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ASSESSMENT OF ALUMINIUM AND COPPER CONTAMINATION LEVEL IN SELECTED CROPS

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A b s t r a c t. Four crop species were used in the study: rye and wheat – monocots from the plant family of grasses, and lupines and clover – dicotyledonous plants from the family Fabaceae grown in hydroponics cultivation. Four weeks after the emergence the pH of the medium (pH = 4.5) was lowered and aluminium ions, at concentrations of 5, 10, 20, 40 and 100 mg dm^{-3} medium, were added in the form of $AlCl_3$. In an alternative experiment, copper ions were added at concentrations of 20, 50 and 100 mg dm^{-3} medium as $CuCl_2$. It turned out that the tested species (in particular rye) tolerated environmental pollution with aluminium better than with copper, despite the fact that the accumulation of aluminium in their tissues was much higher. The lowest resistance against copper and aluminium was noted for clover and wheat. Generally, the species (rye and lupine) which better tolerate the acidic medium also showed better resistance against environmental contamination with aluminium and copper. High indexes of tolerance for those plants are evidence for this thesis. Both analysed elements were mostly accumulated in the roots of plants and the translocation index for aluminium was much lower than that for copper.

K e y w o r d s: aluminium, copper, tolerance index, bioaccumulation factor, translocation index, crops

INTRODUCTION

Aluminium is a common metal on Earth as the crust is composed in 8% of that element. Aluminium toxicity is not correlated with the total content of the element in the soil but is a function of the concentration of the biologically active form in the soil solution which is easily available for plants. Plants absorb ions Al^{3+} just because they exist in their environment. However, no metabolic functions of this metal in plant physiology have been documented and thus this element is recognised as superfluous. Acidic soil (pH < 5) is one of the factors that increase the solubility of aluminium as well as heavy metals including copper

(Sukreeyapongse *et al*. 2002). Generally, copper is strongly bound in the soil. In acidic soils copper easily passes into the soil solution where it is absorbed by the root system. Under the optimal conditions copper, like most other heavy metals, is absorbed by the roots and used as a trace element in order to activate a number of enzymes. It plays a key role in photosynthesis and respiration chain, in electron transport in the detection of ethylene, metabolism, cell wall protection of oxidative stress and biogenesis of molybdenum cofactor (Yruela 2005.). However, a high concentration of aluminium and copper in acidic soils can seriously limit the growth and development of plants and, consequently, the quantity and quality of the yield. Worldwide approx. 50% of agricultural land is acidic (Zheng 2010). Therefore the acidification of soils is a global problem.

In the course of evolution plants have developed many strategies of survival under unfavourable conditions. The strategies of tolerance are the mechanisms associated with the exclusion of aluminium and heavy metals and the mechanisms associated with the tolerance of plants to high concentrations of these elements in symplast. This second mechanism is a typical feature of species which accumulate metals. With respect to aluminium this mechanism was reported for hydrangea (Naumann and Horst 2003), buckwheat (Ma *et al*. 1998) and tea (Carr *et al*. 2003). With respect to copper it was reported for dandelion, horsetail, grass, lettuce and maize.

The first class of the mechanisms of tolerance / exclusion dominates in the majority of plants. These mechanisms are active at the level of apoplast and / or in the rhizosphere. Their task is to prevent the penetration of metal into the sensitive areas of the root cells and further to reduce the phytotoxicity in the aerial parts of the plant. The diversity of plant genotypes, both cultivated and wild, with respect to environmental pollution is very high. The ability of plants to grow on contaminated surfaces it is not always in line with the strategy of the farmer whose primary task is to produce healthy, not contaminated food. Therefore, in practice, in order to evaluate the resistance / sensitivity and the degree of contamination of the plant a large number of indicators are used, including bioconcentration, translocation, tolerance, and the degree of contamination. These indicators were also used in this study.

The aim of the study was to compare the sensitivity of the four plant species (rye, wheat, lupine and clover) to substrate contamination with aluminium and copper and to assess the impact of large doses of these metals on the content and mobility of aluminium and copper in the plants tested.

MATERIALS AND METHODS

The research was conducted on the following plants: rye (*Secale cereale* L.) cv. Rostockie, wheat (*Triticum vulgare* L.) cv. Tonacja, blue lupine (*Lupinus angustifolius* L.) cv. Zeus, and clover (*Trifolium pratense* L.) cv. Jubilatka.

