Study on the mechanisms of phytoremediation

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Abstract. Environmental pollution causes more and more casualties and the improvement of environmental quality is a mandatory requirement for a sustainable development. A large variety of sites can be decontaminated using phytoremediation. Several projects have been developed and applied to large scale or pilot projects. This study presents the mechanisms of phytoremediation which uses plants and their characteristics to extract, neutralize or stabilize different types of contaminants in the soil. Plants should be chosen carefully because a limited number of species can be involved in the implementation of this type of projects. There are many factors that can influence the efficiency of phytoremediation: the type of contaminants, root system, soil organisms, enzymes, soil properties etc. Phytoremediation is a green technology and a cost-effective method that contributes to the improvement of the environment by creating habitats and a better landscape aesthetics. The aim of this study is to identify the treatment mechanisms that are used by plants to clean up different sites.
Key Words: environment, mechanism, phytoremediation, plants.

Introduction. The basic processes for a plant to grow are by developing roots in the soil and producing leaves and woody material. In order to do this, plants use carbon dioxide to convert light energy into chemical energy and produce carbon biomass using leaves and cellular respiration during photosynthesis. Plants also use water and dissolved inorganic nutrients that are uptaken by roots and transported through xylem to finally be transpired as vapors. During the process, oxygen is being released in the atmosphere. The phloem has the role to transport the photosynthetic chemicals into the roots which can exude them in the soil. The biological processes (Figure 1) contribute directly in the remediation or sequestration of contaminants (ITRC 2009).

Transpiration, metabolism, photosynthesis and mineral nutrition are the basic physiological mechanisms that are associated with plants and their microorganisms. Roots can uptake organic and inorganic compounds from soil, sediments and water and can be aided by the microorganisms in the rhizosphere to sequester and bind substances. Plants transport, store, convert or accumulate the different substances that were uptaken in cells and tissues and the aerial plants can exchange gases with the atmosphere both uptaking and releasing of molecules (Marmiroli et al 2006).

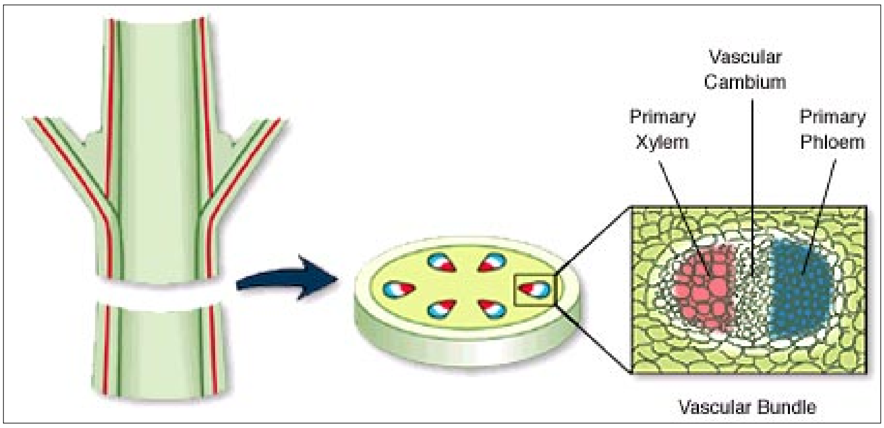

Figure 1. Xylem and phloem – vascular tissues that provide channels for water and nutrients (http://www.mhhe.com/biosci/esp/2001_gbio/folder_structure/pl/m1/s4/).

Plants require essential nutrient elements in order to survive and complete the life cycle (Table 1). There are two criteria that state the essentiality of an element, that the plant cannot complete the life cycle in its absence or that the element is essential to a constituent or metabolite (Hopkins & Huner 2009).

Table 1

The macronutrients and micronutrients which are essential for a normal plant growth (http://www.biologyreference.com/Ph-Po/Plant-Nutrition.html)

Essential element	*Chemical symbol*	*Form absorbed*
	Macronutrients	
Hydrogen	H	H_2O
Carbon	C	CO_2
Oxygen	O	O_2,CO_2
Nitrogen	N	NO_3^-, NH_4^+
Potassium	K	K^+
Calcium	Ca	Ca^{2+}
Magnesium	Mg	Mg^{2+}
Phosphorus	P	HPO_4^-, HPO_4^{2-}
Sulphur	S	SO_4^{2-}
	Micronutrients	
Chlorine	Cl	Cl^-
Iron	Fe	Fe^{2+}, Fe^{3+}
Boron	B	BO_3^{3-}
Manganese	Mn	Mn^{2+}
Zinc	Zn	Zn^{2+}
Copper	Cu	Cu^{2+}
Nickel	Ni	Ni^{2+}
Molybdenum	Mo	Mo_4^{2-}

Even though the understanding of membrane structure suffered different perspectives over the years, there are known three fundamental concepts regarding how solutes cross the membrane: simple diffusion, facilitated diffusion and active transport (Figure 2). These represent the basic transport through the membranes (Hopkins & Huner 2009).

