 |
| 7 | -100 | 69.4 | 3.4 |

The solubility of arsenate increases with increasing pH and the solubility of arsenite increases with decreasing pH (Raven et al., 1998). It was discovered that at low concentration, the adsorption of arsenite to ferrihydrite increases from low pH to high pH. For arsenate, the adsorption decreases from low to high pH at low concentration and the adsorption at high concentration increases from low pH to high pH. This shows that the adsorption of arsenic species to surfaces in the soil such as ferrihydrite is influenced by the pH of the soil.

Norini et al. (2019) were able to conclude from a review on the behavior of As that the ability of As to bind to surfaces on soils such as Fe, Al and Mn oxides is usually influenced by the pH and redox potential of the soil. These findings are in agreement with the results from Masscheleyn et al. (1991).

Masscheleyn et al. (1991) and Norini et al. (2019) claimed that plants cultivated on the contaminated site did not significantly influence the solubility and leaching of arsenic. Several literature search on the effect of Salix on the solubility/leaching of arsenic revealed that there is a knowledge gap on information relating to the influence of plant type and root chemistry on the leaching of arsenic. Consequently, further studies are needed to specifically investigate the influence of exudates from root of tree crops like Salix on the behaviour of arsenic in the soil. This will help with further justification of the phytostabilization of arsenic as the contaminants are trapped in the root of the soil all through their life cycle.

### 4.3. Effect of fertilizer usage on phytostabilization of arsenic contaminated soils

Apart from pH and redox potential, another factor that influences the behavior of arsenic in the soil is the presence of phosphate (Fresno et al., 2012) as it competes with arsenic for adsorption sites in the soil as a result of their similar chemical characteristics (Peryea, 1991)

Having a lot of phosphate present in the soil can cause an increase in the availability of soluble arsenic due to high desorption of the contaminant caused by the addition of phosphate in high doses (Cao et al., 2003, Tassi et al., 2004, Peryea, 1991)

Fresno et al. (2012) carried out experiments to see how increasing doses of phosphate fertilizers will affect the behaviour of arsenic in a phytoremediation attempt using *Salix atrocinerea*. The outcome is shown in Figure 3.

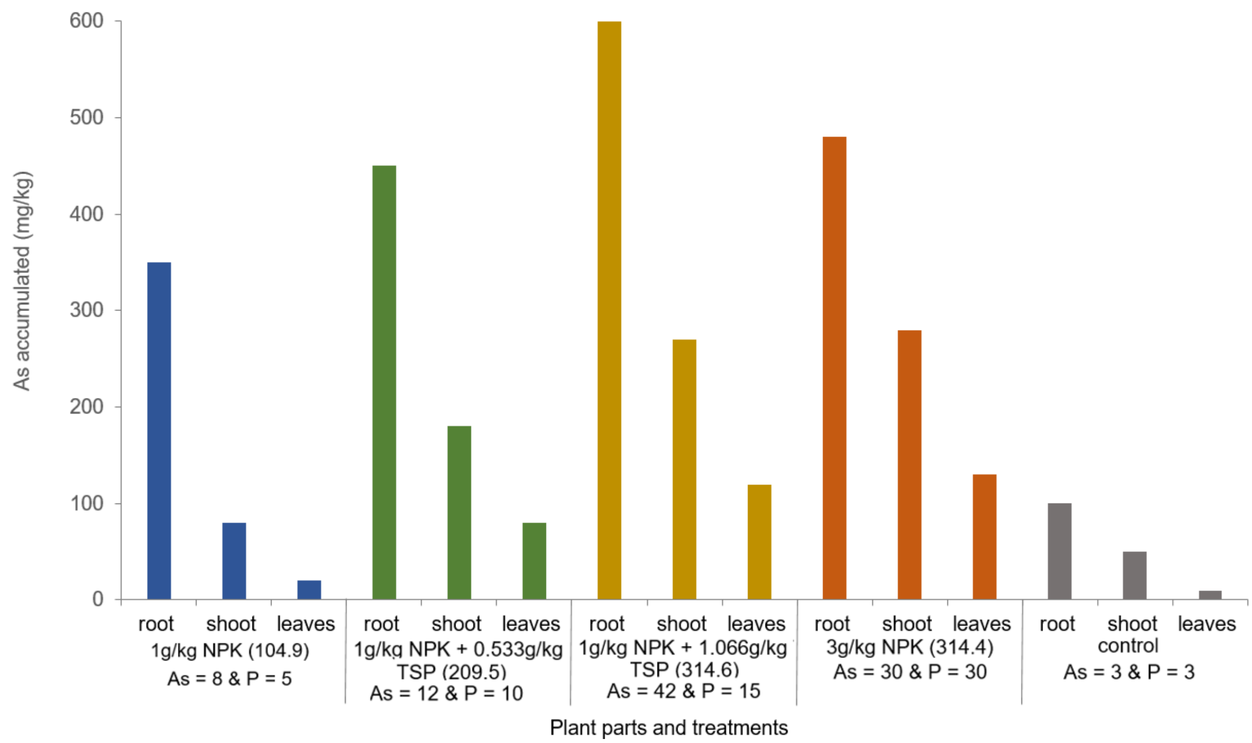


Figure 3: Effect of phosphate fertilizer application on the behavior of As and its accumulation by Salix in a phytoremediation attempt (Fresno et al., 2012). TSP: Triple super phosphate fertilizer; NPK: Nitrogen – Phosphorus - Potassium fertilizer. [Image not reproduced but created using data from Fresno et al. (2012)]