The plants were grown in a nutrient solution prepared according to Hoagland (Marschner 1995, Starck 2007a), at pH 7, with 16/8 h and 23/180°C (day/night) regime induced with sodium 400 W lamps (light intensity = 300 μmol m^{-2} s^{-1} PAR – Photosynthetic Active Radiation). Plant seeds were sown in aerated polyethylene vessels fitted with styrofoam inserts with pre-drilled holes in the underside of the pad to secure the mesh. Filter paper was provided between the insert and the mesh. Seeds of the test plants were planted in polyethylene vessels (with a capacity of 5 dm^3) at the rate of 1g for the small-seed plant – clover (*Trifolium pratense* L) and 80 seeds for the other plant species, and germination continued till the growth of 40 seedlings. The water level was controlled and adjusted every day. The solutions were renewed every 7 days. In order to ensure proper aerobic conditions the medium was additionally aerated using air pumps. In the initial phase of their growth and development the plants were grown in a medium at pH 7 (Szatanik-Kloc 2014). Aluminium and copper phytotoxicity increases in soils with pH < 5, therefore, 4 weeks after plant emergence, the medium pH was lowered to pH 4.5 in some of the containers. The plants were stressed at pH 4.5 during 14 days with different aluminium concentrations of 5, 10, 20, 40 and 100 mg dm^{-3}, added as $AlCl_3$ – aluminium chloride, and with different copper concentrations of 20, 50 and 100 mg dm^{-3}, added as hydrated copper chloride – $CuCl_2$ 2 H_2O. Plants grown continuously at pH7 and pH4,5 (without Al^{3+} and Cu^{2+} addition) were taken as the control treatments. During the stress the solution pH was measured and adjusted to the value of 4.5 every 24 h. The pH of the medium was maintained at pH 7 ± 0.2 for the control material and pH 4.5 ± 0.2 for the stress caused by the low pH and the presence of aluminium ions. If necessary, the pH of the medium was adjusted to value (pH 7 and pH = 4.5) with a 0.1 M dm^{-3} of potassium hydroxide (KOH) solution and a 0.1 M dm^{-3} of hydrochloric acid (HCl) solution. After 14 days of stress, the roots were separated from the upper parts and collected for further analysis. The roots and aboveground parts of the plant were analysed for dry matter and content of aluminium and copper.

In order to determine the dry weight of roots and aboveground parts 10 plants were taken form each variant of the experiment. Roots were separated from the aboveground parts. In order to obtain the dry weight the biomaterial was dried for 24 h at 303K and then for the next 24 h at 378K. Then the dry weight of roots and aboveground parts was determined through weighing. The dry weight was determined as the average from three iterations in mg / 1 plant.

The content of aluminium and copper in the plant material was determined after the dry digestion and dissolving the ash in HNO_3 (1:3), by ICP D-820 Hilger Analitycal (England). More detailed information regarding the determination of the dry weight and the content of aluminium and copper in the studied plants can be found in Szatanik-Kloc (2010)

On the basis of the data obtained the bioaccumulation factor (BAF), translocation index (IT) and the index of tolerance (Ti) were determined.

The plant ability to collect and accumulate metal was determined using the bioaccumulation factor (BAF) which is the ratio of the metal content in the root / aboveground part the plant to its content in the substrate (Skorbiłowicz 2008).

$$BAF = \frac{C_{Me}p}{C_{Me}w} \tag{1}$$

where: Me –Al / Cu and Cp is the concentration of Al / Cu in the root / aboveground part (mg kg^{-1}) and Cw is the concentration of these metals in the culture medium (mg 5 dm^{-3}).

In order to determine the mobility of aluminium and copper in the studied plants the translocation index (IT) was used. The index is determined by the following formula:

$$IT = \frac{C_{Me}b}{C_{Me}a} \tag{2}$$

where: $C_{Me}b$ – the metal concentration in the aboveground part and $C_{Me}a$ – the concentration of the metal in the roots (mg kg^{-1}).

The inhibition of growth of the tested plants due to the contaminated growth medium is determined by the tolerance index (Ti) which is calculated by the following formula (Starck 2007b):

$$Ti = \frac{d.m.\,of\ the\ plants\ contaminated}{d.m.\,of\ the\ control\ plants} \tag{3}$$

The results were statistically analysed including the analysis of variance and the post-hoc Tukey HSD test at the significance level of $\alpha = 0.05$. The Pearson simple correlation coefficient was calculated using Statistica 10.1.

