SOME ASPECTS OF INTERACTIONS BETWEEN HEAVY METALS AND PLANT MINERAL NUTRIENTS

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ABSTRACT

Heavy metals are aggressive environmental pollutants. They are easily taken up by plants and they are strong stress factors for plant metabolism. Heavy metals influence includes also disturbances in plant mineral nutrition by competition with other nutrients. Typical symptoms of heavy metals toxicity are often similar or even the same like symptoms of some essential nutrients deficiency. The aim of this paper is to discuss mechanisms of some heavy metals uptake and possible ways of their influence on some basic and trace nutrients availability for plants. Attention is also paid to regulatory relationships among groups of heavy metals themselves. Moreover, possibilities and limitations in revitalization of heavy metal-treated plants by micro-, and macronutrient supply are discussed.

KEY WORDS: detoxification, heavy metals, heavy metal-induced deficiency, interactions, mineral nutrition, uptake.

INTRODUCTION

Heavy metals (metallic elements with atomic number higher than 20, as defined by Kabata-Pendias and Pendias 1979) are widely known inhibitors of plant metabolism. The influence of many of them on photosynthesis and many other physiological processes in plants is quite well known (for review see Mishra and Kar 1974, Clijsters and Van Assche 1985, Baszyński 1986, Terry and Abadia 1986, Droppa and Horvath 1990, Van Assche and Clijsters 1990, Woźny et al. 1990, Mukhopadhyay and Sharma 1991, Baszyński and Krupa 1992, Drażkiewicz 1994, Palit et al. 1994, Krupa 1995). It should be noted that in many cases there is a strong resemblance between some HM toxicity symptoms and those, for instance, of iron deficiency (Terry 1981, Raven 1990, Thys et al. 1991). Burzyński (1987) pointed out that typical toxicity symptoms observed in Cd- and Pb-treated young cucumber plants were in fact the secondary effects resulting from essential nutrients (K, Ca, Fe) deficiency. On the another hand, some evidence is available about the possibility of detoxification of in vitro Cu, Cd and Pb-treated chloroplasts by Mn (Li and Miles 1975,

Van Duijvendijk-Matteoli and Desmet 1975, Samuelsson and Öquist 1980, Becerril et al. 1988). These phenomena constrain to pay more attention to the relationships between HMs and other essential plant nutrients.

From the view point of plant physiology we can divide HMs into two groups:

1. metals necessary for plant metabolism (as enzyme activators, regulators, etc.), e.g. Fe, Cu, Mn, Mo. They may become toxic if their supply exceeds the plant needs;
2. metals not required for plant metabolism, e.g. Cd, Hg, Pb. They are toxic at much lower concentrations than the first-group. However, some authors, on the basis of data from nutrient solution experiments and wide range of plant species growing on metal-amended sludges, consider Cu as the most toxic heavy metal before Cd (Fernandes and Henriques 1991, Smilde 1982, Wong and Bradshaw 1982).

This short review shall not deal with the relationships between plant metabolism and toxic influence of elements like Al or Mg which, according to the previously cited definition, are not heavy metals.

HEAVY METALS UPTAKE AND DISTRIBUTION IN HIGHER PLANTS

HMs accumulation is related to the form in which they are present in the nutrient solution. The experiments of De Kock and Mitchell (1957) with mustard and tomato showed differences in divalent and trivalent cations uptake depending on their availability in inorganic or chelated form:

Abbreviations:

ABA – abscisic acid;
ATA – ammonia triacetic acid;
ATP-ase – adenosine 5'-triphosphatase;
DNP – 2,4-dinitrophenol;
DTPA – diethylenetriamine-pentaacetic acid;
EDTA – ethylenediamine-tetraacetic acid;
IAA – indole-3-acetic acid;
HM – heavy metal.