As seen in Figure 3, the application of phosphate fertilizers can cause a high mobility of arsenic and also help the accumulation of arsenic through phytostabilization due to the higher bioavailability of arsenic. To avoid heavy leaching of arsenic, phosphate fertilizers should be applied in small doses. This conclusion was further confirmed and agreed on by Cao et al. (2003), Tassi et al. (2004) and Fayiga and Ma (2006) through their experiments showing that usage of phosphate fertilizers in moderate doses boosted the accumulation of arsenic by plants in a phytoremediation attempt. The application of phosphate fertilizer made the phytoremediation process more successful compared to when phosphate fertilizers were not applied. Coupled with the increased accumulation of arsenic in the root of the Salix tree, the application of fertilizer helps increase the woody biomass yield of the Salix tree planted (Fresno et al., 2012). In addition to phosphate fertilizers aiding the accumulation of arsenic by Salix roots, another means of stabilizing arsenic is by using aided phytostabilization by introducing certain oxides and hydroxides that sorb arsenic in the root zone, thereby impeding its leaching. The sorption of arsenic to these oxides and hydroxides does not in anyway inhibit the uptake of arsenic by plants (Kumpiene et al., 2012).

## 4.4. Accumulation of arsenic in the root of salix

The mobility of arsenic is relatively low in soils with high acidity and clay content (McBride, 1994). With arsenic mostly partitioned in the residual fraction of the soil, the first extraction or accumulation of arsenic by Salix roots from an experiement carried out by Otones et al. (2011b) is said to be around 0.2% of the total concentration of arsenic in the soil with a bioaccumulation factor of 0.02. The bioaccumulation factor is estimated by taking the ratio of the concentration of the arsenic accumulated in the root to the total concentration of arsenic in the soil. The use of phosphate fertilizers can help increase the bioaccumulation factor as phosphate competes with arsenic for adsorption sites due to their similar chemical characteristics resulting in more available arsenic for plant uptake.

The root biomass of Salix is usually concentrated in the uppermost 10 – 40 cm of the soil with about 39 – 54% of the total root biomass in this depth (Heinsoo et al., 2009). According to Juliszewski et al. (2015), the measured root biomass per Salix stand after 5 years of planting ranged from 6 kg to 18 kg per square meter occupied by each Salix stand (from 30 stand measured) which was also estimated to a value of 6 to 10 t/ha.

According to Fresno et al. (2012), the root of Salix from two experimental treatments with arsenic contamination and concentration of up to 45 mg As/kg and 30 mg As/kg was able to accumulate arsenic of up to 600 µg/kg and 480 µg/kg after 10 weeks. The bioaccumulation factor was then estimated to a value of 0.07 (0.7%) and ) 0.08 (0.8%), which was much higher compared to Otones et al. (2011b) value of 0.02 (0.2%). The difference in the bioaccumulation factor between Fresno et al. (2012) and Otones et al. (2011b) experiments could be as a result of phosphate fertilizer applied in Fresno et al. (2012) experiment that lead to more arsenic accumulated by the root of Salix due to more available arsenic for uptake. Otones et al. (2011b) and Fresno et al. (2012) were able to conclude that the root of Salix is effective in the stabilization of arsenic in arsenic-contaminated soils or brownfields.

Due to the condition in which arsenic strongly adsorbs to clay colloids and specific minerals such as ferric oxides and hydroxides, arsenic has the potential of remaining in the root zone of the soil, which increases the possibility of it been taken up by Salix roots especially in a situation where there is a presence of phosphorus in the soil (Woolson, 1983).

### 4.5. Effect of soil type on biomass yield of salix

Labrecque et al. (2003) conducted a field experiment to see the effect and importance of soil type on the biomass yield of two different clones of Salix in the presence and absence of fertilizers. The yield were later measured after 6 years of planting (result in Table 4).

Table 4: Biomass Yield of Salix after 6 years of planting as affected by soil type and fertilizer application (Labrecque and Teodorescu, 2003)

| | *Salix discolor* (Fertilized) | *Salix discolor* (Unfertilized) | *Salix viminalis* (Fertilized) | *Salix viminalis* (Unfertilized) |
|---|---|---|---|---|
| Soil Type | Yield (tDM/ha) | Yield (tDM/ha) | Yield (tDM/ha) | Yield (tDM/ha) |
| Sandy | 24.53 | 22.25 | 47.2 | 28.73 |
| Clay | 31.48 | 31.52 | 70.36 | 61.97 |

tDM/ha: tonnes of dry matter per hectare

The yields from the two Salix clones cultivated on the clay soil were significantly higher than those for Salix cultivated on the sandy soil (for both fertilized and unfertilized treatments). This can be as a result of the clay soil having a better cation exchange capacity compared to that of the sandy soil, leading to a greater availability of nutrients, and to a near neutral pH in the clay soil. The sandy soil with its poor nutrient availability and low water retention capacity was still able to produce a considerable biomass yield for both Salix clones, which indicates that Salix trees would produce a considerable biomass yield regardless of the soil type. But a better biomass yield will be obtanied provided they are planted on sites and soils with good soil nutrient and qualities that matches up with the type of clones cultivated (Larsen et al., 2014).