RESULTS AND DISCUSSION

The content of the analysed elements varied depending on the dose of aluminium and copper, and on the species and analysed parts of the plant (Table 1).

The studies showed that with increasing environmental pollution (nutrient solution) with aluminium / copper the content of these elements in the examined plants increased significantly. Analysing the content of aluminium and copper in various parts of the plant, significantly higher accumulation of these elements was noted in the roots of the test plants than in the aboveground parts. Pearson's coefficient of linear correlation between the degree of environmental contamination with aluminium and the content of this element in the roots ranged from 0.95 for rye to 0.56 for lupine, while in the aerial parts it was 0.99 and 0.67, respectively. Whereas, the value for wheat and clover was r = 0.71 and 0.64, respectively, and for aluminium content in the roots and aerial parts it was r = 0.96 in both plants.

Table 1. Content of aluminium and copper in the studied plants, in g kg^{-1} dry matter (av. from 3 measurements, the deviations between individual data did not exceed 20%). The letters in the first row (Al^{3+}) and the line (Cu^{2+}) are homogeneous groups analysed to factor – plant species. The columns analysis was carried out by factor – concentration in the solution. Tukey's HSD test at p = 0.05. The letters represent the same homogeneous groups – no statistically significant differences

	Roots				Aboveground parts			
	Rye	Wheat	Lupine	Clover	Rye	Wheat	Lupine	Clover
Al^{3+}	a	b	c	d	b	a	a	c
pH7	0a	0a	0a	0a	0a	0a	0a	0a
Al5	7.4b	0.06b	0.18b	0.24b	0.15b	0.08b	0.09b	0.17b
Al10	11.1c	32.7c	49.03c	37,1c	0.17c	0.12c	0.13b	0.18b
Al20	24.4d	39.5d	50.02d	51.1d	0.18c	0.13c	0.16b	0.22c
Al40	39.8e	42.5e	52.77e	58.4e	0.26d	0.14c	0.17b	0.26d
Al100	58.7f	52.2f	57.57f	59.3f	0.55e	0.21d	0.17b	1.28e
Cu^{2+}	c	b	a	d	c	a	d	b
pH7	0.27a	0.06a	0.29a	0.17a	0.12a	0.09a	0.03a	0.17a
Cu20	1.66b	1.66b	5.71b	1.27b	0.97b	0.21b	0.13b	0.61b
Cu50	7.79c	2.7c	8.94c	2.15c	1.04c	0.61c	0.27c	1.11c
Cu100	8.81d	4.5d	16.46d	6.54d	4.11d	3.99d	0.75d	8.92d

Higher still values were recorded for the Pearson coefficient of roots and aboveground parts of plants growing on the medium contaminated with copper. In the aerial parts of the plants tested, simple correlation was between 0.92 and 0.98. In the case of roots of wheat and clover r = 0.98, and roots of lupine and rye 0.99 and 0.92, respectively. We can therefore conclude that the contents of the elements studied in plants depend on their concentration in the growth medium. This is also confirmed by the two-factor analysis of variance which showed a significant effect of the concentration of aluminium in the soil on the content in the roots (F_{AL} – 35.97

at p = 0.00000....) and aboveground parts (F_{AL} – 3.08 at p = 0.01). Between plant species, statistically significant differences in the content of aluminium were found in the roots at p = 0.002 and in the aboveground parts at p = 0.02.

Copper content of the tested plants was statistically significantly dependent both on the concentration of copper in the medium and on the plant species. Copper concentration in the medium had a significant effect on the copper content in the roots, at p = 0.003 in aboveground parts at p = 0.007. When analysing the copper content of the plant species studied, significant differences were found in the roots, at p = 0.03, and in the aboveground parts at p = 0.02 for the level of $p < 0.05$. Tukey's HSD test for p = 0.05 showed that all analysed species differed significantly in the content of aluminium and copper.

The potential of plants to collect elements from nutrient solution determines the bioaccumulation factor BAF (Table 2). The higher value it assumes the higher concentration of the element is found in the biomass of plants. It should be emphasised that for all test plants that ratio was higher in the roots than in the aboveground parts and therefore the elements analysed were mostly accumulated in the roots of the plants. The highest values BAF_{Al} and BAF_{Cu} for both the roots and the aboveground parts were noted for the experimental variants with the lower doses of metals. An exception were the roots of wheat, lupine and clover in the first degree of contamination with aluminium, and rye roots in the case of copper in the second variant (Cu50) and clover in the third variant (Cu100). The value of BAF for aluminium ion was found to be higher than for copper, which suggests that aluminium was absorbed from the solution medium much easier than copper ions.

