Annales Universitatis Paedagogicae Cracoviensis
Studia Naturae, 3: 55–69, 2018, ISSN 2543-8832
DOI: 10.24917/25438832.3.4

Iwona Konieczna[1*], Grzegorz Rut[1], Angelika Kliszcz[2]

[1]Institute of Biology, Pedagogical University of Cracow, Podchorążych 2 St. 30-084 Kraków, Poland, *i.konieczna08@gmail.com

[2]Department of Agrotechnology and Agricultural Ecology, University of Agriculture in Kraków, Mickiewicza St. 21, 31-120 Kraków, Poland

Effects of copper and vanadium salts on morphology of carrot (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) and wheat (*Triticum aestivum* L.) plants

Introduction

Plants growing in natural conditions are constantly exposed to biotic and abiotic factors that cause stress reactions. Among the stress factors, a reaction with other organisms can be mentioned from a biotic side, and the abiotic side includes temperature, water availability, solar radiation, salinity, and environmental pollution, among others, by heavy metals (Kozłowska, 2007). In the ecotoxicological context, heavy metals are considered to be poisons, i.e. substances that have toxic properties on living organisms. Toxicity is the ability of matter to cause physiological disturbances or the death of a living organism (Wierzbicka, 2015). The intensive development of industry and means of transport contributes unquestionably to the increase of environmental pollution with heavy metals (Luo et al., 2012).

Copper is a chemical element from the group of transition metals. It creates a large variety of compounds, does not react with water, and it darkens on the air and takes on a red or red-brown colour. Natural sources of copper emissions include volcanic eruptions, the decomposition of organic matter, forest fires, and seawater aerosols. Anthropogenic copper pollution results from industrial activity, including the metallurgical industry, power plants, waste incineration plant effluvium, mining waste dumps, copper mine tailings, sewage (including municipal sewage), agricultural inputs (fungicides), and road transport (Wierzbicka, 2015). Plants collect copper in a passive or active way associated with metabolic processes, usually in the form of divalent Cu^{2+} ions. The amount of copper consumed by plants is proportional to its concentration in the substrate (Kabata-Pendias, Pendias, 1999). Copper from anthropogenic sources is better absorbed than its natural forms found in soils (Grupe, Kuntze, 1988). To meet the physiological needs of plants, small concentrations of copper are sufficient (> 2 ppm/dry mass). Regardless of the harmfulness of excess copper, it is also an indispensable element for the proper growth and development of plants. It participates in the basic processes of photosynthesis, respiration, the transformation of nitrogen and protein compounds, the transport of carbohydrates, the metabolism of cell membranes (affecting their permeability), the standardization of DNA and RNA formation processes, and indirectly participates in the immune mechanisms (Kabata-Pendias, Pendias, 1999; Guerrero, 2005).

Vanadium is an element that belongs to the group of heavy metals. It is generally available in nature, and it is also widely used in industry. It is used, for example, in the production of non-ferrous alloys, highly resistant non-carbon steels, and in the chemical, glass, ceramic, paint, and photographic industries. In the atmosphere, this element comes mainly from anthropogenic sources, such as the combustion of biolites (crude oil), whose emissions are estimated at above 80%. It naturally occurs as a component of marine aerosols and comes from volcanic emissions (Urban et al., 2001). In the dissolved form of anions (VO_4^{3-} and VO_3^{-}), it is easily absorbed by plants. As its concentration and acidity of soil increase, it is intensively absorbed in the soil (Kabata-Pendias, Pendias, 1999). The largest accumulation of vanadium occurs in leaves (280–2700 ppb), but it can also occur in fruits and seeds (0.5–60 ppb). The harmful effect of vanadium for plants can be observed at concentrations from 500 to 1.400 μg/l, which inhibit root development, overall chlorosis, and dwarfism of plants. The vanadium content in soils ranges from 10 to 220 ppm. The largest concentration of that element is found in rendzinas, and the lowest in organic soils. In soil, it is usually associated with iron oxides and clay minerals. Leaching from the level of podzolic soil and concentrations in loamy and ferruginous layers determine its mobility. Vanadium concentration is increasing in industrial areas – metal works, cement plants, coal fired power plants, and oil refineries (Kabata-Pendias, Pendias, 1999).

Carrot (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) belongs to the Apiaceae family (former Umbelliferae). It is a precious vegetable plant cultivated around the world. It was probably brought to Europe about 600 years ago from Afghanistan (Burnie, 2005). Its cultivation is common, and as many as 60 species of this genus are edible plants. In the wild state, an annual, biennial, or perennial plants occur. The proper conditions for cultivation are in airy and non-acidic soils with a permeable subsoil level. It should not be cultivated on wet soils with a high level of groundwater, loam, and poor structure. The edible root has a wide range of applications in the kitchen, because of the content of carbohydrates, proteins, carotene, volatile compounds, and pectins. The vitamins like B, C, E, H, K, PP, and mineral salts (e.g., calcium, iron, copper, or phosphorus) are also found in the roots (Kunachowicz et al., 2017).

Wheat (*Triticum aestivum* L.) is one of the most important cereal species in the world. Like other grasses, it belongs to the Poaceae family. It probably comes from south-west and central Asia. Due to its nutritional value, this species is valued all over the world. Wheat grains contain 69% sugars, 12% protein compounds, and 2% fats. These three main groups of organic compounds account for a total of 83% of the dry mass of the grains. Wheat is also a source of riboflavin, thiamine, niacin, carotene, tocopherol, and mineral salts (e.g., sodium, calcium, potassium, magnesium, phosphorus, sulphur, and iron). It occupies a leading position among arable crops – third place in grain production in the world (Gwóźdź, 2017). Among others, it is used in the food industry, in cosmetics, as well as a raw material for energy production (Karcz, 2013).

