Polish Journal of Environmental Studies Vol. 11, No. 2 (2002), 109-116

Original Research

Bioaccumulation of Al, Mn, Zn and Cd in Pea Plants *(Pisum sativum* L.) Against a Background of Unconventional Binding Agents

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Received: November 3, 2000
Accepted: December 7, 2001

Abstract

This article studies the effect of Aln, sodium humate, and sodium silicate on metal solubility and their bioaccumulation in pea plants. Research was carried out in 1997 using water cultures. There were three series of quick 2-week tests of plant reactions towards Zn^{2+}, Cd^{2+} (series I), Al^{3+} (series II) and Mn^{2+} (series III) added in the form of soluble salts into modified Knopp's substrate. The toxic amounts of Zn and Cd were added into the basic substrate in a form of soluble nitrate. Toxic quantities of Al and Mn were added into the substrate in a form of soluble salts: $A1C1_3 \cdot 6H_2O$ and $MnSO_4 \cdot H_2O$, respectively. Sodium humate, AI13 or both preparates were added into some objects to study zinc and cadmium immobilization (series I). Sodium silicate (IV), humic acid (Aldrich) or both were added into some objects in order to differentiate aluminum and manganese contents in the environment (series II and III).

Accumulation coefficients calculated for Zn and Cd showed that zinc presence in the substrate inhibited cadmium accumulation in the plant. Cadmium was easily accumulated in over-ground parts. Zinc was released due to Ali_3 with humic acid presence and then it accumulated in roots. Silicon compound, especially along with humic acid presence, was the factor determining the mobilization or immobilization of Al and Mn in the environment and thus it affected the yields of plants under study.

Keywords: Zn, Cd, Al, and Mn toxicity; immobilization effect; Al_{13}; sodium humate; sodium silicate; water cultures; pea plants

Introduction

Dynamic development of civilization during the last several years has led to the excessive accumulation of heavy metals (including cadmium and zinc) in the environment causing serious ecological problems. The gradual increase of soil pollution by these elements and their great mobility in the environment threatens to introduce these metals into the trophic cycle, a danger for living organisms [1, 2, 3].

Cadmium is a trace element particularly dangerous for humans, and zinc for plants. Those elements are easily biologically accumulated and thus they negatively affect all elements of the environment [1, 2]. Industrial emissions, municipal and industrial wastes are the main source of soil pollution by cadmium and zinc [2, 4], also fertilisation [3].

Mobilization and immobilization depends on many soil factors, inter-relations between the elements in the environment and unconventional means applied like Al_{13} or Al-montmorillonite [5, 6]. The organic matter and natural and artificial mineral sorbents can be widely utilized by humans in order to reduce the zinc and cadmium hazard [7]. Zinc and cadmium toxicity for plants is clear during their growth, development, and yielding [8, 9, 10].

The physiological function of aluminum in plants is not yet well known and it is supposed that its small amounts in the environment activate some plant enzymes and regulate the physical state of cellular plasma in plants with increased tolerance to that metal [11, 12]. However, aluminum excess is very harmful for plants [7, 13, 26]. Significant reduction of root development and decrease of biomass gains are the results of aluminum toxicity [14, 15].

Manganese plays important metabolic roles in plants including participation in redox processes [11, 15]. Plant requirements for manganese vary, but for the majority of cultivated plants, levels of 10-25 mg/kg is sufficient [10]. Intake of manganese by plants increases in acidic soils (pH < 5.5). Elevated manganese content in the soil is always a potential threat of toxicity that manifests as chlorosis and necrosis symptoms, as well as reduction of plant growth [16, 17, 18].

In some articles, it is proved that silicon presence in the environment antagonistically affects manganese, iron, and aluminum intake by plants. Increased amounts of active organic compounds contained in the environment influence silicon compounds [19, 20].

In this article, the results on Al_{13}, sodium humate, and sodium silicate on metal solubility and their bioaccumulation in pea plants were presented.