Table 2. Bioaccumulation factor (BAF)

	Roots				Aboveground parts			
	Rye	Wheat	Lupine	Clover	Rye	Wheat	Lupine	Clover
BAF_{Al}								
Al5	296	3.2	7.2	9.6	6	3.2	3.6	6.8
Al10	222	654	981	27.4	3.4	2.4	2.6	3.6
Al20	244	395	500	511	1.8	1.3	1.6	2.2
Al40	199	213	264	292	1.3	0.7	0.9	1.3
Al100	118	105	115	119	1.1	0.4	0.3	2.6
BAF_{Cu}								
Cu20	16.6	17	57.1	12.7	9.7	2.1	1.3	6.1
Cu50	31.2	11	35.8	8.6	4.2	2.4	1.1	4.5
Cu100	17.6	9	32.9	13.1	8.2	8.0	1.5	17.9

In assessing the quality of crops, the degree of contamination of plants, as well as in the evaluation of plant resistance to metals or possible use of plants in the process of phytoextraction, an important indicator is the index of metal translocation IT. This index determines the ability to move metal from the roots to the aboveground parts (Jasiewicz and Antonkiewicz 2000). Although the aluminium content of the various parts of the plant is considerably higher (Table 1) than the copper content, the translocation index for aluminium is much lower (Table 3). Thus, the test plants retain aluminium ions mainly in the roots. Dicotyledonous plants transported to the aboveground parts 25 to 35 times more aluminium (at the lowest concentration of the ion in the solution medium) than rye and wheat.

Table 3. Translocation index (IT) of aluminium and copper

	Rye	Wheat	Lupine	Clover
Al^{3+}				
Al5	0.02	0.04	0.45	0.71
Al10	0.02	0.004	0.003	0.13
Al20	0.01	0.003	0.003	0.004
Al40	0.01	0.003	0.003	0.004
Al100	0.01	0.004	0.003	0.02
Cu^{2+}				
control	0.44	1.5	0.1	1
Cu20	0.58	0.12	0.02	0.48
Cu50	0.28	0.23	0.03	0.52
Cu100	0.85	0.89	0.05	1.36

In other variants of the Al-stress experiment the highest index of translocation was characteristic of rye. Copper translocation index increased in direct proportion to the degree of copper contamination of the substrate. The highest index IT was determined for clover. The monocotyledonous plants were characterised by similar values of this parameter. Most copper was retained in lupine roots, as evidenced by the lowest index of translocation.

The causes of the different reactions of the studied plants to the medium contamination with aluminium and copper should be sought in the different manner of uptake and transport of these metals from the roots to the aboveground parts. Although the larger doses of both aluminium and copper resulted in a significant increase of these elements in the different parts of studied plants, the above indicators point to easy uptake of aluminium ions, but a much reduced transport of this element to the aboveground parts the plant compared to Cu-stress.

Aluminium is an element that does not fulfil any metabolic functions in the plant. It is taken from the soil solution (culture medium) as Al^{3+}. In contrast, copper (under optimal environmental conditions) will be charged as Cu^{2+} and used by plants as a trace element in many enzymatic reactions.

Kinraide and Ryan (cit. after Szatanik-Kloc 2010) ranked cations according to their effectiveness in competing for negatively-charged ion exchange sites. This sequence is as follows: $H^+ = Me^{3+} > Me^{2+} > Me^+$. Thus, the more negatively charged the cell wall and the plasmolemma of plant cells, the easier it gets multivalent cations such as aluminium. Aluminium ions are retained first of all in the roots of the plants so multi-level mechanisms (e.g. binding with organic acids or with pectin matrix of the cell wall) are tolerated. However, rye seems to be very tolerant of aluminium, so these mechanisms are less pronounced, as evidenced by the highest translocation index of aluminium in that plant species.