1. divalent cations, like Co, Ni, Zn or Cu were much easier taken up by plants when present in nutrient solution in ionic form than chelates, particularly with EDTA as a ligand. Their uptake was reduced even when EDTA was present in the nutrient solution not as a free acid but in the form of Fe-EDTA (source of iron instead of inorganic salts). The lower sorption of Zn and Mn used as chelates in foliar nutrition experiments was attributed to the limited number of metal cations available for retention by the negative sites of the cuticle. The size of the complex might also decrease the rate of binding on the surface and access to inner sites (Ferandon and Chamel 1988);
2. trivalent cations, like Cr, Ga or In behaved differently. They were easily taken up and translocated to shoots if present in chelated form. The ligand-dependent order of uptake intensity was: EDTA > ATA >> DTPA. Probably the electric charge on the chelating molecules was one of the factors controlling absorption by the roots, because those with no charge or a single negative charge were taken up while complexes with two negative charges were not. If trivalent cations were present in ionic form they were taken up only in trace amounts.

We can also divide HMs into three groups according to their accumulation in plant roots and shoots (Hara et al. 1976 a, b, Jastrow and Koeppel 1980). Fig. 1. illustrates these criteria:

- a) the first group consists of elements usually accumulated in roots rather than in shoots. These are: Cd, Fe, Cu, Co and Mo;
- b) the second group accumulates in roots with very little concentrations in shoots. This group consists of Pb, Sn, Ti, Ag, Cr, Zr, V and Ga;
- c) the third group of elements is uniformly distributed between roots and shoots: Zn, Mn, Ni.

Mechanisms of HMs uptake and distribution are very complex. For Cd, one of HMs strongly accumulated by plants when present in growth medium, they are well recognised. According to Greger (1989) Cd is taken up metabolically in low, and non-metabolically in high supply. Cutler and Rains

(1974) described three mechanisms of its non-metabolic uptake by excised barley roots:

1. exchange adsorption – reversible Cd binding to the root surface. Such metals as Cd, Zn, Cu and Hg were non-selectively bound to this surface and could be easily removed by desorption solutions like diluted acids or diluted chelators. This sorption mechanism could be proposed as the main pattern in short-term experiments;
2. non-metabolic binding – primary accumulation mechanism. Cd binding to the sites located on constituents of the cell wall or macromolecules within the cell maintained a concentration gradient of Cd sufficient to allow its accumulation by diffusion;
3. diffusion – Cd movement across cell membranes. Linear temperature response of sorption, absence of sorption changes with metabolic disturbances at higher temperatures, inhibition by anaerobic conditions and DNP were considered to account for this mechanism to be diffusion and non-metabolic process. This mechanism was responsible for Cd entering into the symplastic pathway necessary for its translocation from roots to shoots.

It is difficult to fully agree with the postulate about the strictly diffusional way of Cd entering the plant because reduced uptake of this metal in anaerobic conditions or in the presence of DNP, which are known to reduce metabolically-dependent membrane permeability, may suggest the metabolic mechanism (Cataldo et al. 1983). Smeyers-Verbeke et al. (1978) divided plant-absorbed Cd into two fractions:

1. non-metabolically bound fraction, which is free diffusible and exchangeable. Its uptake corresponded well with the scheme of Cutler and Rains (1974) described above;
2. metabolically mediated fraction taken up by metabolic processes. Absorption of this fraction was inhibited by Zn and Cu, probably by competition.

Furthermore, when Cd was accumulated in plant tissues it might effect directly and indirectly plant functions including metal uptake (Jastrow and Koeppel 1980). Kwan and Smith (1991) compared Cd and TI uptake by *Lemna minor* L. and showed that Cd was accumulated continuously by plants and its significant amount was located within the cell constituents

Fig. 1. Different schemes of heavy metal distribution between plant roots and shoots.

(50% bound to the cell wall), while TI was probably accumulated in the vacuole, and its absorption was quickly saturated.

The pattern of Cu uptake seemed to be the same as proposed by Greger (1989) for Cd. Mechanisms of active and passive Cu uptake operated simultaneously: a relative importance of the passive uptake mechanisms increased with increasing Cu level in the growth medium, but when Cu concentrations in the environment were low active absorption predominated. The specific ionophore, probably a polypeptide carrier, from the root-cell plasmalemma outer surface was responsible for active Cu uptake. Its configuration change led to Cu ion release into the cytoplasm after passing the membrane (Fernandes and Henriques 1991).