Material and Methods

Research was carried out in 1997 using water cultures. There were three series of quick 2-week tests of plant reactions towards Zn^{2+}, Cd^{2+} (serie I), Al^{3+} (serie II) and Mn^{z+} (serie III) presence added in a form of soluble salts into modified Knopp's substrate [21], which contained the following compounds at listed concentrations:

$Ca(NO_3)_2$	1.0g/dm^3
KNO_3	0.25 g/dm^3
KC1	0.12 g/dm^3
$MgSO_4 \cdot 7H_2O$	0.25 g/dm^3
H_3BO_3	550 mg/dm^3
$MnCl_2$	350 mg/dm^3
$CuSO_4 \cdot 5H_2O$	50 mg/dm^3
$ZnSO_4 \cdot 7H_2O$	50 mg/dm^3
2% $C_6H_5FeO_7 \cdot H_2O$	1.0 cm^3/dm^3

The toxic amounts of Zn and Cd were added into the basic substrate in a form of soluble nitrate. Toxic quantities of Al and Mn were added into the substrate in a form of soluble salts: $A1C1_3 \cdot 6H_2O$ and $MnSO_4 \cdot H_2O$, respectively. Sodium humate, Al_{13} or both preparates were added into some objects to study zinc and cadmium immobilization (serie I). Sodium silicate, humic acid (Aldrich) or both were added into some objects in order to differentiate aluminum and manganese contents in the environment (series II and III)

Polynuclear Al_{13} added into the objects (serie I) at 0.1 mmol Al_{13} / dm^3 was prepared due to the slow addition of NaOH solution to $AlCl_3 \cdot 6H_2O$ solution up to the ratio OH/A1 = 2.45 [22, 25]. Then the solution was filtered through 0.01 µm mesh and total aluminum ion concentration was evaluated. The final Al_{13} polymer concentration was 8.5 mmol Al_{13} / dm^3 of solution.

Table 1. PH values of medium and the content of mobile Zn^{2+} and Cd^{2+} ions - serie III.

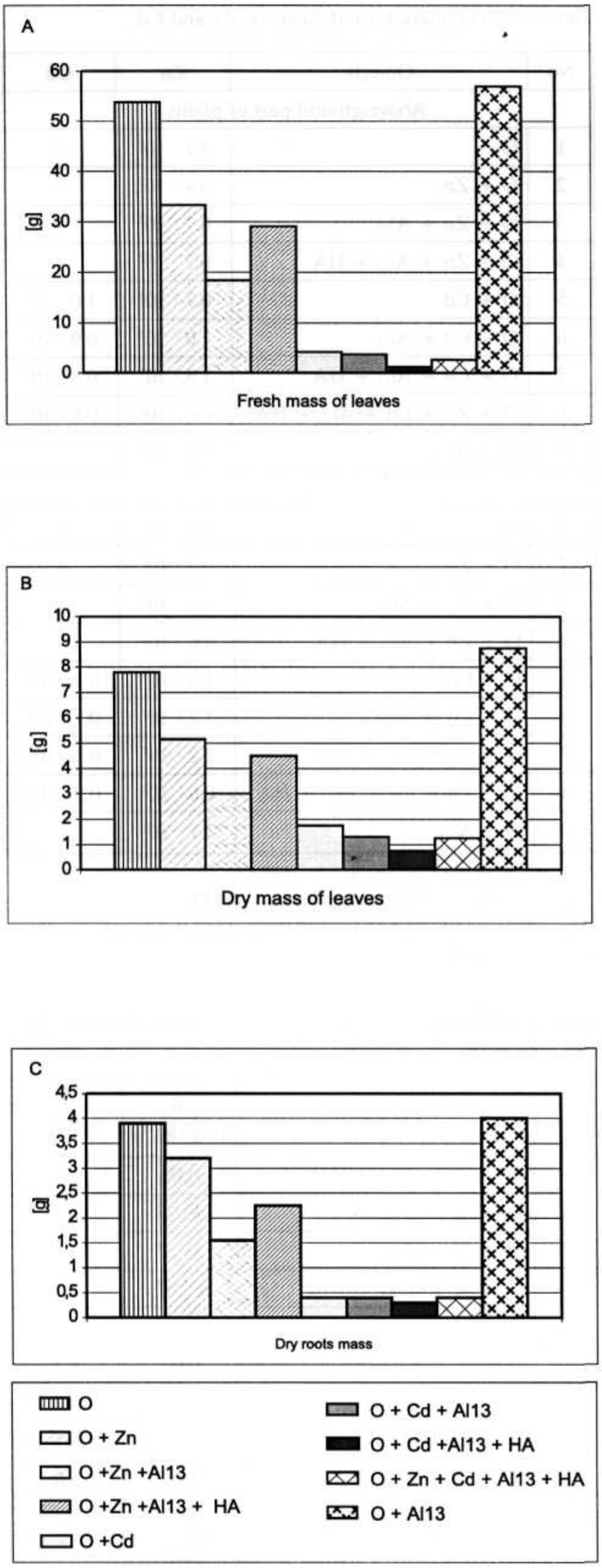
No	Objects	pH	Zn^{2+}(mg/dm^3)	Cd^{2+}(mg/dm^3)
1	O	6.1	0.02	0
2	O + Zn	5.8	6.3	–
3	O + Zn + Al_{13}	5.7	3.06	–
4	O + Zn + Al_{13} + HA	5.8	2.27	–
5	O + Cd	6.3	0.06	4.4
6	O + Cd + Al_{13}	6.1	0.04	4.3
7	O + Cd + Al_{13} + HA	6.4	0.04	5.6
8	O + Zn + Cd + Al_{13} + HA	5.5	3.92	7.0
9	O + Al_{13}	6.5	0.02	–