The aim of this study was to determine the influence of copper and vanadium salts with different molar concentrations on the germination and growth of carrot (*Daucus carota* subsp. *sativus* (Hoffm.) Schübl. & G. Martens) and winter wheat (*Triticum aestivum* L.).

Material and methods

Experiments were carried out under laboratory and greenhouse conditions at the Department of Plant Physiology, Pedagogical University of Cracow. Carrot seeds and wheat grains were used for testing. Morphometric analyses of carrot and wheat treated with copper and vanadium salts at the germination and growth stages were performed. The experiment was carried out in two series in 10 replications.

The copper and vanadium salt solutions were prepared from copper (II) sulphate ($CuSO_4$) and ammonium metavanadate (V) (H_4NO_3V, azanium; oxido(dioxo)vanadium, according to IUPAC), at concentrations of 0.3 mM, 0.6 mM, 3 mM, and 6 mM. The control group was samples watered with distilled water.

50 carrot seeds and 50 wheat grains were placed in sterile Petri dishes with copper and vanadium solutions, using tweezers. The seeds on Petri dishes were kept for 9 days in the dark at room temperature. After this time, biometric analysis, the fresh and dry mass, and the percentage of water content of carrot and wheat seedlings were measured.

A few seedlings with similar morphology were selected from the control group and put in pots. River sand, rinsed several times with running and distilled water, comprised the medium of seedlings in the pots. Then, they were kept in a greenhouse. In the first week, plants were watered regularly 2–3 times a week with distilled water (10 ml each) and once a week with Steiner medium (10 ml each). In the next four weeks, the plants were watered once a week, respectively with copper ($CuSO_4$) and vanadium (H_4NO_3V) salts, with both concentrations of 0.6 mM and 3 mM (10 ml each) and

Steiner medium (10 ml each). The control samples were watered twice a week with distilled water (10 ml each) and once a week with Steiner medium (10 ml each).

Biometric analysis

The biometric analysis of carrot and wheat seedlings was made with a ruler (with an accuracy of 0.1 cm). Measurements of the length of underground and aboveground plant organs were carried out as well.

Fresh, dry mass and water content

Fresh mass FM of seedlings and plants was determined on an electronic balance (Radwag WPS 210C). Dry mass DM was determined after oven-drying (Wamed SUP 100) plant materials at 110°C for 48 hours. On the basis of the obtained results, the percentage of water content WC (%) was determined according to the formula: $\% H_2O = 100 - [(DM \times 100) / FM]$.

The measurements were made on seedlings and on the underground and aboveground parts of carrot and wheat plants.

Statistical analysis

The results presented in the paper are mean values from 10 independent replications with the standard deviation (± SD), calculated for each experimental variant. Analyses of the significance of differences between objects were made using the one-way ANOVA/MANOVA parametric statistical test, single and multi-factorial, based on the Duncan test, with $p \leq 0.05$. Calculations were made using STATISTICA, v. 13.0 (StatSoft, Inc. 2017).

Results

Germination percentage

Copper and vanadium salts had a clear effect on *Daucus carota* subsp. *sativus* seeds and *Triticum aestivum* grain germination (Fig. 1). The negative effect of copper ions on *D. carota* seeds germination in each of the concentrations of copper solution ($CuSO_4$) was observed. Only carrot seeds treated with 0.6 mM copper solutions germinated in the same amount as in the control – 34%. The carrot seed germination was inhibited to 10% on 3 mM $CuSO_4$ solution. On Petri dishes with 6 mM $CuSO_4$, a complete inhibition of germination was revealed. In contrast, vanadium salt solutions (H_4NO_3V), had a positive effect on the germination of carrot seeds as compared to the control treatment.

The germination of *T. aestivum* grains depended on the concentration and the type of used solutions. The copper and vanadium solutions used at the lowest concentration, i.e. 0.6 mM, slightly decreased the amount of germinated grains, compared to

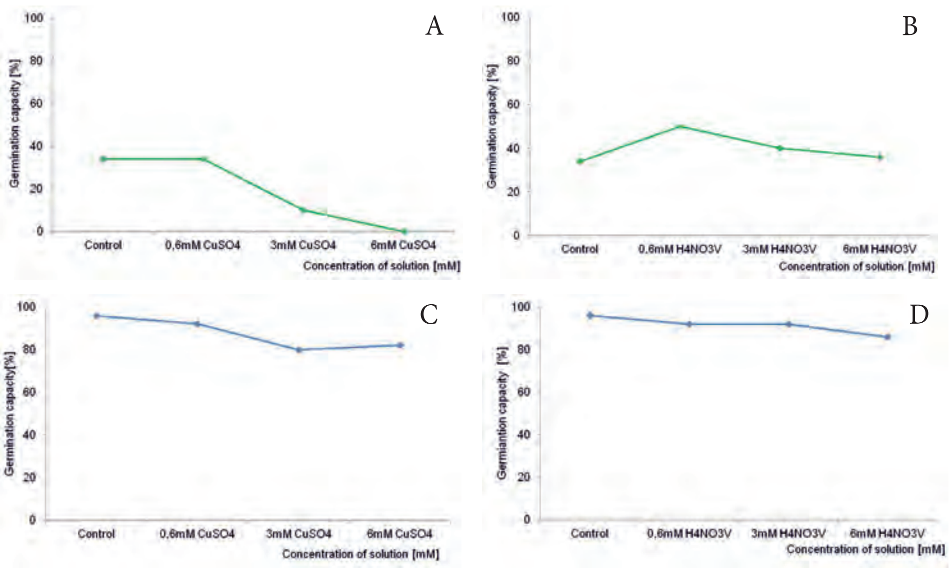

Fig. 1. Germination of carrot seeds (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) – (A and B) and winter wheat grains (*Triticum aestivum* L.) – (C and D), treated with copper ($CuSO_4$) and vanadium (H_4NO_3V) solutions at different concentrations (0.6 mM, 3 mM, and 6 mM)

the control. With the increasing of copper and vanadium concentrations (3 mM and 6 mM, respectively), inhibition of wheat germination was revealed.