The mechanisms of other divalent HMs cations (Co, Mn, Ni, Pb) uptake were reviewed elsewhere, and in general they fulfill the same patterns as described above for Cd and Cu (Mishra and Kar 1974, Mukopadhyay and Sharma 1991, Woźny and Krzesłowska 1993, Palit and Sharma 1994).

RELATIONSHIPS BETWEEN HEAVY METALS AND OTHER NUTRIENTS

One of the most important factors in HMs influence on plant metabolism are their relationships with other mineral nutrients. Regulatory mechanisms in plant HMs nutrition have been only partially known so far and seem to be very dynamic. Symeonidis and Karataglis (1992) divided plant responses to combinations of metals in the growth medium into three basic groups:

1. additive, i.e. plant growth parameters under conditions of multiple metal stress were equal to those observed in the presence of the investigated metals supplied separately;

2. antagonistic, i.e. plant growth parameters under conditions of multiple metal stress were bigger than those observed in the presence of the investigated metals supplied separately;

3. synergistic, i.e. plant growth parameters under conditions of multiple metal stress were smaller than those observed in the presence of the investigated metals supplied separately. Fernandes and Henriques (1991), for instance, found that in a number of plants Cu seemed to be synergistic with Zn and Ni, antagonistic with Cd and additive with Co.

The data in Table 1 showed that all investigated HMs caused a strong Fe deficiency by its decreased uptake or immobilization in roots. Zn and Cu levels were also lowered. The susceptibility order of these necessary trace elements to HMs seems to be: Fe >> Zn ≈ Cu. In all examined plants strong disturbances in K and/or Ca levels were also observed, which resulted in K/Ca ratio changes and could have a great impact on water balance. Also the levels of basic plant nutrients such as N and P were changed by HMs.

Fe is one of the key nutrients for plants (for review see Terry and Abadia 1986) and its HM-induced deficiency may strongly influence plant metabolism, the more that Fe seems to be one of the main targets of HM influence on the plant mineral content. There are data confirming the fact that: Cd, Co, Cr, Pb, Ni, Mn and Zn accumulation causes Fe deficiency in plants (Hunter and Vergnano 1953; Tanaka and Navasero 1966; Walker et al. 1977; Terry 1981; Khan and Khan 1983; Greger and Lindberg 1987; Vazquez et al. 1987; Misra and Ramani 1991; Siedlecka and Baszyński 1993). Terry (1981) showed that almost all symptoms of Co toxicity strongly resembled those of Fe deficiency. Because of a very strong Fe depletion (up to 80%) it might be considered as a main source of Co-induced disturbances in plant metabolism.

TABLE 1. The influence of heavy metals toxic levels on plant mineral composition.

Heavy metal	Plant species	Plant organ	Level of mineral nutrient	
			decreased	increased
Cu	<i>Halimone portulacoides</i>	root	Zn	Fe
	<i>Avena sativa</i>	stem	N, P, K	Ca, Mg
	<i>Halimone portulacoides</i>	leaves	Fe, Zn	
Cd	<i>Raphanus sativa</i>	root	Fe, Zn	
	<i>Cucumis sativus</i>	root	Fe, Mg, K	
	<i>Cucumis sativus</i>	cotyledon	Fe, K, Ca	
	<i>Raphanus sativa</i>	shoot	Fe, Zn, Cu	
	<i>Zea mays</i>	leaves	Fe	
	<i>Cucumis sativus</i>	leaves	Fe, Cu, Zn	Mn
Ni	<i>Avena sativa</i>	stem	N	P, K, Ca, Mg
Co	<i>Avena sativa</i>	stem	K	N, P, Ca, Mg
Mn	<i>Avena sativa</i>	stem	Ca, Mg	N, P
Zn	<i>Halimone portulacoides</i>	root	Cu	Fe
	<i>Avena sativa</i>	stem	N	P, Ca, Mg
	<i>Halimone portulacoides</i>	leaves	Fe, Cu	
Pb	<i>Raphanus sativa</i>	root	Fe, Zn, Cu	
	<i>Cucumis sativus</i>	root	Fe, K, Ca	Mg
	<i>Cucumis sativus</i>	cotyledon	Mg, K, Ca	Fe
	<i>Raphanus sativa</i>	shoot	Fe, Zn, Cu	