Zn - 0.1 mM zinc in $Zn(NO_3)_2 \cdot 6H_2O$

Cd - 0.1 mM cadmium in $Cd(NO_3)_2 \cdot 4H_2O$

HA - 200 mg/dm^3 of humic acid from Aldrich Firma

Al,3 - 0.1 mM Al_{13}/dm^3



Zn - 0,1 mM zinc in $Zn(NO_3)_2 \cdot 6H_2O$
Cd - 0,1 mM cadmium in $Cd(NO_3)_2 \cdot 4H_2O$
H.A. - 200 mg/dm^3 of humic acid from Aldrich Firma
Al_{13}-0,lmMAl_{13}/dm^3

Fig. 1. Yields of pea plants [g] *(Pisum sativum* L.) - serie III.

Pea *(Pisum sativum* L.) was tested plant. Its growth and development was observed during 14 days, then plants were cut, over-ground parts and roots were separated, dried and subjected to chemical analyses. Tested plants were digested using concentrated H_2SO_4 with H_2O_2 additions.

AAS (atomic absorption spectroscopy) technique was employed to record Zn^{2+} and Cd^{2+}, Al^{3+} and Mn^{2+} levels in Knopp's substrate solutions from water cultures, as well in dried plants.

Accumulation coefficients for zinc and cadmium in tested plants were calculated from the ratio of mean concentrations of a given element in a plant to its mean content in a substrate [2].

Results and Discussion

Table 1 presents pH changes and free zinc and cadmium ion content in water cultures. Values of pH ranged from 5.5 to 6.5. Zinc ion additions (object 2) caused slight decrease of pH value in relation to control, and cadmium ion additions (object 5) made pH value elevated by about 0.2 units. The addition of Al_{13} decreased pH by 0.3 units in object 3 with zinc; pH was constant in object 6 with cadmium. Humic acid was added to objects 4 and 7 along with Al_{13} Decrease of pH in objects with zinc, and increase of pH in objects with cadmium by 0.3 units occurred. The lowest pH value was observed in object 8, where Zn and Cd along with Al_{13} + humic acid were present. It is worth mentioning that the highest pH value was recorded in object 9 with no toxic means only with Al_{13} and it exceeded pH in control. No dependence between decrease of zinc and cadmium levels and increase of pH value was observed. Al_{13} and humic acid but not pH, were immobilizing factors. Al_{13} as the mean for free zinc and cadmium ions immobilization was used in objects 3 and 6.