Biometric analysis of seedlings

The growth of carrot seedlings with increasing of copper and vanadium concentrations was significantly inhibited. In comparison to seedlings germinated on distilled water (control), the elongation growth of carrot seedlings was completely inhibited at the highest concentration of copper sulphate solution (6 mM $CuSO_4$). The root length of wheat seedlings was inhibited in each concentration of both the copper and vanadium salt solutions (Fig. 2). The copper and vanadium solutions at concentrations of 6 mM caused the highest inhibition of root growth. The control wheat seedlings had significantly longer coleoptiles than those saturated with copper and vanadium salt solutions. The only exception was the seedlings germinated on 0.6 mM $CuSO_4$, when compared to the control group, no statistically significant differences in the coleoptiles length were found. The length of whole wheat seedlings, independent of the concentration and type of salt solutions, was shorter in relation to the seedlings germinated on distilled water.

Fresh and dry mass values and water content of seedlings

The fresh mass values of carrot seedlings were significantly increased only when saturated with 0.6 mM $CuSO_4$. In other cases, no significant changes in the values of this

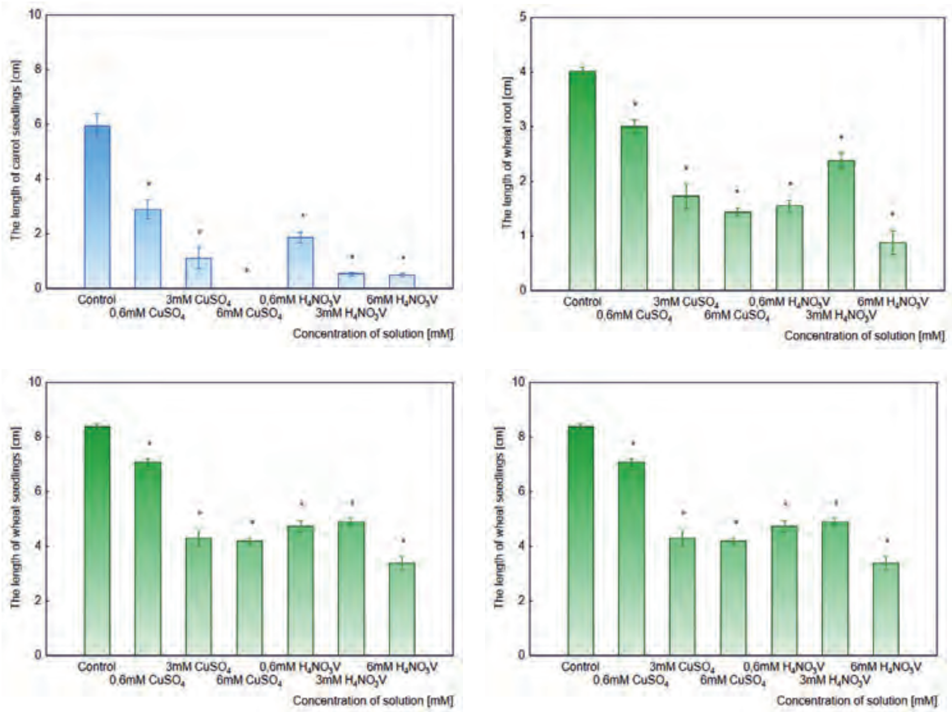

Fig. 2. Length of carrot seedlings (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) – (A), roots – (B), coleoptiles – (C) and whole seedlings – (D) wheat (*Triticum aestivum* L.), germinated on substrates with copper ($CuSO_4$) and vanadium (H_4NO_3V) solutions, at various concentrations (0.6 mM, 3 mM and 6 mM); mean values (n = 10) marked with an asterisk (*) differ significantly according to Duncan test at $p \leq 0.05$

parameter were noted as compared to the control group. The dry mass of carrot seedlings was not significantly different than seedlings germinated on salt solutions and distilled water (control). The percentage of water content only significantly increased in carrot seedlings treated with copper solutions at a 0.6 mM concentration. None of the other concentrations of copper and vanadium were found to significantly differ in the case of water content relative to control seedlings (Tab. 1).

The fresh mass of wheat seedlings germinated on 3 mM and 6 mM $CuSO_4$ and 6 mM H_4NO_3V was significantly decreased, compared to the control. The dry mass values of wheat seedlings significantly increased both at concentrations of 3 mM and 6 mM copper and vanadium salt solutions. The water content of wheat seedlings decreased with the increasing of concentrations of salt solutions when compared to the control. Differences in water content values were observed between seedlings treated the 3 mM and 6 mM $CuSO_4$, 6 mM H_4NO_3V solutions and control (Tab. 1).

