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Review

Nickel, cadmium and lead phytotoxicity and potential of halophytic plants in heavy metal extraction

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ABSTRACT

Among heavy metals, nickel, cadmium and lead have received a particular attention not only as potent hazards to human health but also given their constant increase in the environment and bioaccumulation throughout the food-chain. In plants, these metals may either directly or indirectly cause a broad range of physiological and biochemical dysfunctions culminating ultimately in the sharp decline of crop production. Here, we present new insights regarding the mechanisms governing metal phytotoxicity. In addition, we emphasize the potential interest of halophytic plants in the framework of the phytoremediation approach which has emerged as an environmental-friendly technology contributing to the extraction of heavy metal from contaminated sites. Indeed, recent reports suggest that halophyte species could be more suitable for heavy metal extraction than glycophytes most frequently used so far.

Contents

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1. Introduction

Contamination of environment by excessive heavy metals concentration represents a threatening risk to human, animal and plant health. Nowadays, land contamination with heavy metals has become a serious environmental problem which requires effective but also affordable technological solutions. Heavy metals and metalloids are particularly challenging soil contaminants due to their persistence in the environment. Generally, majority of heavy metals are released into environment by industrial and mining activities: manure, paints, battery manufacture and disposal or leakage of industrial wastes, as well as irrational application of minerals fertilizers and pesticide containing metals (Barrutia et al., 2010). Among heavy metals, lead (Pb), cadmium (Cd), and nickel (Ni) are recognized as significant environmental pollutants (Bernard, 2008; Gillette, 2008; Brunet et al., 2009). The current worldwide mine production of Cd and Pb is considerable. In the polluted soils, concentration of Ni can be 20- to 30-fold (200–26,000 ppm) more than the overall range (10–1000 ppm) (Sarvajeet et al., 2012). Ni was classified as "Allergen of the Year", in 2008 (Gillette, 2008). Cd and Pb are also widespread heavy metal pollutants in the environment with a long biological half-life (Brunet et al., 2009; Sarvajeet et al., 2012). The world production of Cd is continually expanding (Ghosh et al., 2013). In 1992, it was estimated at 16,000 tons (Juste et al., 1995) and it amounted to 17,800 tons in 2004 (Bertin and Averbeck, 2006). Pb has become also a particular concern, as its concentration in cultivated areas increases continuously (Tatár et al., 1999), thus confirming the risk induced by the consumption of contaminated food for human health.

During the last decade, the toxicity of heavy metals to plants has drawn the attention of many environmental scientists notably because plants represent the main route of heavy metal entry into the food-chain, presenting a danger to human health. In plants, metal toxicity affects various physiological processes such as water relationship and photosynthesis activity (Gopal and Rizvi, 2008; Chen et al., 2009) nitrogen metabolism and nutrient uptake (Alam et al., 2007; Gajewska et al., 2009) cell elongation (Molas, 2002; Demchenko et al., 2005). At the biochemical level, excess metals have a deleterious effect on membrane function and inhibit enzymes activities (Gajewska et al., 2009; Yusuf et al., 2010). In addition, there is increasing evidence that metal toxicity is associated with oxidative stress (Romero-Puertas et al., 2007; Yan et al., 2010) as reflected by the increase in the concentration of hydroxyl radicals, superoxide anions, nitric oxide and hydrogen peroxide (Hao et al., 2006; Yan et al., 2010). All of these alter physiological processes culminating finally in reduced crop yield and quality (Gajewska et al., 2006).

The growing concerns about environmental pollution have stimulated the efforts to propose new approaches on the remediation of environment. In this way, several physicochemical techniques were tested for treating metal-contaminated sites. Yet, these metal removing processes are rather expensive. In addition, these techniques often employ stringent physicochemical which can severely inhibit soil fertility with subsequent negative impacts on the ecosystem. Hence, the biological treatment, especially phytoremediation has emerged as a promising technology contributing to the recovery of sites contaminated with heavy metals (Petra et al., 2009). It is a relatively recent technique and is perceived as cost-effective, efficient, eco-friendly, and solar-driven technology with good public acceptance. This approach based on the capability of selected plants to grow and accumulate metals is an environmental-friendly and relatively cheap technique comparatively to physicochemical methods.