From the results it follows that Al_{13} acted more preferentially in relation to zinc than to cadmium. Zinc content became twice lower as compared to object 2 (O + Zn) without Al_{13}. Al_{13} with humic acid were used as means for Zn and Cd immobilization in objects 4 and 7. Cadmium mobilization in object 7, and 3-fold decrease of Zn content in relation to object 2 with zinc and without mobilizing means was noted. Similar tendencies were observed in object 8 with Cd, Zn and mobilizing means. Zinc content decreased about twice as compared to object 2 (O + Zn), and cadmium levels increased almost twice compared with object 5 (O + Cd) which, as confirmed by literature data, can result from Cd and Zn antagonism [2, 23].

Pea yielding is presented in Fig. 1. As compared to control, the presence of toxic zinc in the substrate lowered the fresh and dry matter over 1.5 times, and root yield changed only slightly. Also, cadmium excess clearly did not favor plant yielding. Fresh matter yield decreased 13-fold and those of dry matter and dry root over 4-fold compared to control. Al_{13} addition into object 3 with toxic Zn did not affect the increase of yield but its decrease in relation to object 2 (O + Zn). The presence of Al_{13} in object 6 with Cd did not influence yield changes as compared to object 5 (O 4- Cd). Humic acid was applied along with Ali3 in objects 4 and 7. In the case of zinc, it caused an increase of yields compared to object 3 (without humic acid and with Al_{13}). In the case of cadmium, both means presence decreased yields. Both toxic elements with Al_{13} and humic acid occurred in object 8. Significantly lower yields as compared to object 4 where Zn with Al_{13} and humic acid was applied, and little higher than in object 7 where Cd was used along with immobilizing means were observed (Fig. 1). Higher fresh and dry matter yields as compared to those for control were recorded in object 9 where Aln only was added into the substrate in order to find out the toxicity of the mean towards pea (Fig. 1).

The results showed that polynuclear Aln displayed greater affinity to Zn than to Cd, which is consistent with other reports [23, 24]. It is worth underlining that organic matter presence along with Al_{13} helped in zinc mobilization [24]. Humic acid presence with Al_{13} led to cadmium mobilization, which corresponds with previous research of Badora et al. [26] carried out using soil samples from Switzerland. The highest Cd mobilization was found in objects where the element occurred along with Zn, which confirms the opinion of Alloway [1] that zinc inhibits cadmium absorption in the solution.

Many authors state [4, 9] that plant yields change due to changes of Zn and Cd toxicity, which was confirmed in the present research. Present studies are consistent with Alloway's [1] opinion that cadmium is more toxic for plants than zinc, and that Zn presence in the substrate inhibits the negative effect of Cd on plant yielding. Cadmium with Ali3 and humic acid lowered much more the fresh and dry matter yields than zinc only. Present studies also prove that in objects where only Ali3 without An and Cd was applied, plant yields were similar as for control and no toxicity symptoms were observed on leaf blades and root systems. Therefore, these studies do not confirm the opinion of Pokojska [27] upon high toxicity of polynuclear Al_{13}.

Kabata-Pendias and Pendias [2] and Alloway [1] state that the excess of cadmium as a redundant element for plant development blocked Zn accumulation in overground parts of plants, which is confirmed by results obtained.

Accumulation coefficients calculated for Cd and Zn in tested pea clearly show easy accumulation of cadmium in over-ground parts of plants (Table 2). The more free Cd ions in the environment, the more quantities were found in plants, which was confirmed by Curyto [28] and Kabata-Pendias and Pendias [2]. It was also observed that the increase of Zn content in the environment was associated with zinc transport in the plant. The presence of both Zn and Cd in the substrate along with Al_{13} and humic acid caused great increases of zinc content in both plant parts as compared to previous objects with only Zn or only Cd presence in the solution medium (Table 2). It was also observed that the increase of Zn content in the environment was associated with zinc transport in the plant [29].