Tab. 1. Fresh, dry mass and percentage of the water content of carrot seedlings (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) – A and wheat grains (*Triticum aestivum* L.) – B, treated with copper ($CuSO_4$) and vanadium (H_4NO_3V) salt solutions at different concentrations (0.6 mM, 3 mM and 6 mM)

Parameters	Control		Concentration of the solution [mM]											
			$CuSO_4$						H_4NO_3V					
			0.6		3		6		0.6		3		6	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
FM [g]	0.19	9.31	0.35*	8.69	0.11	5.44*	0.11	5.31*	0.16	6.64	0.12	6.14	0.13	5.59*
DM [g]	0.06	1.47	0.05	1.60	0.04	1.77*	0.05	1.77*	0.03	1.62	0.04	1.74*	0.04	1.80*
WC [%]	67	84	85*	82	60	68*	54	67*	83	76	67	72	71	68*

FM – fresh mass [g], DM – dry mass [g], WC (%) – water content [%]; average values (n = 10) marked with an asterisk (*) differ significantly according to Duncan test at $p \leq 0.05$

Tab. 2. Fresh mass values of carrot (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) – A and wheat (*Triticum aestivum* L.) – B organs, watered with copper ($CuSO_4$) and vanadium (H_4NO_3V) salt solutions, at various concentrations (0.6 mM, 3 mM and 6 mM)

Organ	Control		Concentration of solution [mM]							
			$CuSO_4$				H_4NO_3V			
			0.6		3		0.6		3	
	A	B	A	B	A	B	A	B	A	B
Root	0.40	4.20	0.25*	4.54	0.24*	4.10	0.21*	4.65	0.20*	4.38
Fourth leaf	0.25	1.86	0.23	1.82	0.22	1.68	0.22	1.58	0.18*	1.35
Other leaves	0.22	1.69	0.19	1.44	0.16*	1.34	0.22	1.73	0.20	1.62
The whole plant	0.87	7.75	0.67*	7.80	0.62*	7.12	0.65*	7.96	0.57*	7.35

Mean values (n = 10) marked with an asterisk (*) differ significantly according to Duncan test at $p \leq 0.05$

Biometric analysis of plant organs

Tab. 3. Dry mass values of carrot (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) – A and wheat (*Triticum aestivum* L.) organs – B, treated with copper ($CuSO_4$) and vanadium (H_4NO_3V) salt solutions at various concentrations (0.6 mM, 3 mM, and 6 mM)

Organ	Control		Concentration of the solution [mM]							
			$CuSO_4$				H_4NO_3V			
			0.6		3		0.6		3	
	A	B	A	B	A	B	A	B	A	B
Root	0.18	0.40	0.10	0.24*	0.03*	0.28*	0.07*	0.21*	0.02*	0.20*
Fourth leaf	0.08	0.25	0.08	0.22	0.01*	0.22	0.06	0.22	0.04*	0.18
Other leaves	0.15	0.22	0.15	0.19	0.01*	0.16*	0.12	0.22	0.08*	0.20
The whole plant	0.41	0.87	0.33	0.66	0.04*	0.630	0.21*	0.65	0.19*	0.57*

Mean values (n = 10) marked with an asterisk (*) differ significantly according to Duncan test at $p \leq 0.05$

The biometric analysis of carrot roots showed a slower growth trend both on 3 mM $CuSO_4$ and H_4NO_3V solutions, relative to control conditions. The length of carrot leaves was not significantly different than copper and vanadium solutions and the control group. The copper and vanadium salts in none of the concentrations significantly affected changes in wheat root length. The growth of wheat leaves was stimulated by $CuSO_4$ solutions at concentrations of 0.6 mM and 3 mM, compared to the plant watered with vanadium solutions and distilled water (control) (Fig. 3).

Fresh and dry mass and the percentage of water content in organs of plants

Fresh mass of carrot organs watered with copper and vanadium salt solutions clearly differed from the control sample (Tab. 2).

The fresh mass of root in each of the used solutions was decreased. For the fourth leaf, a significant mass reduction was observed with 3 mM H_4NO_3V. Compared to the control carrot organs, the fresh mass of other leaves decreased only in plants watered with 3 mM $CuSO_4$. Generally, the fresh mass of the whole plant decreased under the influence copper and vanadium salts. The dry mass of carrot plants decreased in samples treated with solutions of the highest salts concentrations. The vanadium salts decreased the dry mass values in each concentration. For the root and the whole plant, significant differences in dry mass values were revealed. The water content increased for all carrot organs treated with 3 mM copper and vanadium solutions compared to the control group (Tab. 3–4).

The fresh mass of wheat organs treated with copper and vanadium solutions did not significantly differ relative to the control plants. The only change was noticed in the dry mass of wheat root. The dry mass of whole plants decreased in plants watered with 3 mM H_4NO_3V. The percentage of water content did not differ from the control treatment (Tab. 2–4).

Tab. 4. Comparison of the water content in carrot organs (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) – A and wheat (*Triticum aestivum* L.) – B, treated with copper ($CuSO_4$) and vanadium (H_4NO_3V) salt solutions at various concentrations (0.6 mM, 3 mM and 6 mM)

Organ	Control		Concentration of the solution [mM]							
			$CuSO_4$				H_4NO_3V			
			0.6		3		0.6		3	
	A	B	A	B	A	B	A	B	A	B
Root	54	90	59	95	88*	94	65	95	91*	95
Fourth leaf	67	86	66	87	98*	87	71	86	78	87
Other leaves	34	87	24	87	96*	88	43	87	62*	88
The whole plant	53	89	51	92	94*	91	68	92	92	92

Mean values (n = 10) marked with an asterisk (*) differ significantly according to Duncan test at $p \leq 0.05$