The optimum copper content in the dry matter of plants is estimated to be 5-20 mg kg^{-1}. Generally, copper ions accumulate in the roots of the plant, but with a high degree of contamination of the substrate, contamination with the metal is also observed in the aboveground parts of plants (Manivasagaperumal *et al.* 2011). With regard to the BAF and IT valued determined for aluminium and copper, the latter element, in small quantities, was absorbed by plants from the substrate much easier than copper and its ions moved from the roots to the aboveground parts. However, according to Korzeniowska and Stanisławska-Glubiak (2007) and Aries and Jasiewicz (2009), the BAF and IT indexes cannot be regarded as indicators of tolerance of plants to environmental contamination with aluminium ions or heavy metals. In fact it is in only very few cases that these factors are associated with the respective reactions of plants under stress. The measure of tolerance of plants to environmental contamination is their ability to maintain vital processes under stress, or even to produce yields. In the assessment of the tolerance of plants to aluminium and copper it is better to use the tolerance index (Ti) which determines the degree of growth inhibition of the test plants in growing conditions in a contaminated medium. This index is expressed as the ratio of the dry matter of plants grown on a contaminated substrate to the dry matter of plants grown in the control medium (Starck 2007b). The higher tolerance index (Ti) the better the survival of the plant under stress conditions.

In this publication, Ti index (Tab. 5) determined based on the results of the dry matter of roots and aboveground parts is presented in Table 4.

Analysis of the dry matter of roots and aboveground parts of the plants that grow under Al-stress showed differences in the dry matter of the roots under the influence of aluminium concentration ($F = 6.47$ to $p = 0.002$) and between the test plant species ($F = 68.8$ for $p = 0.0000...$). Less statistically significant changes were demonstrated for the aboveground parts. The dry matter of the aboveground parts between the species decreased significantly ($F = 5.37$ to $p = 0.01$), while there were no (Tukey's HSD test) statistically significant differences between the monocotyledonous plants. The plant species studied under Cu stress did not differ significantly in terms of the value of root mass. Whereas, the weight of the aboveground parts was statistically significantly different between monocots and clover and lupine. As applied in the experiment, the concentration of copper contributed to the decrease in the mass of roots and aboveground parts between the stressed and control plants, wherein there were no statistically significant differences between the mass of the aboveground parts grown at various concentrations of copper. The weight of roots, however, decreased in proportion to the contamination of the medium with copper.

Table. 4. Dry matter of roots and aboveground parts in mg^{-1} / plant (av. of 10 plants, the deviations between individual data did not exceed 20%). The letters in the first row (Al^{3+}) and the line (Cu^{2+}) are homogeneous groups analysed to factor – plant species. The columns analysis was carried out by factor – concentration in the solution. Tukey's HSD test at p = 0.05.

		Roots					Aboveground parts			
		Rye	Wheat	Lupine	Clover		Rye	Wheat	Lupine	Clover
Al^{3+}		a	a	c	b		a	a	c	b
pH7	a	0.027	0.027	0.085	0.018	a	0.17	0.189	0.272	0.096
Al5	b	0.025	0.021	0.068	0.007	ab	0.20	0.153	0.276	0.054
Al10	b	0.024	0.017	0.064	0.007	ab	0.18	0.152	0.283	0.05b
Al20	bc	0.021	0.016	0.055	0.005	abc	0.18	0.131	0.255	0.04b
Al40	c	0.018	0.015	0.041	0.004	bc	0.167	0.129	0.204	0.03b
Al100	c	0.014	0.014	0.035	0.003	c	0.151	0.118	0.146	0.03b
Cu^{2+}		ab	ab	b	a		a	a	c	b
pH7	a	0.027	0.027	0.085	0.018	a	0.17	0.189	0.272	0.096
Cu20	b	0.017	0.014	0.029	0.004	b	0.135	0.090	0.226	0.036
Cu50	bc	0.013	0.008	0.0165	0.002	b	0.125	0.081	0.206	0.028
Cu100	c	0.01	0.005	0.0145	0.001	b	0.108	0.071	0.206	0.025

In the case of Al-stress, rye and lupine, characterised by the highest values of the tolerance index, fared the best by far. The lowest tolerance index (Ti) was calculated for clover. Clover also had the lowest Ti for high doses of copper. Generally, the level of the tolerance index (Ti) for copper concentrations toxic to plants was lower than that for aluminium ions, as evidenced by the lower values of Ti. It follows that the plants are less tolerant of elevated concentrations of heavy metals such as copper which are generally absorbed as microelements than of aluminium – an element with no documented role in plant physiology.

Thus, in the case of the analysed species the resistance to copper is rather induced resistance, i.e. the activation of defence mechanisms occurs through the action stressor. Among the plant species investigated, the highest copper contamination was noted for clover and then for wheat. This was also confirmed in the data on the root length inhibition, decrease in the content of micro and macroelements, die-back of aboveground parts of plants under stress (Szatanik-Kloc 2010). Probably, in these species of plants, the high intensity stressor led to rapid destabilisation of the body before the onset of activation of defence mechanisms, which also noted by Sheldon and Menzies (2005).