Addition of free aluminum or manganese ions into the substrate (Tables 3 and 4) caused its pH decrease by 2 and 1 units, respectively. In objects treated with sodium silicate in order to immobilize free aluminum and manganese ions and in objects with sodium silicate plus humic

Table 2. Accumulation coefficients of Zn and Cd.

No	Objects	Zn	Cd
	Above-ground part of plants		
1	O	$1.1 \cdot 10^3$	–
2	O + Zn	$0.4 \cdot 10^2$	–
3	O + Zn + Al_{13}	$0.7 \cdot 10^2$	–
4	O + Zn + Al_{13} + HA	$0.7 \cdot 10^2$	–
5	O + Cd	$0.7 \cdot 10^3$	$1.0 \cdot 10^2$
6	O + Cd + Al_{13}	$1.0 \cdot 10^3$	$0.9 \cdot 10^2$
7	O + Cd + Al_{13} + HA	$1.5 \cdot 10^3$	$0.8 \cdot 10^2$
8	O + Zn + Cd + Al_{13} + HA	$0.6 \cdot 10^2$	$0.8 \cdot 10^2$
9	O + Al_{13}	$1.6 \cdot 10^3$	–
	Roots		
1	O	$9.0 \cdot 10^3$	–
2	O + Zn	$0.3 \cdot 10^1$	–
3	O + Zn + Al_{13}	$0.8 \cdot 10^2$	–
4	O + Zn + Al_{13} + HA	$0.6 \cdot 10^2$	–
5	O + Cd	$1.0 \cdot 10^3$	$0.1 \cdot 10^2$
6	O + Cd + Al_{13}	$1.2 \cdot 10^3$	$0.1 \cdot 10^2$
7	O + Cd + Al_{13} + HA	$2.2 \cdot 10^3$	$0.1 \cdot 10^2$
8	O + Zn + Cd + Al_{13} + HA	$0.6 \cdot 10^2$	$0.5 \cdot 10^1$
9	O + Al_{13}	$3.1 \cdot 10^3$	–

Zn - 0.1 mM zinc in $Zn(NO_3)_2 \cdot 6H_2O$
Cd - 0.1 mM cadmium in $Cd(NO_3)_2 \cdot 4H_2O$
HA - 200 mg/dm_3 of humic acid from Aldrich Firma
Al_{13}- 0.1 mM Al_{13}/dm^3

Table 3. PH values of medium and the content of mobile Al^{3+} ions - serie II.

No.	Objects	Al (mg dm^{-3})	pH
1	O	0.00	6.3
2	O + Al	39.25	4.1
3	O + Al + HA_1	31.27	4.1
4	O + Al + HA_2	27.07	4.1
5	O + Si_1	0.00	6.4
6	O + Si_2	0.00	6.8
7	O + Al + Si_1	27.85	4.2
8	O + Al + Si_2	0.03	6.1
9	O + Al + Si_2 + HA_1	0.08	5.0
10	O + Al + Si_2 + HA_2	0.23	5.2
	$\bar{x}$	12.58	
	LSD (p -0.05)	14.89	

Al - 54 mg aluminium • dm^{-3} in $A1C1_3 \cdot 6H_2O$
Si_1 - 1.67 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
Si_2 - 3.34 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
HA_1 - 100 mg • dm^{-3} of humic acid from AJdrich Firma
HA_2 - 200 mg • dm^{-3} of humic acid from Aldrich Firma

Table 4. PH values of medium and the content of mobile Mn^{2+} ions - serie III.

No.	Objects	Mn (mg dm^{-3})	pH
1	O	$9 \cdot 10^{-4}$	6.0
2	O + Mn	60.33	5.1
3	O + Mn + HA_1	55.07	5.4
4	O + Mn + HA_2	41.67	5.7
5	O + Si_1	0.01	6.7
6	O + Mn + Si_1	43.47	5.6
7	O + Mn + Si_1 + HA_1	38.53	5.3
8	O + Mn + Si_1 + HA_2	44.73	5.5
9	O + Si_2	$3 \cdot 10^{-3}$	6.8
10	O + Mn + Si_2	26.60	5.5
11	O + Mn + Si_2 + HA_1	39.27	5.2
12	O + Mn + Si_2 + HA_2	44.73	5.5
$\bar{x}$		32.87	
LSD (p -0.05)		14.76	