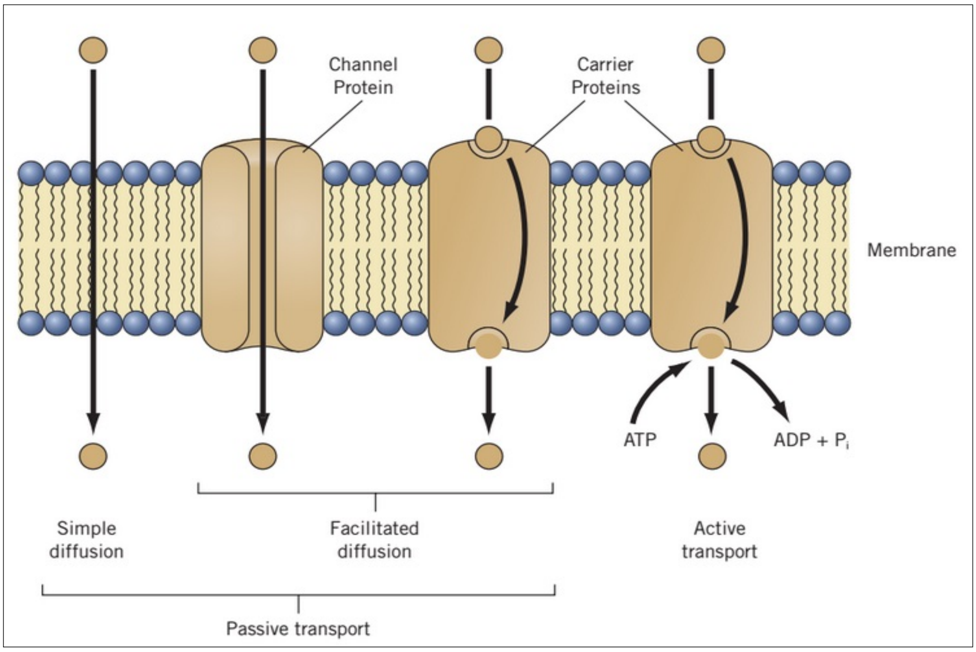

Figure 2. Exchanging ions and solutes across membranes (Hopkins & Huner 2009).

The possible mechanisms that cause the tolerance of heavy metals in plant cells are:

- binding of metals to the cell wall;
- decreased transport through the cell membrane;
- active efflux;
- compartmentalization;
- chelation (Prasad 1995; Revathi & Venugopal 2013).

Mechanisms of phytoremediation. Plants have the capacity to uptake, degrade, transform, sequester contaminants in addition to producing biomass. The duration of phytoremediation, the type and number of species required at a particular site depend on the site characteristics and mostly the contaminant type. The most important factors that have to be taken into consideration to a site where phytoremediation is used are:

- category of contaminant (Figure 3):
- plant species;
- levels of contamination;
- contaminated area - size and depth;
- site conditions (nutrient availability, soil organic matter content, soil water, soil aeration);
- type and number of plants required (Hettiarachchi et al 2012).

Plants have the ability to remediate contaminated sites using several ways. The root system is where the principal mechanisms that prevent the toxicity can be found. The contaminants are uptaken by roots, while they release organic and inorganic exudates in the rhizosphere. Root exudates have an important role in affecting the number and activity of microorganisms, aggregation and stability of the soil particles, availability of contaminants. Plants are hosts for the aerobic and anaerobic microorganisms and the roots and shoots increase the microbial activity. They also increase evapotranspiration, adsorb compounds in the roots and slow the movement of contaminants in soil (http://wgbis.ces.iisc.ernet.in/energy/water/paper/phyto/introduction.htm).