The success of metal extraction is however limited by the bioavailability of some heavy metals, especially Pb which is usually poorly bioavailable in polluted soils (Adriano, 2001) and the basic hallmarks of plants used for this process (Lestan, 2006). Plants used in soil remediation must be also adapted to cropping with abiotic constraints, including soil salinity. Nevertheless, saline soils are encountered in industrial contaminated sites (Ghnaya et al., 2005, 2007). Recently, it has been suggested that halophytes species, *i.e*. native salt tolerant species could be more suitable for heavy metal phytoremediation than glycophytes, most frequently used so far (Zaier et al., 2010; Mazharia and Homaeed, 2012; Amari et al., 2014). Interestingly, literature indicates that halophytes may be useful for phytoremediation (Nedjimi and Daoud, 2009; Eisa and Eid, 2011; Milić et al., 2012) increasing the interest for halophytic plant utilization to extract several toxic metals (Agoramoorthy et al., 2008; Lefèvre et al., 2010). These plants show high potential to tolerate and concentrate heavy metal in their tissues by triggering mechanisms detoxification (Zornoza et al., 2002; Sousa et al., 2008).

The objective of the present article is to review the current achievements in the context of understanding heavy metal (especially Ni, Cd and Pb) phytotoxicity mechanisms and to better highlight the importance of halophyte species for the environmental remediation purpose.

2. Chemical properties

Ni, Cd and Pb are among the 23 metals that are of great concern to environment and human health (Philp, 1995; de Burbure et al., 2006; Brunet et al., 2009). In soils, they can exist in various mineral forms (Table 1). Ni is the 24th most abundant elements (twice as Cu) forming about 0.008% of the earth's crust, where it occurs in igneous rocks as a free metal or together with iron (Hedfi et al., 2007). It is a hard, ductile and silvery-white heavy metal that can take a high polish. It has an atomic number of 28 in the periodic table and an atomic weight of 58.71. Natural nickel is a mixture of five stable isotopes. Although it can occur in several different oxidation states, the prevalent oxidation state under environmental conditions is Ni^{2+}. The ion radii of Ni^{2+} is similar to other cations (Ca, Mg) (Chen et al., 2009). Unlike Pb and Cd, Ni has a high mobility and an elevated rate of transport (Page et al., 2006).

Lead is a soft metal, gray, naturally present in soils. It is the Group XIV b of the periodic table and an atomic weight of 207.2. It is a trace constituent of common rock-forming and readily weatherable minerals and a major constituent of various sulphide, sulphate, oxide, carbonate and silicate minerals (Reimann and de Caritat, 1998). Pb can also exist in different oxidation states (Pb, Pb^{2+}, Pb^{4+}). The Pb^{2+} cation is an acid in the Lewis sense, it can bind several ions in the medium (Sposito et al., 1982).

Cadmium is a silver white metal, slightly bluish. This element, belonging to the family of transition metals, has eight stable natural isotopes and an atomic weight of 112,4. In soil solution, it is mostly in the cation form (Cd^{2+}) (Tricot, 1999). Its chemical properties have many similarities to those of zinc and calcium. Hence, it can cross biological barriers and accumulate in tissues.

3. Metal uptake

Cd, Pb and Ni uptake by plant roots is not mediated by the same mechanisms. Cd and Ni uptakes are mainly carried out by roots via a passive diffusion and/or active transport (Costa and Morel, 1993; Seregin and Kozhevnikova, 2006). More recently, Li et al. (2012) demonstrated that Cd uptake is regulated by Ca transporters or channels in root cell plasma membranes of the halophyte *Suaeda salsa*. Pb is generally taken up through the root system via passive diffusion (Tung and Temple, 1996b). Histological observations have shown that Pb is

Table 1
Main chemical form of Ni, Cd and Pb in soils (Bur, 2008).

Elements	Chemical form in soil	Chemical forms in the soil solution
Ni	Ni^{2+}, $NiSO_4$, $NiHCO_3^+$, $NiCO_3$	Ni^{2+}
Cd	Cd^{2+}, $CdSO_4^-$, $CdCl^+$, $CdHCO_3^+$, CdO, $CdCO_3$, $Cd(PO_4)_2$, CdS, $CdCl_2$	Cd^{2+} or chelates acid fulvic
Pb	Pb^{2+}, $PbHCO_3^+$, $PbOH^+$, PbS, $PbSO_4$, $Pb(OH)_2$, $PbCO_3$, PbO, $Pb(PO_4)_2$, $PbCl^+$	Pb^{2+} or chelates acid fulvic