Mn - 100 mg manganese • dm^{-3} in $MnSO_4 \cdot H_2O$
Si_1 - 1.67 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
Si_2 - 3.34 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
HA_1 - 100 mg • dm^{-3} of humic acid from Aldrich Firma
HA_2 - 200 mg • dm^{-3} of humic acid from Aldrich Firma

acid higher pH values than in objects with only Al or Mn ions were recorded. However, it was found that only after the addition of $Na_2SiO_3 \cdot 5H_2O$ at the level of Si-2 (3,34 mmol • dm^{-3}) and along with humic acid, pH values were close to that of control in serie II of the experiment (with Al) (Table 3). In the serie III (with Mn) in all objects with Mn, pH values were close to that of object 2 (O + Mn). In the objects with silicate at both levels (objects 5 and 9) pH values exceeded even that of control (Table 4).

Both means for immobilization of toxic amounts of aluminum and manganese in the substrate contributed to the decrease of free Al ions level in the solution, but the highest immobilization effect was obtained in object where silicate was added at higher concentration and also in the object with silicate along with humic acid (Tab. 3 and 4). It is worth mentioning that effect of free Al^{3+} ion immobilization due to sodium silicate applied itself or along with humic acid was significantly higher than in a case of humic acid alone (Table 3). Immobilization of free Mn^{2+} ions in the presence of sodium silicate was also evident, but lower as compared to Al^{3+} ions (Tab. 4), which could be the result of higher pH values in the substrate [18, 30]. Additional presence of humic acid in the substrate favored rather manganese re-mobilization (objects 11 and 12, compared to object 10) (Table 4). However, presence of sodium silicate at Si-2 level along with humic acid also contributed to the highest reduction of free Mn ions.

According to Cocker's *et al.* [19] the impact of solubilization abilities of silicon compounds on the transfer of mobile aluminum forms into non-toxic ones through Al-Si bond formation is potentially very important. In

Table 5. Yields of pea plants in [g] *(Pisum sativum* L.) - serie II.

No.	Objects	Fresh mass [g] of leaves	Dry mass [g] of leaves	Dry mass of roots [g]	Average length of roots [cm]
1	O	21.30	3.32	2.03	22.00
2	O + Al	8.00	1.79	0.60	9.17
3	O + Al + HA_1	8.47	1.68	0.59	8.58
4	O + Al + HA_2	8.77	1.70	0.56	6.58
5	O + Si_1	16.73	2.76	1.96	28.00
6	O + Si_2	14.80	2.21	1.69	28.08
7	O + Al + Si_1	10.50	1.99	0.69	7.92
8	O + Al + Si_2	18.93	2.77	1.84	23.67
9	O + Al + Si_2 + HA_1	13.83	1.92	1.07	11.42
10	O + Al + Si_2 + HA_2	15.07	1.95	1.20	13.67
$\bar{x}$		13.64	2.21	1.22	15.91
LSD (p – 0.05)		5.13	0.76	0.37	8.06

Al - 54 mg aluminium • dm^{-3} in $A1C1_3 \cdot 6H_2O$
Si_1 - 1.67 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
Si_2 - 3.34 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
HA_1 - 100 mg • dm^{-3} of humic acid from Aldrich Firma
HA_2 - 200 mg • dm^{-3} of humic acid from Aldrich Firma

some publications, the main interests are focused on the chemistry of Al-Si interactions in solution [31, 32]. Lindsay and Walthall [33] state that Al-Si compound spetiations are determined by pH value.