### 4.6. **How much biomass can be produced from one hectare of Salix plantation?**

In Sweden, commercial willow plantations have a double row design with 1.5 m and 0.75 m spacing between rows and approximately 0.75 m between plants in each row yielding a planting density of about 12,000 cuttings per hectare (Rytter, 2012). This can be compared to Northern England, were a single design spacing of 0.75 m between the individual rows and 1.5 m between the pair of rows is used giving a total of 15,000 cuttings per hectare (Wilkinson et al 2007). These spacing are advised in order to give the plantation a good screen and windbreak. For a more dense hedge, the spacing can be closer (BowhayesTrees, 2019), giving an average of 20,000 cuttings per hectare.

Table 5: Biomass produced by Salix per hectare

| Reference | Range of planting density per hectare | Cycle of harvest | Rage of biomass yield (tonnes of dry matter per hectare) |
|---|---|---|---|
| Castaño-Díaz et al 2018 | 9 000 - 14 000 | 5 years | 1.6 - 10.7 tDM/ha |
| Bergkvist et al 1998 | 10 000 - 20 000 | 5 years | 14.2 - 18 tDM/ha |
| Yudego et al 2008 | 15 0000 | 3 years | 2.6 - 4.5 tDM/ha |
| Labrecque et al 2003 | 20 000 | 6 years | 22 - 70 tDM/ha |
| Larsen et al 2014 | 10 000 - 20 000 | 3 years | 1.12 - 25.35 tDM/ha |

tDM/ha: tonnes of dry matter per hectare

Castaño-Díaz et al. (2018) conducted a SRC trial on a former mining land in northern Spain over a period of five years with the aim of evaluating the effect of planting densities on the yield of three different clones of Salix cultivated on a contaminated land. The Bjorn clone (*Salix schwerinii* E. wolf x *Salix viminalis* L.), the Inger clone (*Salix triandra* L. x *Salix viminalis* L.) and the Olof clone (*Salix viminalis* L. x the Bjorn clone) were the three clones used and all were of Swedish origin. Two planting densities were used (9876 and 14,815 cuttings per hectare) with a spacing of 0.75 m x 0.9 m spacing to achieve the low planting density and 1.5 m x 0.6 m to achieve the high planting density. Each planting density was subject to three treatments (control, NPK 6:20:12 and weed control using glyphosate herbicide). The yield per hectare was measured in mega-grams of dry matter per hectare (1 Mg = 1 ton) and this was done by multiplying the average dry biomass of the 5 stools collected by an expansion factor of 14,815 cuttings (0.6 m plant spacing within each row) or 9876.5 cuttings (0.9 m plant spacing within each row). The range of biomasses produced by the different Salix clones are seen in Table 5. Castaño-Díaz et al. (2018) were also able to conclude that the treatment effect had little effects on the yield.

A similar study was carried out by Bergkvist and Ledin (1998) to see the effect of planting design and spacing on the biomass yield of Salix species (*Salix viminalis*) with an intended cycle of 5 years before the first harvest. The planting spacing used, ranged from 10,000 - 20,000 cuttings per hectare. The biomass yield of the lower planting density is significantly lower than that of the high planting density with 14.2 and 18 tonnes of dry matter per hectare respectively. From the study it was seen that planting spacing and the number of plant cuttings per hectare had more influence on the biomass yield compared to the planting design. Comparing with other studies in Table 6, it can be concluded that the denser the planting density, the higher the possibility of having more biomass yield after harvesting.

Mola-Yudego and Aronsson (2008) carried out a yield model prediction for willow plantation for bio-energy production in Sweden. The model predicted a yield for the first three harvest cycles and the predictions were 2.6, 4.2 and 4.5 oven dried tonnes per hectare respectively.

The yields shown in Table 5 correlate inversely with the harvest cycle as harvest of longer cycle had more yield compared to those of shorter harvest cycle even though they had more planting density.

Several factors like missing plant stand after planting, fertilizer application, weed control, planting design and soil quality may affect the yield but not to a significant level, as these can be corrected with proper management procedures. Also, the quality of the soil in terms of contamination did not affect the biomass yield (Castaño-Díaz et al., 2018).

In most European countries and the UK, it is considered that economic return is achieveable when the woody biomass of short rotation coppice yield up to 7 – 10 tons per hectare per annum (Mitchell et al., 1999). Since the yield produced by the three Salix species planted on arsenic-contaminated soil from the study of Navazas et al. (2019) and Sylvain et al. (2016) were in the range of 7 – 7.5 tDM/ha/yr, it can be assumed that there is a potential for economic return when Salix is cultivated on arsenic-contaminated soils.