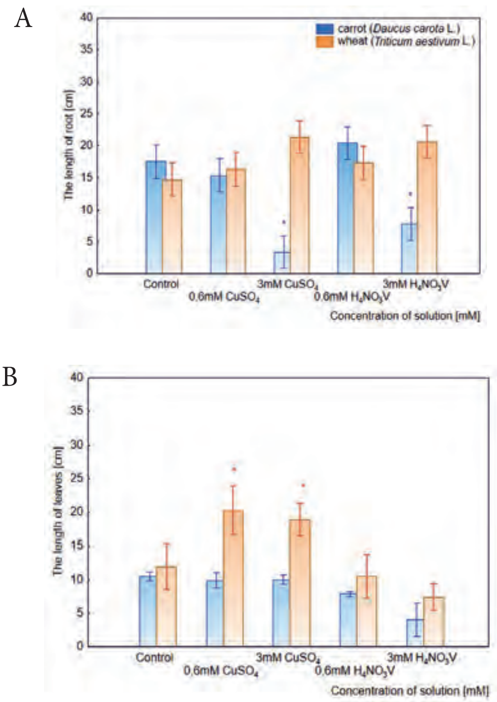

Fig. 3. Comparison of the length of roots and leaves of carrot (*Daucus carota* L. subsp. *sativus* (Hoffm.) Schübl. & G. Martens) and wheat (*Triticum aestivum* L.), treated with the copper ($CuSO_4$) and vanadium (H_4NO_3V) salt solutions, at different concentrations (0.6 mM and 3 mM); mean values (n = 10) marked with an asterisk (*) differ significantly according to Duncan test at $p \leq 0.05$

Discussion

Unlike other undesirable substances, heavy metals cannot be broken down only by biotransformation, due to complex physico-chemical and biological processes occurring in the soil. These processes affect their mobility and bioavailability in the soil – plant system (Qishlaqi, Moore, 2007). Depending on the form, type, and concentration in the environment, heavy metals may have a positive or negative effect on organisms. The positive influence refers to those of elements that are essential in the metabolic processes (e.g., Fe, Mn, Cu, Zn, and Mo), whereas toxic elements (i.e. As, Hg, Pb, Cr, and Cd) present in environment in trace amounts have a negative impact on the living organisms (Gil et al., 2006).

Germination is a set of complex physiological processes regulated at the molecular, subcellular, and cellular level. The imbibition phase includes intensive water intake and increased respiration. In the catabolic phase, the hydrolytic decomposition of storage materials occurs, and the synthesis of cellular components begins in the anabolic phase. The shoot that grows from the seed penetrates the seed coating, becoming a sprout and then a seedling (Bewley, 1997). Heavy metals at the early phase of the germination process affect the functioning of cellular organelles, including cell membranes, mitochondria, lysosomes, endoplasmic reticulum, and nucleus. They also affect enzymes involved in metabolism, detoxification, and the repair of cell damage (Wang, Shi, 2001). Heavy metal ions interfere with DNA and nuclear proteins and cause damage to genetic material. Moreover, they induce conformational changes that may intrude the cell cycle modulation or cause carcinogenesis and apoptosis (Beyersmann, Hartwig, 2008). The experiments showed that, even during germination, the copper and vanadium ions significantly influenced the germination of *D. carota* subsp. *sativus* and *T. aestivum* L. An inhibition in the germination of seeds was observed with increasing concentration of metals (Fig. 1). Zandi et al. (2017), and Możdżeń and Rzepka (2016) also demonstrated similar symptoms of the negative impact of heavy metals on plant germination. The maximum capacity of each plant to absorb heavy metals depends on the gradient of their concentration and availability in the soil. Plants imbibe heavy metals by diffusion or selective transport (Peralta-Videa et al., 2009). In the first stage, some of the metals are absorbed by the apical area of the plant's roots, and some are absorbed by the entire root surface. Usually, heavy metal ions are retained in the root system and only in very small quantities transported to the shoots (Krzesłowska, 2011; Hossain et al., 2012; Barberon, Geldner, 2014). The most common symptoms of excessive accumulation of heavy metals in plants are growth disorders and changes in the biomass of organs. In the root, there are bulges in the apical part, a reduction in diameter and number of transport vessels, browning, discoloration of cell structures, lipid disturbances, and ion destabilisation (Rucińska-Sobkowiak, Pukacki, 2006; Qureshi et al., 2007). As a consequence, the suppression of the entire plant growth occurs, and, in extreme cases, the plants die (Ciećko et al., 2000).

After analysing the results of these studies, both changes in the mass and the morphometric properties of carrot's and wheat's seedlings were observed (Fig. 1–3, Tab. 1–4). With the increase in the concentration of heavy metals, the inhibition of plant growth and their masses has been demonstrated. The largest differences at the highest concentrations of copper and vanadium solutions in relation to the control plants were noted. The toxic effects of copper on growth and DM in tobacco (*Nicotiana tabacum* L.), mung beans (*Vigna radiata* (L.) R. Wilczek), and chinese tea (*Camellia sinensis* (L.) Kuntze) have also detected (Gori et al., 1998; Manivasagaperumal et al., 2011; Dey et al., 2015). Similarly, Janas et al. (2010) found a significant influence of copper on growth, lipid peroxidation, and the accumulation of phenolic compounds in lentil seedlings (*Lens culinaris* Medic.). Możdżeń et al. (2017) observed a reduction in the growth of one-year-old needles of scots pine (*Pinus sylvestris* L.) in the Warcino Forest District (Northwest Poland). However, in numerous studies, copper has positively influenced the growth of rape (*Brassica napus* L.) (Purnhauser, Gyulai, 1993), barley (*Hordeum vulgare* L.) (Wojnarowiez et al., 2002), and annual peppers (*Capsicum annuum* L.) (Joshi, Kothari, 2007).