Pea yields of this part of the study are presented on Tables 5 and 6. The presence of toxic elements in the substrate (Al, Mn) clearly contributed to an over 5-fold decrease of fresh and dry matter yield of over-ground parts of plants, as well as dry matter of roots. The highest pea yields in serie II (with Al) were recorded in objects where the following substrates were added: sodium silicate at Si-2 level (3,34 mmol • dm^{-3}), and sodium silicate at Si-2 level along with humic acid for aluminum detoxication. The presence of humic acid alone did not show such great effects as for above discussed ameliorants. In the case of Mn-serie (serie III) the influence of all investigated agents for manganese detoxication did not show clearly effects like in the case with Al (Table 6). However, the big effect of the addition of sodium silicate alone for the pea yields, as in the Al-serie, as well in the Mn-serie was founded.

In the opinion of some researchers [34, 35, 36], silicon can reduce the toxic action of aluminum towards growth of such plants as millet, soybean, barley, but not rice, cotton, wheat or pea [37], which was not confirmed by present results. However, some authors tend to suppose that silicon influences Al toxicity change not because of Al-Si chemistry in the solution, but due to the fact that the mechanism of amelioration occurs inside the plant [19, 31, 32].

Mn accumulation coefficients in tested plants (Table 8), quite high concentrations of Mn in roots of objects with sodium silicate alone or along with sodium humate was observed. In some objects quite high plant yields were obtained (Table 8). In the case of Al-serie (Table 7), the highest Al accumulation coefficient was recorded in roots of object (O + Al + Si_2) and in this object pea yields were quite high. The low accumulation coefficients were obtained in roots and in above-ground parts in the objects: O + Al + Si_1 and O + Al + Si_2 + HA_2 (HA_2 - the level of 200 mg humic acid • dm^{-3}) Probably low-molecular organic acids released by plants played an important role in Al, but not Mn ions detoxication [38]. Positive immobilizing effects of sodium silicate and humic acid presence could also cause such effect.

Conclusions

Polynuclear Ali_3 affected Zn^{2+} more than Cd^{2+} immobilization. Sodium humate along with Al_{13} help to immobilize Zn ions, but Cd immobilization by those means was clearly inhibited by the presence of zinc ions. It was noted that polynuclear Aln did not negatively affect the growth, development and yields of pea plants.

Accumulation coefficients calculated for Zn and Cd showed that zinc presence in the substrate inhibited cadmium accumulation in the plant. Cadmium was easily accumulated in over-ground parts. Zinc was released due to Al_{13} with humic acid presence and then accumulated in roots.

The presence of sodium silicate affected the decrease of free aluminum and manganese ions in the substrate,

Table 6. Yields of pea plants in [g] *(Pisum sativum* L.) - serie III.

No.	Objects	Fresh mass [g] of leaves	Dry mass [g] of leaves	Dry mass of roots [g]	Average length of roots [cm]
1	O	24.92	4.05	2.61	17.67
2	O + Mn	7.56	1.46	1.04	22.67
3	O + Mn + HA_1	9.21	1.66	1.10	26.50
4	O + Mn + HA_2	11.40	2.08	1.24	29.33
5	O + Si_1	31.14	5.31	2.84	24.00
6	O + Mn + Si_1	8.34	1.53	1.15	21.50
7	O + Mn + Si_1 + HA_1	10.88	1.97	1.22	26.83
8	O + Mn + Si_1 + HA_2	11.09	1.91	1.25	24.17
9	O + Si_2	28.97	4.57	2.67	21.50
10	O + Mn + Si_2	12.30	2.04	1.48	26.33
11	O + Mn + Si_2 + HA_1	13.11	2.02	1.31	25.67
12	O + Mn + Si_2 + HA_2	11.70	1.76	1.13	26.50
$\bar{x}$		15.05	2.53	1.59	24.39
LSD (p – 0.05)		3.18	0.59	0.36	8.17

Mn - 100 mg manganese • dm^{-3} in $MnSO_4 \cdot H_2O$
Si_1 - 1.67 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
Si_2 - 3.34 mmol • dm^{-3} in $Na_2SiO_3 \cdot 5H_2O$
HA_1 - 100 mg • dm^{-3} of humic acid from Aldrich Firma
HA_2 - 200 mg • dm^{-3} of humic acid from Aldrich Firma

Table 7. Accumulation coefficients of Al for pea plants *(Pisum sativum* L.).