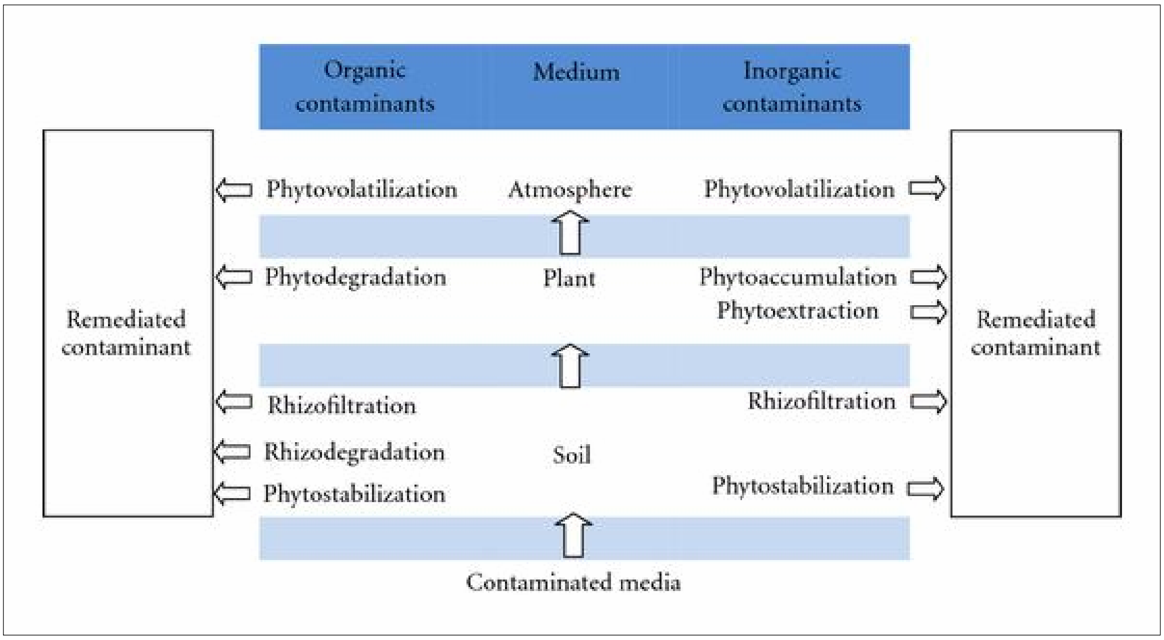

Figure 3. Uptake mechanisms of organic and inorganic contaminants and the possible technologies applied (Tangahu et al 2011).

Research studies classified the phytoremediation technologies into major categories: phytoextraction, phytovolatilization, phytodegradation, rhizodegradation, rhizofiltration, phytostabilization and hydraulic control. There are similarities between them, so a combination of the technologies may be more successful. All of the technologies affect the contaminant mass in soils, sediments or water (EPA 2000; Kvesitadze et al 2006; Van Epps 2006; Dordio & Carvalho 2011; Ali et al 2013).

The basic mechanisms and principles that are involved in the phytoremediation technologies are briefly presented in Table 2.

Table 2
Basic mechanisms and principles that are part of phytoremediation technologies (Marmiroli et al 2006)

Mechanisms	*Principles*
	Heavy metals and inorganic contaminants
Uptake and transport	- Plants and metals interact in the root environment; - The contaminant has to be in contact with the roots in order to be uptaken; - The same kind of transporters that are used for the macronutrients and micronutrients entrance are also used by plants for the heavy metals uptake; - Metals are stored in the subcellular compartments like vacuoles and lignocellulosic material (cell wall); - Research is being developed to discover other mechanisms that may be active to direct the metals in cells.
Accumulation and sequestration	- Analytical techniques (X-ray emission - scanning electron microscopy, microanalysis) can provide information on speciation and localization of metals in plants tissue; - It is important to understand the molecular bases of the capacity of some plants to hyperaccumulate and store the metals.
Identification of genes and proteins involved in tolerance and accumulation	- Genomics and proteomics approaches are being used to study the molecular and biochemical mechanisms of the process of hyperaccumulation.
Genetic bases of tolerance	- Genetic studies are being taken in order to determine the genetic bases of tolerance, accumulation; - Gene identification studies using genomic and proteomic approaches.
New contaminants	- Most common contaminants include radionuclides, heavy metals and nutrients; - New contaminants that are subject of research: arsenic, mercury.
	Organic contaminants
Mechanisms of genetic controls – candidate genes	- Gene identification studies using genomic approaches; - In the xenobiotics metabolism, specific candidate genes can code for enzymes that are part of the process.
Analysis and identification of enzymes and proteins	- In the metabolism of xenobiotics, the identification of new enzymes is determined due to proteomic approaches.
Transgenic approaches	- Transgenic approaches that can modify/improve the enzyme that is responsible for metabolic modification and degradation of xenobiotic molecule.
In vitro studies for implementation	- Bioassessment studies that use cell cultures are being taken before practical application when it comes to more complex contaminants.

Phytoremediation mechanisms of heavy metals. A living plant can be seen as a solar-driven pump because it is able to extract and concentrate particular elements from the contaminated environment. After harvesting the plants that are rich in accumulated contaminants, the following processes may be drying, ashing or composting (Raskin et al 1997).

There are a lot of factors that are affecting the uptake of heavy metals in the plants (Figure 4). The success of phytoremediation depends on taking into account as many factors as possible when it comes to the implementation of phytoremediation projects.