### 4.7. **Wood chips production and sale**

Swedish bioenergy use has grown from 40 Terawatt hours (TWh) per year in the 1970s to over 140 TWh in 2012, overtaking oil to become the country's leading energy source (BASIS 2012). In Sweden an average of 6 848 000 oven-dried tonnes of wood per year is consumed nationwide for energy production. 56% of this is consumed by combined heat production plants (CHP) and 44% is consumed by heating plants. In comparison to this an average of 67,687,500 oven dried tonnes of wood/year is consumed by other industries in Sweden. These industries include pulp mills, pellet manufacturers, wood log users etc. During a phone interview with the president of Svebio (The Swedish Bioenergy Association), Gustav Melin (April 2020), he said that wood chips are purchased per MWh or GJ of energy and that the price could range from 190 to 200 SEK/MWh. He also mentioned that to calculate the energy content of wood chips, factors such as the moisture content of the wood chip, weight in kg, ash content etc. must be known. The cost of cutting harvested woody biomass into wood chips varies depending on the wood chipper used as different wood chipping machines have different efficiency and turn in time. This cost can range from 44 SEK/$m^3$ to 47 SEK/ $m^3$ (Unpublished data from a survey carried out by the research institute Skogforsk)

### 4.8. Economic benefit calculations.

To determine how much profit can be made from cultivating a hectare of Salix, a survey containing the cost of production of two different farms in Sweden was reviewed. This survey, which was carried out by Dimitriou and Rutz (2015), showed the cost incurred by the farmers of the two farms in the process of cultivating Salix over a year, for details see Table 7. The cost of land purchase and initial planting cost were not included because these costs do not reoccur and only reoccurring expenses were selected. These were totaled and compared with the amount generated from the harvest yield to see its profit margin. Salix farmers in Sweden also get up to 10,000 SEK as subsidy for planting Salix per hectare (Andersson, 2012).

Table 6: Cost of Salix production and revenue generated from sales of wood chips from two Salix farms in Puckgården and Enköping, Sweden (Dimitriou and Rutz, 2015)

| **Expenses** | **Amount (SEK/ha/yr.) (Dimitriou and Rutz, 2015)** | **Amount (SEK/ha/yr.) (Dimitriou and Rutz, 2015)** |
|---|---|---|
| **Farm Location** | *Puckgården* | *Enköping* |
| Fertilizers | 342 | - |
| Maintenance | 198 | 198 |
| Harvest | 1251 | 2 142 |
| Transportation | 945 | 1 332 |
| General Expenses | 495 | 495 |
| Interest rate | 99 | 135 |
| **Total** | **3 330** | **4 302** |
| Biomass Produced | 9.5 tDM/ha/yr. | 9 tDM/ha/yr. |
| **Revenue** | **Amount (SEK/ha/yr.)** | **Amount (SEK/ha/yr.)** |
| Sale of Wood Chips (For Energy in (KWh)) | 7 776 | 8 064 |

| Expenses | Amount (SEK/ha/yr.) (Dimitriou and Rutz, 2015) | Amount (SEK/ha/yr.) (Dimitriou and Rutz, 2015) |
|---|---|---|
| Wastewater compensation | | 1 971 |
| **Total** | **7 776** | **10 035** |
| Profit/loss | Amount (SEK/ha/yr.) | Amount (SEK/ha/yr.) |
| **Profit** | **4 446 (57% profit made)** | **5 733 (57% profit made)** |

The calculation in Table 6 for the Puckgården farm was made from a Salix field of 4 years harvest cycle. All costs were included except the land ownership cost, the cost of ploughing and the cost of planting. The reason for this is because the cost were calculated after the fifth harvest equaling 20 years after setting up the forest plantation. The planting was first done in 1991 and the fifth harvest was done in 2011. For the farm in Enköping the calculation was made from a Salix field of 4 years harvest cycle after the third harvest equaling 12 years after the first planting. The first planting was done in 1999 and the third harvest was done in 2011.

From the calculations on the economy of willow short rotation coppice made by Dimitriou & Rutz, 2015, it can be seen that apart from the possibility of having willow trees for phytoremediation, they are also able to generate revenue through sales of their biomass for energy production when converted into woodchips.

Granting that the soil quality in the farms in which the survey shown in Table 6 were obtained from was of good quality as the soils were on agricultural land, the calculations made are still feasible to use as a reference for Salix cultivated on arsenic-contaminated soils, which is in agreement with the conclusions made by Labrecque and Teodorescu (2003) and Larsen et al. (2014) according to which the soil type and quality did not have a significant effect on the biomass yield of Salix. Salix can be planted on an arsenic-contaminated soil and still produce considerable biomass yield which will be enough to generate substantial profit. To further support this claim, the amount of biomass yield produced by Salix cultivated on contaminated soil was reviewed and compared to the yield obtained from the survey. According to Navazas et al. (2019) and Sylvain et al., (2016), the biomass yield produced by Salix cultivated on a gold mine area and on a brown field ranged between 7 and 7.5 tDM/ha/year, which as stated earlier is enough to achieve economic returns and to make profit.