No.	Objects	Al
	Above-ground part	
1	O	–
2	O + Al	$0.1 \cdot 10^2$
3	O + Al + HA_1	$0.2 \cdot 10^2$
4	O + Al + HA_2	$0.2 \cdot 10^2$
5	O + Si_1	–
6	O + Si_2	–
7	O + Al + Si_1	$0.1 \cdot 10^2$
8	O + Al + Si_2	$4.5 \cdot 10^3$
9	O + Al + Si_2 + HA_1	$3.1 \cdot 10^3$
10	O + Al + Si_2 + HA_2	$1.3 \cdot 10^3$
	Roots	
1	O	–
2	O + Al	$4.3 \cdot 10^2$
3	O + Al + HA_1	$5.3 \cdot 10^2$
4	O + Al + HA_2	$4.5 \cdot 10^2$
5	O + Si_1	–
6	O + Si_2	–
7	O + Al + Si_1	$4.1 \cdot 10^2$
8	O + Al + Si_2	$5.2 \cdot 10^4$
9	O + Al + Si_2 + HA_1	$4.9 \cdot 10^3$
10	O + Al + Si_2 + HA_2	$1.2 \cdot 10^3$

Al - 54 mg Al/ dm^3 ($A1C1_3 \cdot 6 H_2O$)
Si_1 - 1.67 mmol / dm^3 ($Na_2SIO_3 \cdot 5 H_2O$)
Si_2 - 3.34 mmol / dm^3 ($Na_2SIO_3 \cdot 5 H_2O$)
HA_1 - 100 mg / dm^3 (humic acid from Aldrich)
HA_2 - 200 mg / dm^3 humic acid from Aldrich)

Table 8. Accumulation coefficients of Mn for pea plants *(Pisum sativum* L.).

No.	Objects	Mn
	Above-ground part	
1	O	–
2	O + Mn	$0.2 \cdot 10^2$
3	O + Mn + HA_1	$0.2 \cdot 10^2$
4	O + Mn + HA_2	$0.2 \cdot 10^2$
5	O + Si_1	–
6	O + Mn + Si_1	$0.2 \cdot 10^2$
7	O + Mn + Si_1 + HA_1	$0.2 \cdot 10^2$
8	O + Mn + Si_1 + HA_2	$0.1 \cdot 10^2$
9	O + Si_2	–
10	O + Mn + Si_2	$0.3 \cdot 10^2$
11	O + Mn + Si_2 + HA_1	$0.2 \cdot 10^2$
12	O + Mn + Si_2 + HA_2	$0.3 \cdot 10^2$
	Roots	
1	O	–
2	O + Mn	$0.2 \cdot 10^2$
3	O + Mn + HA_1	$0.4 \cdot 10^3$
4	O + Mn + HA_2	$0.7 \cdot 10^3$
5	O + Si_1	–
6	O + Mn + Si_1	$0.8 \cdot 10^3$
7	O + Mn + Si_1 + HA_1	$0.9 \cdot 10^3$
8	O + Mn + Si_1 + HA_2	$0.7 \cdot 10^3$
9	O + Si_2	–
10	O + Mn + Si_2	$1.3 \cdot 10^3$
11	O + Mn + Si_2 + HA_1	$0.9 \cdot 10^3$
12	O + Mn + Si_2 + HA_2	$1.1 \cdot 10^3$

Mn - 100 mg Mn / dm^3 ($MnSO_4 \cdot H_2O$)
Si_1 - 1.67 mmol / dm^3 ($Na_2SIO_3 \cdot 5 H_2O$)
Si_2 - 3.34 mmol / dm^3 ($Na_2SIO_3 \cdot 5 H_2O$)
HA_1 - 100 mg / dm^3 (humic acid from Mndrich Firma)
HA_2 - 200 mg / dm^3 (humic acid from Mndrich Firma)

which essentially affected the concentration of Al and Mn mobile forms in the environment.

Silicon compound, especially along with humic acid presence, was a factor determining the mobilization or immobilization of Al and Mn in the environment and thus it affected the yields of plants under study.

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