Nutrient decrease – maximum 95% of control, nutrient increase – minimum 105% of control. Data taken from: Hunter and Vergnano 1953, Burzyński and Buczek 1983, Khan and Frankland 1983, Burzyński 1987, Siedlecka and Baszyński 1993, Reboredo 1994.

Fe and Zn are antagonistic – this might explain why both low and high Fe levels depressed corn plant growth (Adriano et al. 1971). Retarded plant growth may be caused by a low Fe level in the nutrient medium or by inhibited Zn uptake at a high Fe level. Conversely, the effect of Zn on Fe was similar, although Zn affected Fe translocation more than its absorption. Misra and Ramani (1991) confirmed that Zn toxicity induces Fe deficiency due to Fe-Zn interaction and competition. They explained it by similar ionic radii of hydrated cations and cell regulatory mechanisms. Zn cation had a regulatory effect on Fe absorption which could be toxic at high concentrations. In high Zn supply this mechanism induced Fe deficiency. However, Rosen et al. (1977) noticed that in Zn-poisoned corn plants chlorosis occurred without Fe deficiency and was relieved by increased nutritional Fe, probably by diminishing Zn transport to leaves. Among graminaceous species the relationships between Fe and Zn are stronger and phytosiderophores are supposed to enhance also Zn absorption (Walter et al. 1994). There are other important Fe-Mn regulatory relations except the Fe-Zn relationships described above (Gupta and Chipman 1976). Fe significantly decreased Mn uptake when its supply was above optimum (Gupta and Chipman 1976). If Fe content in the nutrient medium was too high plants developed Mn deficiency (Tanaka et al. 1966).

There are many nutritional factors that may cause interactions between HMs and transport as well as metabolic processes. The main function of iron plaque formed on roots of waterlogging rice plants is provide a proper Fe supply for plants and it also protects plants against Cu and Ni toxicity (Greipsson 1994, Greipsson and Crowder 1991). Root exudates enhanced bioavailability of some toxic metals, e.g. Cd (Mench and Martin 1991).

Cd uptake might be also inhibited by Mn or other essential nutrients (Tab. 2). Thys et al. (1991) showed that Fe supply significantly diminished Cd content in lettuce leaves with parallel increase in K and Zn content. Cd itself could interfere with the uptake of various nutrient elements probably by its influence on root membranes, ATP-ases and other carriers and by decrease in root respiration which in turn may diminish the uptake of elements actively transported into the roots (Greger 1989, Ros et al. 1992). Root damage or root growth inhibition by Cd or other HMs may cause decreased uptake of nutrients like Fe, Ca, Mn taken by young, unsuberized root tips (Greger 1989, Godbold and Kettner 1991). Both Pb and Zn interacted with Cd by depressing its uptake, while their own intake increased drastically.

Zn also decreased Pb uptake (Symeonidis and Karataglis 1992). Pb itself caused Ca and Mn depletion in *Picea abies* needles which was due to decreased number of root tips and apoplastic solution flux through the endodermis (Godbold and Kettner 1991). However, in the opinion of Burzyński and Grabowski (1984) the decrease in water content and nitrogen uptake was the main reason of Pb-induced plant metabolism disturbances.

Unfortunately, increased supply of other essential metallic nutrients may be dangerous for HM-treated plants. Ni toxicity was increased in the presence of Co, Cr, Zn, Mn, Mo (Hunter and Vergnano 1953). All these elements, if present in elevated amounts, intensified the Ni-type specific chlorosis and necrosis. Moreover, Ni-, Co- and Zn-treated oat plants had even a three times higher P level in stems than control plants (Hunter and Vergnano 1953). Such disturbances in the level of basic nutrients must have had further effect on plant metabolism.