## 5. CONCLUSION

- Based on multiple studies reviewed, Salix was found to tolerate arsenic and that it can be cultivated on brown fields contaminated with arsenic to accumulate arsenic in its below ground biomass.
- The accumulation of arsenic in the below ground biomass of contributes to phytostabilization as the spread and leaching of the contaminant is mitigated by the tree as the contaminant is accumulated in its roots. But due to limited studies on the effect of Salix plant on the leaching and solubility of arsenic, the phytostabilizing potential of Salix cannot be fully evaluated and these calls for further investigation on the relationship between the root and root exudates of Salix and the leaching of arsenic.
- To aid a higher accumulation of arsenic in the root of Salix, sorbents such as ferric oxides and hydroxides can be introduced as they will help stabilizing arsenic in the soil which is known as aided phytostabilization.
- Cultivating Salix on arsenic-contaminated soil or brown-field also has a good potential for profit-making as the tree crop can survive on arsenic contaminated soil with the ability to produce biomass yield up to an average of 7 tDM/ha/year, which is sufficient for economic returns. The revenue generated from a hectare of Salix could range from 8,000 to 10,000 SEK/ha/year through the sales of the biomass for energy production, regardless of whether it has been cultivated on agricultural soil or on an arsenic-contaminated brown-field, as arsenic is accumulated in the below-ground biomass of Salix, leaving the above-ground biomass contaminant free and of good quality for energy production.

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## REFERENCES


ABBAS, G., MURTAZA, B., BIBI, I., SHAHID, M., NIAZI, N. K., KHAN, M. I., AMJAD, M. & HUSSAIN, M. 2018. Arsenic uptake, toxicity, detoxification, and speciation in plants: physiological, biochemical, and molecular aspects. *International Journal of Environmental Research and Public Health,* 15**,** 59.

ANDERSSON, K. 2012. *Bioenergy-the Swedish Experience: How Bioenergy Became the Largest Energy Source in Sweden*, Svebio.

ARGUS, G. W. 1986. The genus Salix (Salicaceae) in the southeastern United States. *Systematic Botany Monographs***,** 1-170.

BERGKVIST, P. & LEDIN, S. 1998. Stem biomass yields at different planting designs and spacings in willow coppice systems. *Biomass and Bioenergy,* 14**,** 149-156.

BERGQVIST, C. 2011. *Arsenic accumulation in various plant types.* Department of Botany, Stockholm University.

BERGQVIST, C. 2013. *Arsenic accumulation in plants for food and phytoremediation: Influence by external factors.* Department of Ecology, Environment and Plant Sciences, Stockholm University.

BERGQVIST, C. & GREGER, M. 2012. Arsenic accumulation and speciation in plants from different habitats. *Applied Geochemistry,* 27**,** 615-622.

BHATTACHARYA, P., JACKS, G., VON BRÖMSSEN, M. & SVENSSON, M. 2010. *Arsenic in Swedish groundwater - mobility and risk for naturally elevated concentrations,* KTH Royal Institute of Technology, Stockholm, Sweden.

BHATTACHARYA, P., MUKHERJEE, A. B., BUNDSCHUH, J., ZEVENHOVEN, R. & LOEPPERT, R. H. 2007. *Arsenic in soil and groundwater environment: biogeochemical interactions, health effects and remediation*, Elsevier.

BIOTECHNOLOGY, E. 2011. *The use of genetic engineered organisms for pollution abatement* [Online]. Available: https://knowhowtogmo.wordpress.com/2011/01/31/phytovolatilization/ [Accessed March 2020].

BISONE, S., CHATAIN, V., BLANC, D., GAUTIER, M., BAYARD, R., SANCHEZ, F. & GOURDON, R. 2016. Geochemical characterization and modeling of arsenic behavior in a highly contaminated mining soil. *Environmental Earth Sciences,* 75**,** 306.

BOLAN, N., KUNHIKRISHNAN, A., THANGARAJAN, R., KUMPIENE, J., PARK, J., MAKINO, T., KIRKHAM, M. B. & SCHECKEL, K. 2014. Remediation of heavy metal (loid) s contaminated soils–to mobilize or to immobilize? *Journal of Hazardous Materials,* 266**,** 141-166.

BOLAN, N. S., PARK, J. H., ROBINSON, B., NAIDU, R. & HUH, K. Y. 2011. Phytostabilization: a green approach to contaminant containment. *Advances in agronomy.* Elsevier.

BOWHAYESTREES. 2019. *Soil Type, Preparation and Spacing for Willows and Poplars Cultivation* [Online]. Available: https://www.bowhayestrees.co.uk/soil-and-spacing [Accessed April 2020].

BRANQUINHO, C., SERRANO, H. C., PINTO, M. J. & MARTINS-LOUÇAO, M. A. 2007. Revisiting the plant hyperaccumulation criteria to rare plants and earth abundant elements. *Environmental Pollution,* 146**,** 437-443.

BUTCHER, D. J. 2009. Phytoremediation of arsenic: fundamental studies, practical applications, and future prospects. *Applied Spectroscopy Reviews,* 44**,** 534-551.

CAO, X., MA, L. Q. & SHIRALIPOUR, A. 2003. Effects of compost and phosphate amendments on arsenic mobility in soils and arsenic uptake by the hyperaccumulator, Pteris vittata L. *Environmental Pollution,* 126**,** 157-167.