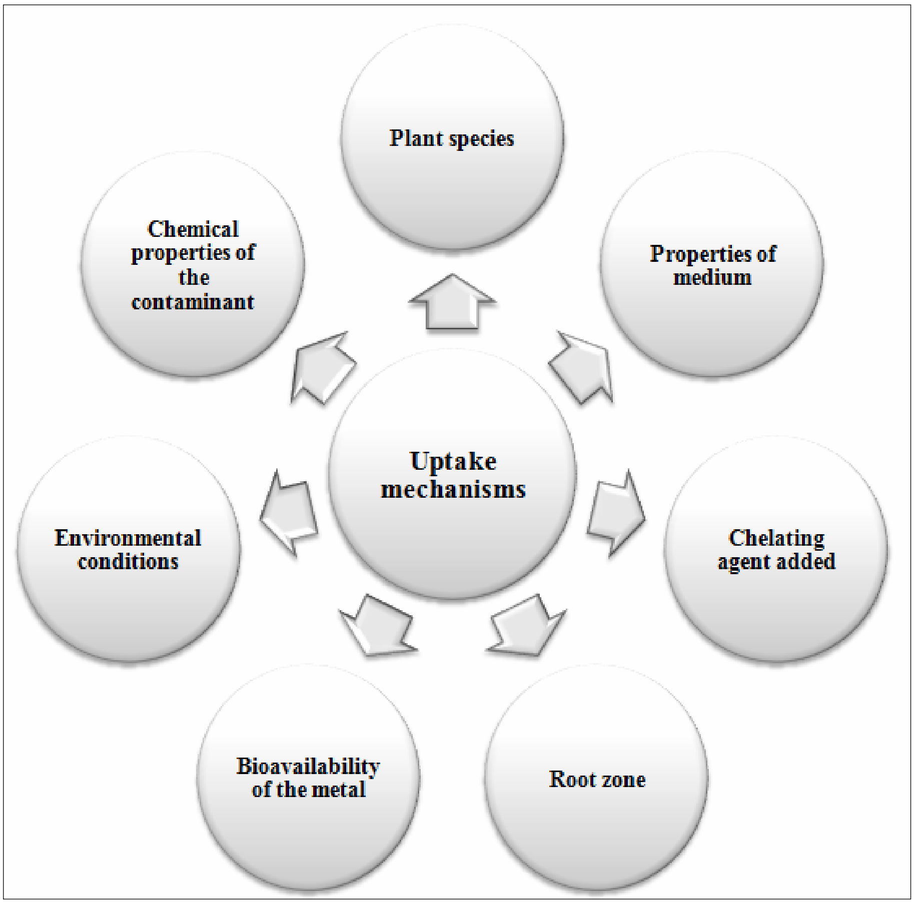

Figure 4. Factors that affect the uptake of heavy metals (Tangahu et al 2011).

Plant biochemical mechanisms in the case of phytoremediation of heavy metals are presented by Revathi & Venugopal (2013):

1. *Adsorption* – root surface is the key factor because it absorbs the elemental nutrients, binds pollutants and nutrients and favors the interaction between plant roots and soil microbes with the aim of increasing metal bioavailability;
2. *Accumulation and transport*:

- role of transporter proteins – proteins and peptides that increase metal binding in plants can improve metal tolerance or accumulation;

- chelating agents (natural and synthetic chelators) – chelating agents added to the soil help increase the metal bioavailability, uptake and translocation of heavy metals;

3. *Translocation* – root cells uptake metal ions and transport them to the shoots, process in which the membrane transport systems have a major role;
4. *Detoxification* – hyperaccumulators possess a great characteristic of being very efficient in detoxification and sequestration without having phytotoxic effects due to the adsorption of huge amounts of heavy metals;

- vacuolar compartmentalization – vacuoles are the main storage place of heavy metals in the cells of a plant and there is a vacuolar compartmentalization to control the distribution and concentration of metal ions in order to restrict other parts of the cell to have access to the contaminants;

- volatilization – metal ions are converted into volatile state;

5. *Hyperaccumulation* – the metal ion is concentrated to > 0.1 - 1 % of the dry weight of the plant.

Conclusions. Research on phytoremediation has an extreme importance in developing the new sustainable technologies. Understanding the biological mechanisms help improve phytoremediation and also identify the suitable candidate plant for the remediation. Further knowledge about adsorption, transport, accumulation and translocation can conduct to different strategies of environment improvement with the help of plants. Physiological and biochemical responses of a plant represent the basis of all technologies applied in phytoremediation. Future phytoremediation studies must be undertaken in order to understand more about the mechanisms and processes that take place in the relationship between plants, soil and microorganisms.

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