Another pair of elements with a strong relationship is that of Mn and Mg, and plant tissue Mn/Mg ratio appeared to be the most important factor in maintaining a good condition of plants, even cultivated at a phytotoxic Mn concentration (Gossand Carvalho 1992, Le Bot et al. 1990).

Adedeji and Fanimokun (1984) observed a close linear relationship between increasing Cu and N concentration in leaves of *Amaranthus dubius* Marl. ex Thell and *Celosia argentea* L. In wheat plants Cu reduced N level of the leaves. This reaction slightly depended on N source (antagonism was greater with NH_4^+ than with NO_3^- containing sources). N and Cu had an antagonistic influence on their concentrations in plants and the sequence of different N sources acting decreasingly on Cu content was: $\text{Ca}(\text{NO}_3)_2 > \text{NH}_4\text{NO}_3 > \text{NH}_4\text{Cl}$ (Cheshire et al. 1982, Kumar et al. 1990). Weber et al. (1991) noticed significant decrease in nitrogen in the forms of $\text{NO}_3^-/\text{NO}_2^-$, NH_4^+ , aminoacid-N and protein-N in Cu-treated *Silene vulgaris* (Moench.) Garcke shoots, while no changes were observed in the nitrogen level of roots. Plants grown on NH_4^+ source of N were less susceptible to Cu-induced nitrogen deficiency than those on NO_3^- source. Such results suggested various possible ways of Cu influence on N metabolism: competition between Cu^{2+} and NH_4^+ for membrane carriers, changes in the activity of some enzymes like nitrite reductase, glutamine synthase or amino acid transferase and resulting lack of certain amino acids. In *Amaranthus dubius* Marl. ex Thell and *Celosia argentea* L. excess of Cu induced a strong depletion of shoot Fe and P and a slight decrease of Mn, Mo and K content. Variable valency, a similar ion diameter and atom weight, and the affinity to proteins and proteids lead to antagonism between Cu and Fe, Mn and P (Adedeji and Fanimokun 1984). Reboredo (1994) reported data showing that a high Cu concentration in short-term experiment on young *Halimione portulacoides* L. plants caused Fe and Zn level increase in leaves, while a ten times lower concentration in a long-term exposition of the same plants caused severe (37% of control) Fe deficiency, mainly by its immobilization in roots. A strong inhibitory effect of Cu on other nutrient elements like Ca, Mg, Fe and particularly K level in shoots could be explained by divalent Cu ions binding sulfhydryl groups and root membrane lipid peroxidation. This in turn, led to damage of the permeability barrier of root cells and to K ions leakage and Cu ions diffusion into roots (De Vos et al. 1991, Strange and Macnair 1991, De Vos et al. 1993, Ouzounidou 1994).

Another mechanism involved in nutrient regulation of HM-treated plants might include changes in root reductase activities. Fe-deficient pea plants showed increased reduction rate of Fe^{3+} , Cu^{2+} and Mn^{3+} and enhanced uptake of Cu, Mn, Fe, Mg and K. Depriving pea or soybean plants of Cu or Zn stimulates the Fe^{3+} reduction (Norwell et al. 1993, Welch et al. 1993). Changes in the root redox status of HM-treated plants, their Fe deficiency (Tab. 1) and root redox changes in Fe-deficient plants are well documented (Gabielli et al. 1990, Van Assche and Clijsters 1990, Norwell et al. 1993, Schmidt 1993, Burzyński and Buczek 1994). It allows to taking into consideration the mechanism of increased Fe^{3+} reduction rate described by Norwell et al. (1993) operating in HM-poisoned plants, although no supporting data have been obtained yet. Among trees interaction mechanisms of HM/other nutrients were complicated by mycorrhiza and were not well investigated (Kahle 1993).