CASTAÑO-DÍAZ, M., BARRIO-ANTA, M., AFIF-KHOURI, E. & CÁMARA-OBREGÓN, A. 2018. Willow short rotation coppice trial in a former mining area in Northern Spain: effects of clone, fertilization and planting density on yield after five years. *Forests,* 9**,** 154.
COLLINS, C. 2013. Uptake of organic pollutants and potentially toxic elements (PTEs) by crops. *Persistent Organic Pollutants and Toxic Metals in Foods.* Elsevier.
COMMISSION, F. R. 2006. *Establishment practices-Short rotation coppice establishment* [Online]. Available: https://www.forestresearch.gov.uk/tools-and-resources/urban-regeneration-and-greenspace-partnership/greenspace-in-practice/greenspace-establishment-practices/short-rotation-coppice-establishment/ [Accessed April 2020].
DE TEMMERMAN, L., RUTTENS, A. & WAEGENEERS, N. 2012. Impact of atmospheric deposition of As, Cd and Pb on their concentration in carrot and celeriac. *Environmental Pollution,* 166**,** 187-195.
DI LONARDO, S., CAPUANA, M., ARNETOLI, M., GABBRIELLI, R. & GONNELLI, C. 2011. Exploring the metal phytoremediation potential of three Populus alba L. clones using an in vitro screening. *Environmental Science and Pollution Research,* 18**,** 82-90.
DIMITRIOU, I. & RUTZ, D. 2015. *Sustainable Short Rotation Coppice: A Handbook*, WIP Renewable Energies.
FAYIGA, A. O. & MA, L. Q. 2006. Using phosphate rock to immobilize metals in soil and increase arsenic uptake by hyperaccumulator Pteris vittata. *Science of the Total Environment,* 359**,** 17-25.
FORSLUND, J. & BARREGÅRD, L. 2008. Remediaiton of Sites Contaminated by Arsenic; Data to Estimate the Giverment Cost for Risk Reductions.  . *Brief paper. National Institute of Economic Research (Konjunkturinstitutet), Stockholm, Sweden*.
FORSLUND, J., SAMAKOVLIS, E., JOHANSSON, M. V. & BARREGARD, L. 2010. Does remediation save lives?—On the cost of cleaning up arsenic-contaminated sites in Sweden. *Science of the Total Environment,* 408**,** 3085-3091.
FRESNO, T., PEÑALOSA, J. & CARPENA, R. Effect of phosphate fertilizers on arsenic mobility in arsenic-contaminated soil: Possible assistance in phytoremediation.  Understanding the Geological and Medical Interface of Arsenic-As 2012: Proceedings of the 4th International Congress on Arsenic in the Environment, 22-27 July 2012, Cairns, Australia, 2012. CRC Press, 352.
GANSAUER, G. 2012. *Trees in Phytoremediation* [Online]. Available: https://sites.biology.colostate.edu/phytoremediation/2012/Phytoremediation%20with%20Trees%20by%20Grete%20Gansauer.pdf [Accessed].
GAWRONSKI, S. W. & GAWRONSKA, H. 2007. Plant taxonomy for phytoremediation. *Advanced Science and Technology for Biological Decontamination of Sites Affected by Chemical and Radiological Nuclear Agents.* Springer.
GULZ, P. A., GUPTA, S.-K. & SCHULIN, R. 2005. Arsenic accumulation of common plants from contaminated soils. *Plant and soil,* 272**,** 337-347.
HEINSOO, K., MERILO, E., PETROVITS, M. & KOPPEL, A. 2009. Fine root biomass and production in a Salix viminalis and Salix dasycludos plantation. *Estonian Journal of Ecology,* 58.
ITRC 2009. Fact sheet: Phytoremediation of inorganic compounds. *Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised. PHYTO-3. Interstate Technology & Regulatory Council, Phytotechnologies Team, Washington, DC, USA, Tech Reg Update* Phase II.
JORDBRUKSVERKET 2017. *Handbok för salixodlare*.
JULISZEWSKI, T., KWAŚNIEWSKI, D., PIETRZYKOWSKI, M., TYLEK, P., WALCZYK, J., WOŚ, B. & LIKUS, J. 2015. Root biomass distribution in an energy willow plantation. *Agricultural Engineering,* 19**,** 43--49.