Plants have a network of defence strategies that allow them to avoid or tolerate stress factors, including heavy metals. The first line of defence is physical barriers, which include some morphological structures (thick skin) and biologically active tissues (hair and cell walls). For example, trichomes are used for the detoxification of heavy metals or the secretion of various secondary metabolites to protect against the adverse effects of metals. When heavy metals overcome biophysical barriers and metal ions get into tissues and cells, plants initiate the second line of defence, i.e. cellular defence mechanisms that eliminate or alleviate the negative effects of heavy metals (Emamverdian et al., 2015). Soil is one of the main reservoirs that accumulate significant amounts of harmful chemicals. Slow but continuous pollution in the environment with heavy metals leads to serious threats to microorganisms, plants, and animals. The basic condition for limiting the uptake of heavy metals by plants is to provide them with optimal growth conditions. Cultivated areas should be located away from busy roads or mills. Farmers should care about maintaining a stable pH of soils (pH = 6.5–7), regular organic fertilisation, such as manure, compost or 'green manures' (Luo et al., 2012).

There have been many experiments on the impact of heavy metals on living organisms at various levels of their organisation. For example, for cadmium (Cd) and zinc (Zn) as suggested by current studies, the uptake of their ions by plants is genetically correlated, and these metals are taken by the same or different transporters and controlled by common regulators (Oves et al., 2016). In order to restore the ecological balance of the environment and learn about the laws governing it, it is necessary to conduct further research on the mechanisms of interaction of heavy metals on various plant species. Only comprehensive laboratory experiments at the level of whole plants, organs, cells, and molecules combined with field research will be able to reveal the positive and negative significance of various heavy metal ions in nature and indicate effective ways to eliminate their excess (Tchounwou et al., 2014).

Conclusion

In this experiment, the copper and vanadium ions reduced the number of germinated carrot seeds (*Daucus carota* subsp. *sativus*) and winter wheat grains (*Triticum aestivum*) with the increase in the concentration of their solutions. Growth of carrot and wheat seedlings in copper and vanadium salt solutions was inhibited, compared to control seedlings. The fresh mass of carrot seedlings on Petri dishes watered with 0.6 mM $CuSO_4$ was increased. The dry mass of wheat seedlings increased in 3 mM and 6 mM copper and vanadium salts solutions. The percentage of water content in carrot seedlings was only higher in 0.6 mM $CuSO_4$.

In the growth phase, the reduction in the root length of carrot was observed. As for wheat, the stimulation of leaf growth of the specimens watered with solutions of concentrations of 0.6 mM and 3 mM was assessed. In comparison to the control group, with the concentration of copper and vanadium ions, there has been a reduction in the fresh mass of carrot's organs. The dry mass values of carrot and wheat plants decreased under the influence of copper and vanadium salts. Copper and vanadium ions, in the highest concentrations, significantly influenced the water content of carrot organs. The salts used in the experiment, both in germination and growth phases, significantly affected the morphology of carrot and wheat plants.

References

Barberon, M., Geldner, N. (2014). Radial transport of nutrients: the plant root as a polarized epithelium. *Plant Physiology*, *166*, 528–537. DOI: 10.1104/pp.114.246124

Bewley, J.D. (1997). Seed germination and dormancy. *Plant Cell*, *9*, 1055–1066. DOI: 10.1105/tpc.9.7.1055

Burnie, G. (2005). *Botanica: the illustrated A-Z of over 10,000 garden plants and how to cultivate them*. Germany, Königswinter: Ullmann Publishing.

Ciećko, Z., Wyszkowski, M., Żołnowski, A. (2000). Działanie zanieczyszczenia gleby ołowiem i nawożenia wapniem na plonowanie i skład chemiczny kukurydzy. *Zeszyty Problemowe Postępów Nauk Rolniczych*, *472*, 129–136. [In Polish]

Dey, S., Mazumder, P.B., Paul, S.B. (2015). Copper-induced changes in growth and antioxidative mechanisms of tea plant (*Camellia sinensis* (L.) O. Kuntze). *African Journal of Biotechnology*, *14*, 582–592.

Emamverdian, A., Ding, Y., Mokhberdoran, F., Xie, Y. (2015). Heavy metal stress and some mechanisms of plant defense response. *The Scientific World Journal*, 1–18. DOI: 10.1155/2015/756120

Gil, F., Capitán-Vallvey, L.F., De Santiago, E., Ballesta, J., Pla, A., Hernández, A.F., Gutiérrez-Bedmar, M., Fernández-Crehuet, J., Gómez, J., López-Guarnido, O., Rodrigo, L., Villanueva, E. (2006). Heavy metal concentrations in the general population of Andalusia, South of Spain: A comparison with the population within the area of influence of Aznalcóllar mine spill (SW Spain). *Science of the Total Environment*, *372*, 49–57. DOI: 10.1016/j.scitotenv.2006.08.004

Gori, P., Schiff, S., Santandrea, G., Bennici, A. (1998). Response of shape in vitro cultures of shape *Nicotiana tabacum* L. to copper stress and selection of plants from Cu tolerant callus. *Plant Cell Tissue and Organic Culture*, *53*, 161–169. DOI: 10.1023/A:1006048031956

Grupe, M., Kuntze, H. (1988). Zur Ermittlung der Schwermetallverfügbarkeit lithogen und anthropogen belasteter Standorte. I. Cd und Cu. *Zeitschrift für Pflanzenernährung und Bodenkunde*, *151*, 319–324. DOI: 10.1002/jpln.19881510510 [In German]

Guerrero, I.Y. (2005). Copper in plants. *Brazilian Journal of Plant Physiology*, *17(1)*, 145–156. DOI: 10.1590/S1677-04202005000100012

Gwóźdź, E. (2017). Pszenica – opis, właściwości i zastosowanie. Zboże pszenica ciekawostki. http://www.ekologia.pl/styl-zycia/zdrowa-zywnosc/pszenica-opis-wlasciwosci-i-zastosowanie-zboze-pszenica-ciekawostki,23129.html [In Polish]