TABLE 2. The influence of mineral nutrition on the heavy metals uptake and distribution.

NE	Plant	Plant organ	HM decreased	HM increased
N	<i>Triticum aestivum</i>	shoot	Fe, Zn, Mn,	
Cu	<i>Glycine max</i>	root	Cu	
	<i>Glycine max</i>	shoot	Cd	
Mn	<i>Glycine max</i>	root	Cd	
	<i>Glycine max</i>	shoot	Cd	
Fe	<i>Glycine max</i>	root	Cd	
	<i>Lactuca sativa</i>	leaves	Cd	Fe, Zn
	<i>Phaseolus</i>	leaves	Cd	Fe
Mo	<i>vulgaris</i>	leaves	Cd	Fe, Mn
Pb	<i>Cucumis sativus</i>	root	Cu	Pb
	<i>Holcus lanatus</i>	shoot	Cd	Pb
Zn, Pb	<i>Holcus lanatus</i>	root	Cd	Pb
	<i>Holcus lanatus</i>	shoot	Cd	Pb, Zn
Zn	<i>Holcus lanatus</i>	root	Cd	Zn
	<i>Holcus lanatus</i>	root	Cd, Pb	
	<i>Glycine max</i>	shoot	Cd	Pb, Zn
	<i>Holcus lanatus</i>	shoot	Cd	
	<i>Glycine max</i>		Cd	

NE – nutrient element. Heavy metals decrease or increase – at least 5% of control values. Data taken from: Cataldo et al. 1983, Burzyński and Buczek 1989, Singh et al. 1990, Thys et al. 1991, Symeonidis and Karatagliis 1992, Siedlecka and Krupa unpubl.

NUTRIENT ELEMENT INTERACTIONS AS MECHANISMS INVERTING THE TOXICITY OF HEAVY METALS

HMs may cause essential nutrient deficiency, therefore, series of experiments on reversing their toxicity by elevated macronutrients supply were carried out by a number of authors.

John (1976) showed that increasing K and P supply caused a significant decrease in Cd absorption. Also Trivedi and Erdei (1992) found that plants with a high K supply accumulated less Cd and Pb than plants with low K status. They explained it by predomination of either active or passive K transport. In low K plants its transport was an active process regulated by negative feedback, while in high K plants it was passive. Detoxifying effects of K on HM toxicity symptoms in high K plants could be explained by a competition between these elements (Singh and Dahya 1976).

P was also able to decrease HM uptake by plants but was itself decreased by excess Fe (Singh and Dahya 1976).

HMs themselves can also be used for plant detoxification. Table 2 shows that HMs revitalize plants by intensifying the uptake and/or transport of other nutrients, or by inhibiting the uptake of other HMs. Competition in uptake was particularly strong among elements with similar chemical properties like Zn, Pb and Cd. Moreover, detoxicating mechanisms, in contrast to HMs susceptibility of plants, seem to depend only a little on plant growth stages.

According to Burzyński and Buczek (1989) Mo appeared to be a good antidotum for Cd-treated plants because it stimulated translocation of some essential nutrients like Fe, Cu, Mn, Zn from roots to leaves, resulting in a strong stimulatory effect on plant metabolism without decreasing Cd concentrations in leaves. Additional Mn or Fe supply also lowered Cd

content in leaves (Baszyński et al. 1980, Tukendorf and Baszyński 1991, Siedlecka and Krupa unpublished). Cu caused a reduction of Ni-toxicity symptoms by preventing necrosis (Hunter and Vergnano 1953). Ni-induced chlorosis is also prevented by higher Fe supply or even higher N supply because of N stimulatory effect on Fe translocation to leaves in Ni-treated plants. Nitrogen in the form of urea increased toxic Ni influence by decreased Fe, Zn, Cu and Mn content in shoots (Singh et al. 1990, Tab. 2). Wong and Bradshaw (1982) comparing the toxicity sequence of HMs for plants obtained by different researchers with their own for *Lolium perenne* (Cu > Ni > Mn > Pb > Cd > Zn > Hg > Cr > Fe) found them compatible with the order of stability of metal organic complexes. This explains why chelating by soil organic matter decreased metal availability for plants.