KELLER, C., HAMMER, D., KAYSER, A., RICHNER, W., BRODBECK, M. & SENNHAUSER, M. 2003. Root development and heavy metal phytoextraction efficiency: comparison of different plant species in the field. *Plant and Soil,* 249**,** 67-81.
KHALID, S., SHAHID, M., NIAZI, N. K., MURTAZA, B., BIBI, I. & DUMAT, C. 2017. A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of Geochemical Exploration,* 182**,** 247-268.
KUMPIENE, J., FITTS, J. P. & MENCH, M. 2012. Arsenic fractionation in mine spoils 10 years after aided phytostabilization. *Environmental Pollution,* 166**,** 82-88.
LABRECQUE, M. & TEODORESCU, T. I. 2003. High biomass yield achieved by Salix clones in SRIC following two 3-year coppice rotations on abandoned farmland in southern Quebec, Canada. *Biomass and Bioenergy,* 25**,** 135-146.
LARSEN, S. U., JØRGENSEN, U. & LÆRKE, P. E. 2014. Willow yield is highly dependent on clone and site. *BioEnergy Research,* 7**,** 1280-1292.
LARSSON, S., LINDEGAARD, K. & AGROBRÄNSLE, A. 2003. Full scale implementation of short rotation willow coppice SRC in Sweden. *Örebro: Agrobränsle AB*.
LASAT, M. M. 2000. *The use of plants for the removal of toxic metals from contaminated soils*, US Environmental Protection Agency.
LIM, K., SHUKOR, M. & WASOH, H. 2014. Physical, chemical, and biological methods for the removal of arsenic compounds. *BioMed research international,* 2014.
LUNDH, D., LARSSON, D., NAHAR, N. & MANDAL, A. 2010. Arsenic accumulation in plants–outlining strategies for developing improved variety of crops for avoiding arsenic toxicity in foods. *Journal of Biological Systems,* 18**,** 223-241.
MALIK, M. F. & QAYYUM, A. 2018. Phytoremediation of arsenic-contaminated soils by Eucalyptus camaldulensis, Terminalia arjuna and Salix tetrasperma. *Journal of Applied Botany and Food Quality 91, 8 - 13 (2018),* .
MARMIROLI, M., PIETRINI, F., MAESTRI, E., ZACCHINI, M., MARMIROLI, N. & MASSACCI, A. 2011. Growth, physiological and molecular traits in Salicaceae trees investigated for phytoremediation of heavy metals and organics. *Tree Physiology,* 31**,** 1319-1334.
MASSCHELEYN, P. H., DELAUNE, R. D. & PATRICK JR, W. H. 1991. Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil. *Environmental Science & Technology,* 25**,** 1414-1419.
MCBRIDE, M. B. 1994. Oxidation - Reduction Reaction. *ENVIRONMENTAL CHEMISTRY OF SOILS.* Oxford, New York: Oxford University Press
MEERS, E., VANDECASTEELE, B., RUTTENS, A., VANGRONSVELD, J. & TACK, F. 2007. Potential of five willow species (Salix spp.) for phytoextraction of heavy metals. *Environmental and Experimental Botany,* 60**,** 57-68.
MENCH, M., LEPP, N., BERT, V., SCHWITZGUÉBEL, J.-P., GAWRONSKI, S. W., SCHRÖDER, P. & VANGRONSVELD, J. 2010. Successes and limitations of phytotechnologies at field scale: outcomes, assessment and outlook from COST Action 859. *Journal of Soils and Sediments,* 10**,** 1039-1070.
MITCHELL, C., STEVENS, E. & WATTERS, M. 1999. Short-rotation forestry–operations, productivity and costs based on experience gained in the UK. *Forest ecology and management,* 121**,** 123-136.
MOLA-YUDEGO, B. & ARONSSON, P. 2008. Yield models for commercial willow biomass plantations in Sweden. *Biomass and Bioenergy,* 32**,** 829-837.
MOLA-YUDEGO, B., DÍAZ-YÁÑEZ, O. & DIMITRIOU, I. 2015. How much yield should we expect from fast-growing plantations for energy? Divergences between experiments and commercial willow plantations. *BioEnergy Research,* 8**,** 1769-1777.
NAVAZAS, A., HENDRIX, S., CUYPERS, A. & GONZÁLEZ, A. 2019. Integrative response of arsenic uptake, speciation and detoxification by Salix atrocinerea. *Science of the Total Environment,* 689**,** 422-433.

NEGRI, M., GATLIFF, E., QUINN, J. & HINCHMAN, R. 2003. Root development and rooting at depths. *Phytoremediation: Transformation and control of contaminants*, 233-262.
NORINI, M.-P., THOUIN, H., MIARD, F., BATTAGLIA-BRUNET, F., GAUTRET, P., GUÉGAN, R., LE FORESTIER, L., MORABITO, D., BOURGERIE, S. & MOTELICA-HEINO, M. 2019. Mobility of Pb, Zn, Ba, As and Cd toward soil pore water and plants (willow and ryegrass) from a mine soil amended with biochar. *Journal of Environmental Management,* 232**,** 117-130.
OTONES, V., ÁLVAREZ-AYUSO, E., GARCÍA-SÁNCHEZ, A., SANTA REGINA, I. & MURCIEGO, A. 2011a. Arsenic distribution in soils and plants of an arsenic impacted former mining area. *Environmental Pollution,* 159**,** 2637-2647.
OTONES, V., ÁLVAREZ-AYUSO, E., GARCÍA-SÁNCHEZ, A., SANTA REGINA, I. & MURCIEGO, A. 2011b. Mobility and phytoavailability of arsenic in an abandoned mining area. *Geoderma,* 166**,** 153-161.
PAJEVIĆ, S., BORIŠEV, M., NIKOLIĆ, N., ARSENOV, D. D., ORLOVIĆ, S. & ŽUPUNSKI, M. 2016. Phytoextraction of heavy metals by fast-growing trees: a review. *Phytoremediation.* Springer.
PANDEY, D., ZOOMI, I., AKHTAR, O., SRIVASTAVA, P. & KEHRI, H. 2018. Approaches for Remediation of Arsenic Contamination from Soil and Water: A Review. 6**,** 146-162.
PERYEA, F. J. 1991. Phosphate-induced release of arsenic from soils contaminated with lead arsenate. *Soil Science Society of America Journal,* 55**,** 1301-1306.
PULFORD, I. & WATSON, C. 2003. Phytoremediation of heavy metal-contaminated land by trees—a review. *Environment International,* 29**,** 529-540.
RAVEN, K. P., JAIN, A. & LOEPPERT, R. H. 1998. Arsenite and arsenate adsorption on ferrihydrite: kinetics, equilibrium, and adsorption envelopes. *Environmental Science & Technology,* 32**,** 344-349.
RAVI NAIDU, E. S., GARY OWENS, PROSUN BHATTACHARYA, PETER NADEBAUM 2006. Managing Arenic in the Environment 3-127.
ROSSELLI, W., KELLER, C. & BOSCHI, K. 2003. Phytoextraction capacity of trees growing on a metal contaminated soil. *Plant and Soil,* 256**,** 265-272.
RYTTER, R.-M. 2012. The potential of willow and poplar plantations as carbon sinks in Sweden. *Biomass and Bioenergy,* 36**,** 86-95.
SADIQ, M. 1997. Arsenic chemistry in soils: an overview of thermodynamic predictions and field observations. *Water, Air, and Soil Pollution,* 93**,** 117-136.
SANDHI, A. & GREGER, M. Phytostablization of arsenic: Is it possible by growing Salix spp. in the contaminated sites? Understanding the Geological and Medical Interface of Arsenic-As 2012: Proceedings of the 4th International Congress on Arsenic in the Environment, 22-27 July 2012, Cairns, Australia, 2012. CRC Press, 328.
SMITH, E. R. G., NAIDU, R. & ALSTON, A. 1998. *Arsenic in the soil environment.* Academic Press Cambridge, MA.
SMITH, P. G., KOCH, I. & REIMER, K. J. 2008. Uptake, transport and transformation of arsenate in radishes (Raphanus sativus). *Science of the Total Environment,* 390**,** 188-197.
SWEDISH_EPA. 2019. *State of the Environment: Statistics and facts* [Online]. Sweden Available: http://www.swedishepa.se/State-of-the-environment/Mark/Contaminated-areas-in-Sweden/ [Accessed 11th of March 2020].
SYLVAIN, B., MIKAEL, M.-H., FLORIE, M., EMMANUEL, J., MARILYNE, S., SYLVAIN, B. & DOMENICO, M. 2016. Phytostabilization of As, Sb and Pb by two willow species (S. viminalis and S. purpurea) on former mine technosols. *Catena,* 136**,** 44-52.
TASSI, E., PEDRON, F., BARBAFIERI, M. & PETRUZZELLI, G. 2004. Phosphate-assisted phytoextraction in As-contaminated soil. *Engineering in Life Sciences,* 4**,** 341-346.