Hossain, M.A., Piyatida, P., da Silva, J.A.T., Fujita, M. (2012). Molecular mechanism of heavy metal toxicity and tolerance in plants: central role of glutathione in detoxification of reactive oxygen species and methylglyoxal and in heavy metal chelation. *Journal of Botany*, 37. DOI: 10.1155/2012/872875

IUPAC nomenclature, https://pubchem.ncbi.nlm.nih.gov

Janas, K.M., Zielińska-Tomaszewska, J., Rybaczek, D., Maszewski, J., Posmyk, M.M., Amarowicz, R., Kosińska, A. (2010). The impact of copper ions on growth, lipid peroxidation, and phenolic compound accumulation and localization in lentil (*Lens culinaris* Medic.) seedlings. *Journal of Plant Physiology*, *167(4)*, 270–276. DOI: 10.1016/j.jplph.2009.09.016.

Joshi, A., Kothari, S.L. (2007). High copper levels in the medium improves shoot bud differentiation and elongation from the cultured cotyledons of *Capsicum annuum* L. *Plant Cell Tissue and Organic Culture*, *88*, 127–133. DOI: 10.1007/s11240-006-9171-6

Kabata-Pendias, A., Pendias, H. (1999). *Biogeochemia pierwiastków śladowych*. Warszawa: Wydawnictwo Naukowe PWN. [In Polish]

Karcz, H., Kantorek, M., Grabowicz, M., Wierzbicki, K. (2013). Możliwość wykorzystania słomy jako źródła paliwowego w kotłach energetycznych. *Piece przemysłowe i kotły*, *11–12,* 8–15. [In Polish]

Kozłowska, M. (2007). *Fizjologia roślin. Od teorii do nauk stosowanych*. Warszawa: Państwowe Wydawnictwo Rolnicze i Leśne, pp. 466–468. [In Polish]

Krzesłowska, M. (2011). The cell wall in plant cell response to trace metals: polysaccharide remodelling and its role in defense strategy. *Acta Physiologiae Plantarum*, *33*, 35–51. DOI: 10.1007/s11738-010-0581-z

Kunachowicz, H., Przygoda, B., Nadolna, I., Iwanow, K. (2017). *Tabele składu i wartości odżywczej żywności*. Warszawa: Wydawnictwo Lekarskie PZWL. [In Polish]

Luo, Ch., Yang, R., Wang, Y., Li, J., Zhang, G., Li, X. (2012). Influence of agricultural practice on trace metals in soils and vegetation in the water conservation area along the East River (Dongjiang River), South China. *Science of the Total Environment*, *431*, 26–32. DOI: 10.1016/j.scitotenv.2012.05.027

Manivasagaperumal, R., Vijayarengan, P., Balamurugan, S., Thiyagarajan, G. (2011). Effect of copper on growth, dry matter yield and nutrient content of *Vigna radiata* (L.) Wilczek. *Journal of Phytology*, *3*, 53–62.

Możdżeń, K., Rzepka, A. (2016). Rola łupiny nasiennej podczas kiełkowania i wzrostu nasion bobu (*Vicia faba* L.) w obecności siarczanu ołowiu. *Annales UMCS Sectio E Agricultura*, *71(4)*, 55–65. [In Polish]

Możdżeń, K., Wanic, T., Rut, G. Łaciak , T., Rzepka, A. (2017). Toxic effect of high copper content on the physiological processes in *Pinus sylvestris* L. *Photosynthetica*, *55(1)*, 193–200. DOI: 10.1007/s11099-016-0229-3

Oves, M., Saghir Khan, M., Huda Qari, A., Nadeen Felemban, M., Almeelbi, T. (2016). Heavy Metals: Biological Importance and Detoxification Strategies. *Journal of Bioremediation and Biodegradation*, *7(2)*, 1–15. DOI: 10.4172/2155-6199.1000334

Peralta-Videa, J.R., Lopez, M.L., Narayan, M., Saupe, G., Gardea-Torresdey, J.L. (2009). The biochemistry of environmental heavy metal uptake by plants: implications for the food chain. *The International Journal of Biochemistry and Cell Biology*, *41*, 1665–1677. DOI: 10.1016/j.biocel.2009.03.005.

Purnhauser, L., Gyulai, G. (1993). Effect of copper on shoot and root regeneration in wheat, triticale, rape and tobacco tissue cultures. *Plant Cell Tissue and Organic Culture*, *35*, 131–139. DOI: 10.1007/BF00032962

Qishlaqi, A., Moore, F. (2007). Statistical analysis of accumulation and sources of heavy metals occurrence in agricultural soils of Khoshk River Banks, Shiraz, Iran. *American-Eurasian Journal of Agriculture and Environmental Science*, *2(5)*, 565–573.

Qureshi, M.I., Abdin, M.Z., Qadir, S., Iqbal, M. (2007). Lead-induced oxidative stress and metabolic alterations in *Cassia angustifolia* Vahl. *Biologia Plantarum*, *51*, 121–128. DOI: 10.1007/s10535-007-0024-x

Rucińska-Sobkowiak, R., Pukacki, P.M. (2006). Antioxidative defense system in lupin roots exposed to increasing concentrations of lead. *Acta Physiologiae Plantarum*, *28*, 357–364. DOI: 10.1007/s11738-006-0032-z

Starck, R. (1984). *Uprawa roli i nawożenie roślin ogrodniczych*. Warszawa: Państwowe Wydawnictwo Rolnicze i Leśne. [In Polish]

Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K., Sutton, D.J. (2014). Heavy metals toxicity and the environment. *National Institiutes Health*, 1–30. DOI: 10.1007/978-3-7643-8340-4_6

The Plant List. A working list of all plant species. http://www.theplantlist.org/browse/A/Poaceae/Triticum/

Wang, S., Shi, X. (2001). Molecular mechanisms of metal toxicity and carcinogenesis. *Molecular and Cellular Biochemistry*, *222*, 3–9.