Application of macronutrients (like P) or metallic elements (like K or Fe) may revitalize HM-treated plants, but in field conditions they must be used with a particular care because of very complicated relations between all mineral compounds and soil organic matter, different for individual soil types (Hodgson 1963, Bjerre and Schierup 1985, Kiekens et al. 1984). Moreover, data obtained even in in vivo experiments cannot be simply transferred to natural conditions because they differ with regard to plant sensitivity, growth stage at which HM is supplied, and the period of its presence in the nutrient medium (short- or long-term experiments) (Gabbrielli et al. 1990, Paliouris and Hutchinson 1991, Goss and Carvalho 1992, Macfie and Tylor 1992, Von Frenckell-Insam and Hutchinson 1993, Maksymiec et al. 1994, Reboredo 1994). Even the choice of plant organs for monitoring changes in the physiological processes may be important because of differences in susceptibility to HMs and their distribution mechanisms (Marsh and Peterson 1990, Sieghardt 1990). The form of metal (inorganic or chelated), way of its supply (soil or fo-

liar nutrition) and concentration are also of great importance (Kiekens et al. 1984, Ferrandon and Chamel 1988, Xian 1989).

SUMMARY

The knowledge about regulatory mechanisms in plant mineral nutrition may help us to solve the problem of plant detoxification during HM stress. However, the mechanisms of HMs interactions are very complex and still only fragmentarily known. HMs can inhibit the uptake of other nutrients by: competition, influence on root membranes (e.g. root membrane lipid peroxidation or damage of proteins), ATP-ases and other carriers, decreased root respiration (diminishing the active transport of elements), root damage and root retarded growth resulting in decreased unsuberized root tips area and damage of the permeability barrier of root cells. Decreased essential nutrient content is also caused by ion leakage from damaged roots (K) and immobilization of elements in roots resulting in their strong deficiency in shoots despite their intensive uptake. Even for one pair of elements the interaction mechanisms may be different: increased Fe supply diminishes Zn uptake, while Zn does not decrease Fe uptake but its translocation to shoots by a strong immobilization in roots. Interaction between HM and other nutrients may also lead to toxic increase of some nutrients level in shoots (Ni/P). HMs used as detoxification factors may influence plant metabolism not only by decreased uptake of harmful element but also by increased transport of other essential metallic and non-metallic elements to shoots. HMs/other nutrients and HMs/HMs interactions despite the factors described above involve also changes in water balance, functioning of enzymes and even in plant hormone levels. Unfortunately, the influence of none of HMs on plants has been fully elucidated so far.

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PEWNE ASPEKTY INTERAKCJI MIĘDZY METALAMI CIĘŻKIMI A SKŁADNIKAMI MINERALNYMI ROŚLIN

STRESZCZENIE

Metale ciężkie są poważnym problemem w ochronie środowiska. Łatwo pobierane, silnie oddziałują na metabolizm roślin oraz powodują zaburzenia w żywieniu mineralnym roślin poprzez konkurencję z innymi składnikami. Typowe objawy toksycznego wpływu metali ciężkich są często podobne lub nawet identyczne z objawami deficytu niektórych niezbędnych pierwiastków. Celem tego przeglądu jest omówienie mechanizmów pobierania niektórych metali ciężkich oraz wyjaśnienie w jaki sposób metale te mogą wpływać na dostępność dla roślin niektórych mikro- i makroelementów. Rozważane są również mechanizmy regulacyjne istniejące pomiędzy metalami ciężkimi oraz możliwości i ograniczenia w stosowaniu makro- i mikroelementów do detoksyfikacji roślin traktowanych metalami ciężkimi.

SŁOWA KLUCZOWE: deficyt indukowany metalem ciężkim, detoksyfikacja, interakcje, metale ciężkie, pobieranie, żywienie mineralne.