TLUSTOŠ, P., SZÁKOVÁ, J. I., VYSLOUŽILOVÁ, M., PAVLÍKOVÁ, D., WEGER, J. & JAVORSKÁ, H. 2007. Variation in the uptake of arsenic, cadmium, lead, and zinc by different species of willows Salix spp. grown in contaminated soils. *Central European Journal of Biology,* 2**,** 254-275.
TRIPATHI, R. D., SRIVASTAVA, S., MISHRA, S., SINGH, N., TULI, R., GUPTA, D. K. & MAATHUIS, F. J. 2007. Arsenic hazards: strategies for tolerance and remediation by plants. *Trends in Biotechnology,* 25**,** 158-165.
TU, C. & MA, L. Q. 2003. Effects of arsenate and phosphate on their accumulation by an arsenic-hyperaccumulator Pteris vittata L. *Plant and Soil,* 249**,** 373-382.
VAMERALI, T., BANDIERA, M., COLETTO, L., ZANETTI, F., DICKINSON, N. M. & MOSCA, G. 2009. Phytoremediation trials on metal-and arsenic-contaminated pyrite wastes (Torviscosa, Italy). *Environmental Pollution,* 157**,** 887-894.
VANGRONSVELD, J., HERZIG, R., WEYENS, N., BOULET, J., ADRIAENSEN, K., RUTTENS, A., THEWYS, T., VASSILEV, A., MEERS, E. & NEHNEVAJOVA, E. 2009. Phytoremediation of contaminated soils and groundwater: lessons from the field. *Environmental Science and Pollution Research,* 16**,** 765-794.
VATAMANIUK, O. K., BUCHER, E. A., WARD, J. T. & REA, P. A. 2001. A New Pathway for Heavy Metal Detoxification in Animals PHYTOCHELATIN SYNTHASE IS REQUIRED FOR CADMIUM TOLERANCE INCAENORHABDITIS ELEGANS. *Journal of Biological Chemistry,* 276**,** 20817-20820.
VATAMANIUK, O. K., MARI, S., LU, Y.-P. & REA, P. A. 2000. Mechanism of heavy metal ion activation of phytochelatin (PC) synthase blocked thiols are sufficient for PC synthase-catalyzed transpeptidation of glutathione and related thiol peptides. *Journal of Biological Chemistry,* 275**,** 31451-31459.
WANG, S. & MULLIGAN, C. N. 2006. Natural attenuation processes for remediation of arsenic contaminated soils and groundwater. *Journal of Hazardous Materials,* 138**,** 459-470.
WANI, B. A., KHAN, A. & BODHA, R. 2011. Salix: A viable option for phytoremediation. *African Journal of Environmental Science and Technology,* 5**,** 567-571.
WHO EDITION, T. 2008. Guidelines for Drinking-water Quality. *WHO Chronicle,* 1**,** 334-415.
WOOLSON, E. A. 1983. *Emissions, cycling and effects of arsenic in soils*, Elsevier, Amsterdam.