Weber, R., Hryńczuk, B. (2000). Effect of leaf and soil contaminations on heavy metals content in spring wheat crops. *Nukleonika*, *45(2)*, 137–140.

Wierzbicka, M. (2015). *Ekotoksykologia rośliny, gleby, metale*. Warszawa: Wydawnictwo Uniwersytetu Warszawskiego, p. 17. [In Polish]

Wojnarowiez, G., Jacquard, C., Devaux, P., Sangwan R.S., Clement, C. (2002). Influence of copper sulfate on anther culture in barley (*Hordeum vulgare* L.). *Plant Science*, *162*, 843–847. DOI: 10.1016/S0168-9452(02)00036-5

Zandi P., Możdżeń K., Basu S.K., González-Valdivia N.A., Cetzal-Ix W. (2017). Effect of different cadmium nitrate concentrations on sweet maize (*Zea mays* L. cv. Landmark). In: S.K. Basu, P. Zandi (eds.), *Environment at crossroads: challenges, dynamics, solutions*. Iran: Haghshenass Publication.

Abstract

Around the world, a major concern in researches on heavy metals is placed on their toxic effect on living organisms. The problem with heavy metals occurrence in the environment is not only associated with their toxicity, but also with their ability to accumulate inside living organisms. This study presents the effect of copper and vanadium ions on the germination and growth of carrot and wheat plants. The experiment was carried out in two independent series with ten repetitions each. The water solutions of copper ($CuSO_4$) and vanadium (H_4NO_3V) salts with the concentrations of 0.3 mM, 0.6 mM, 3 mM, and 6 mM were used. The control groups were objects watered with distilled water. The conducted experiment showed that the copper and vanadium ions had negative effects on the germination and growth of tested plants. With the increasing concentration of heavy metal ions, an inhibition of seeds germination was observed. The length of carrot and *wheat* seedlings in each salt solution was inhibited, compared to the control group. During the growth phase, the stimulation of wheat leaves growth only in copper solutions with concentration 0.3 mM and 0.6 mM was observed. Depending on the copper and vanadium ions concentrations, changes in the fresh and dry masses and the content of water were observed.

Key words: cereal, root crop, germination, fresh and dry mass, copper, vanadium

Received: [2018.02.09]

Accepted: [2018.10.15]

Wpływ jonów miedzi i wanadu na morfologię marchwi uprawnej (*Daucus carota* L. *subsp. sativus* (Hoffm.) Schübl. & G. Martens) oraz pszenicy (*Triticum aestivum* L.)

Streszczenie

Na całym świecie prowadzone są badania nad toksycznym wpływem metali ciężkich na organizmy żywe. Problem z ich występowaniem w środowisku wynika nie tylko z toksyczności, lecz także ze zdolności akumulowania w organizmach żywych. W pracy przedstawiono wyniki badań nad wpływem jonów miedzi i wanadu na kiełkowanie i wzrost marchwi uprawnej oraz pszenicy zwyczajnej. Doświadczenie przeprowadzono dla każdego gatunku w dwóch niezależnych seriach, po 10 powtórzeń. W badaniach stosowano wodne roztwory soli miedzi ($CuSO_4$) i wanadu (H_4NO_3V), o stężeniach molowych: 0,3 mM; 0,6 mM; 3 mM i 6 mM. Grupę kontrolną stanowiły obiekty podlewane wodą destylowaną. Przeprowadzone eksperymenty wykazały negatywny wpływ jonów miedzi i wanadu na kiełkowanie oraz wzrost badanych roślin. Wraz ze wzrostem koncentracji jonów metali ciężkich obserwowano zahamowanie zdolności kiełkowania nasion, a siewki podlewane roztworami soli miedzi i wanadu były krótsze, względem podlewanych wodą. W fazie wzrostu, jedynie u pszenicy zaobserwowano stymulację przyrostu liści pod wpływem związków miedzi o stężeniach 0,3 mM i 0,6 mM. W zależności od koncentracji jonów miedzi i wanadu odnotowano istotne zmiany w wartościach świeżej i suchej masy oraz procentowej zawartości wody w siewkach.

Słowa kluczowe: roślina okopowa, zboże, zdolność kiełkowania, świeża i sucha masa, miedź, wanad

Information about authors

Iwona Konieczna https://orcid.org/0000-0002-9538-8516
She is a student of biology. She is interested in allelopathic interaction between plants and effect of heavy metals on plant morphology and physiology.

Grzegorz Rut https://orcid.org/0000-0001-6719-3060
His research topic concerns the course of basic physiological processes in plants (photosynthesis, respiration, chlorophyll fluorescence, transpiration), concentration chlorophyll, antocyanins, and reactions of plants, mainly mosses (*Polytrichum piliferum*, *Mnium undulatum*), ferns (*Platycerium bifurcatum*) and vascular plants (*Oxalis acetosella*, *O. corniculata*) on abiotic stress factors (excess and deficiency of solar radiation, hypoxia, anoxia, excess heavy metals, herbicides, salinity, changes in carbon dioxide concentrations, drought stress and low temperature).

Angelika Kliszcz
She is focusing on enhancing the understanding of the influence of different factors on soil structure and fertility. Particularly, she is investigating the interaction of plants with the physical, chemical, and biological properties of the soil. She is also interested in organic methods of plant production and soil-enriching substances.