Table 5. Tolerance index (Ti) the examined plants for aluminium and copper

	Rye		Wheat		Lupine		Clover	
Al^{3+}	a*	b	a	b	a	b	a	b
Al5	1	1.3	0.7	0.7	0.9	1.1	0.4	0.2
Al10	1	1.2	0.6	0.7	0.8	1.1	0.4	0.1
Al20	0.8	1.2	0.5	0.6	0.8	1	0.3	0.1
Al40	0.6	1.1	0.5	0.6	0.5	0.8	0.3	0.1
Al100	0.5	0.9	0.5	0.5	0.5	0.6	0.2	0.1
Cu^{2+}								
Cu20	0.6	0.7	0.5	0.2	0.4	0.8	0.2	0.1
Cu50	0.5	0.7	0.3	0.3	0.3	0.8	0.1	0.1
Cu100	0.4	0.3	0.2	0.3	0.2	0.8	0.1	0.1

*Explanation: a – roots, b – aboveground parts

Al-stress resistance is rather constitutive, i.e. defence mechanisms exist stably throughout the life span of plants, which is observed in particular in such species as rye which has a high tolerance to Al^{3+} (Silva *et al.* 2012). The results presented in this study also suggest that among the species tested rye was characterised by the highest tolerance to aluminium, as evidenced by the highest index of tolerance. Also the uptake and translocation ability of rye in relation to this element was higher than in other species investigated.

The different reactions of the examined plant species to the contamination of the growth medium with aluminium and copper were due to the different ways of uptake and transport of these metals from the roots to the aboveground parts. This is related both with the different chemical specificity of the metals themselves and with the different (constitutive or induced) the sensitivity / resistance of the plant species.

CONCLUSIONS

1. Generally, of the two metals under study, Cu^{2+} ions showed a greater degree of mobility from the roots to the aboveground parts, as evidenced by higher values of translocation index (IT) for copper than for aluminium, despite the fact that Al^{3+} ions were absorbed by plant roots more easily and in larger amounts, the result of which was a high bioaccumulation factor BAF_{Al}

2. The plant species that tolerate acidic medium, such as rye and then lupine, were characterised by greater tolerance to the respective stressors (as evidenced by the high indexes of tolerance for those plants), which in particular related to aluminium tolerance in rye.

3. On the other hand, clover and then wheat, which have high requirements for an abundance of nutrient medium with neutral pH, showed the lowest toler-

ance to environmental contamination with both aluminium and copper, as indicated by the low indices of tolerance (Ti) in those species.

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OCENA STOPNIA SKAŻENIA GLINEM I MIEDZIĄ WYBRANYCH ROŚLIN UPRAWNYCH

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Streszczenie. W badaniach wykorzystano cztery gatunki roślin uprawnych: żyto i pszenicę – rośliny jednoliścienne z rodziny traw oraz łubin i koniczynę – rośliny dwuliścienne z rodziny bobowatych, które pochodziły z upraw hydroponicznych. Po czterech tygodniach od wschodów obniżono pH pożywki (pH = 4,5) i dodano jony glinu w stężeniach 5, 10, 20, 40, i 100 mg·dm^{-3} pożywki jako $AlCl_3$, a w drugim wariancie dodano jony miedzi w stężeniach 20, 50, 100 mg·dm^{-3} pożywki jako $CuCl_2$. Stwierdzono, że badane gatunki, zwłaszcza żyto, lepiej tolerowały skażenie środowiska glinem niż miedzią, pomimo znacznie wyższej akumulacji glinu w swoich tkankach. Najniższą odporność na miedź i glin odnotowano u koniczyny a następnie u pszenicy. Generalnie gatunki roślin (żyto i łubin), które z reguły lepiej tolerują kwaśny odczyn podłoża, wykazały również lepszą odporność na skażenie środowiska glinem i miedzią, o czym świadczą wysokie indeksy tolerancji dla tych roślin. Oba badane pierwiastki akumulowane były przede wszystkim w korzeniach roślin, przy czym indeks translokacji dla glinu był znacznie niższy niż dla miedzi.

Słowa kluczowe: glin, miedź, wskaźnik tolerancji, wskaźnik bioakumulacji, wskaźnik translokacji, rośliny