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GROWTH, YIELD, LEAD, ZINC AND CADMIUM CONTENT OF RADISH, PEA AND PEPPER PLANTS AS INFLUENCED BY LEVEL OF SINGLE AND MULTIPLE CONTAMINATION OF SOIL. III. CADMIUM

Velitchka Georgieva*[1], Christo Tasev[2], Georgi Sengalevitch[3]

[1]*Acad. M. Popov Institute of Plant Physiology, Acad. G. Bonchev Str., Bl. 21, 1113 Sofia, Bulgaria*
[2]*Ministry of Environment, 67 W. Gladstone Str., 1000 Sofia, Bulgaria*
[3]*Agricultural University, 12 D. Mendeleev Str., 4000 Plovdiv, Bulgaria*

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Summary. The influence of 4 gradually enhancing levels of single and multiple soil contamination with Cd, Pb and Zn (5, 10, 15, 30 ppm Cd; 250, 500, 1000, 2000, 3000 ppm Pb and Zn) on growth, yield and Cd content of radish, pea and pepper plants was studied. The concentrations used model the conditions around PbZn smelter, Plovdiv.
At a level of $Cd_5Pb_{250}Zn_{250}$ Pb^{2+} and Zn^{2+} have protective effect and decrease the phytotoxic effect of Cd^{2+} on pepper, pea and radish plants. At higher levels, growth and yield are reduced parallel to the enhancement of Cd concentration, Pb^{2+} alleviate Cd toxicity by lower and Zn^{2+} by higher levels of contamination. Cd content of peppers increases 111 fold compared to the control, followed by pea and radish tubers. At a level of $Cd_5Pb_{250}Zn_{250}$, Zn^{2+} ions are more effective antagonists of Cd^{2+} than Pb^{2+} for peppers; the opposite is true for peas. Above the level $Cd_{10}Pb_{500}Zn_{500}$, Pb^{2+} and Zn^{2+} interact synergistically with Cd^{2+}; in triple combinations their effect is additive. The reduction of tissue Cd content is not always accompanied by an alleviating effect of Cd phytotoxity. The combination CdZn decreases tissue Cd content more than CdPb but its phytotoxic effect is more pronounced. Probably Cd toxicity depends more on free Cd^{2+} ions than on total tissue Cd content.

Key words: Cd content; interactions among Cd, Zn, Pb; level of contamination; pepper; peas; radishes

* Corresponding author

Introduction

Cadmium has been shown to cause adverse effects on the health of living organisms (Fergusson, 1991). Soils, waters, air, plants and animals are the routes by which human beings come into contact with Cd. Pyrometalurgic smelting of Zn, Pb and Cu ores is the main source of Cd contamination (Purves, 1985).

The concentration of Cd in unpolluted soils varies within the ranges of 0.07–2.1 mg/kg, or 0.5–0.8 mg/kg on the average (Page, 1972). Cadmium contamination of the soils is regarded as a great danger for living organisms, because its concentration in top soils continuously increases and its surface flux from aerosols is greater than the looses by leaching and plant uptake (Kabata-Pendias and Pendias, 1989; Fergusson, 1991).

The flux of Cd from the soil solution into the roots of plants occures by passive diffusion or by active transfer (Cataldo et al., 1983; Clarkson and Lutge, 1989). Cd content of different plants grown on the same soil varies about 100 times (Kabata-Pendias and Pendias, 1989; Wallace and Berry, 1989; Fergusson, 1991; Sauerbeck, 1994). The mechanism of Cd phytotoxicity is complex and includes damage of biomembranes, enzymatic changes, interaction with other macro- and microelements (Purvis, 1985; Clarkson and Lutge, 1989).

Cd content of plants cultivated on unpolluted soils varies from 0.05 to 2.00 ppm, the differences among species and cultivars increase as much as the increase of level of contamination (Purves, 1985; Kabata-Pendias and Pendias, 1989; Fergusson, 1991). Page (1972) established that Cd tolerance of plants grown on nutrient solution lies within a range of 0.1–10 ppm. Maize plants grown as water culture respond similarly to Cd concentration (Kamenova-Youchimenko et al., 1986). Cd^{2+}, Zn^{2+} and Pb^{2+} interact competitively for uptake in higher plants (Clarkson and Lutge, 1989). Zn^{2+} and Pb^{2+} in some cases increase Cd content of plants (Girling and Peterson, 1981), but there is no satisfactory explanation of this phenomenon (Kabata-Pendias and Pendias, 1989). The combined toxic effect of Cd^{2+}, Zn^{2+} and Pb^{2+} is more pronounced compared to their single treatments.

Cd contaminated agricultural lands around Plovdiv and Kurdjaly Pb and Zn smelters are about 10 728 ha, 3112 ha out of them are polluted by 2 times the admissiable concentration limits (Sengalevitch, 1993; Novak et al., 1995). These data show the gravity of the problem for Bulgaria. Cd contaminated agricultural lands probably are more because some local pollutants are not included.

The present study examines the influence of interactions among Cd^{2+}, Zn^{2+} and Pb^{2+} ions on the growth, yield and Cd content of pepper, pea and radish plants under conditions of single and multiple contamination in concentration limits and soil type around smelter Plovdiv.

Materials and Methods

The experiments were carried out with three plants: peppers cv. Plovdivska kapia, radishes cv. Tcherveni s beli opashki and peas cv. Auralia. The plants were grown in the green house of the N. Pushkarov Institute of Soil Science, Sofia, during the period 1990–1992. The plants were harvested at technical maturity. The soil contamination, analytical methods used for soil and plants and treatment patterns are described in our previous paper (Tasev et al., 1997). The plants were grown on unpolluted soil (control) and four gradually increasing levels of contamination: 5, 10, 15, 30 Cd mg/kg soil, 250, 500, 1000, 3000 Pb and Zn mg/kg soil. There were single and combined treatments with the three contaminants, the highest level of combined treatments for Zn and Pb was 2000 mg/kg in double and triple treatments. The last level of single and combined treatments in the case of pepper was not included. Soil moisture was kept near 70% of field water capacity. The results concerning accumulated fresh and dry matter and Cd content were statistically processed by the method of multiple variance analysis.

Results and Discussion

The soil concentration of Cd used in the experiments was lower than the average concentration of unpolutted soil (Fergusson, 1991) and lower than the average for Bulgarian soils – 0.3 mg/kg. The concentration limits cover the range: excess —> toxicity. From the data presented on Fig. 1 concerning the effect of single and multiple contamination of Cd with Zn and Pb on growth and yield of radish, pea and pepper plants is obvious that at single contamination they respond similarly to increasing Cd soil contamination – reduce growth and yield parallel to the increase of the Cd soil concentration.

Under low combined level of contamination ($Cd_5Pb_{250}Zn_{250}$) radishes reduce the accumulated biomass of top parts equally at single and double contamination – Cd and CdPb, CdZn have an alleviating effect. The decrease in tuber yield is more significant, CdPb is more effective than CdZn. The triple combination in comparison with single and double treatments decreases mostly radish growth and yield. At higher levels of multiple contamination, the combination CdZn decreases growth and yield more effectively than CdPb and Cd. At triple combinations the influence of Zn^{2+} predominates over Pb^{2+} and growth is greately inhibited. Radishes do not form tubers over Zn_{500}.

Pea plants compared to radishes respond differently to the level $Cd_5Zn_{250}Pb_{250}$. The growth of top parts and yield are slightly reduced under conditions of single contamination. Double combined treatment CdPb causes statistically significant increase of growth and yield, CdZn and CdZnPb do not differ from Cd_5. There is a tendency

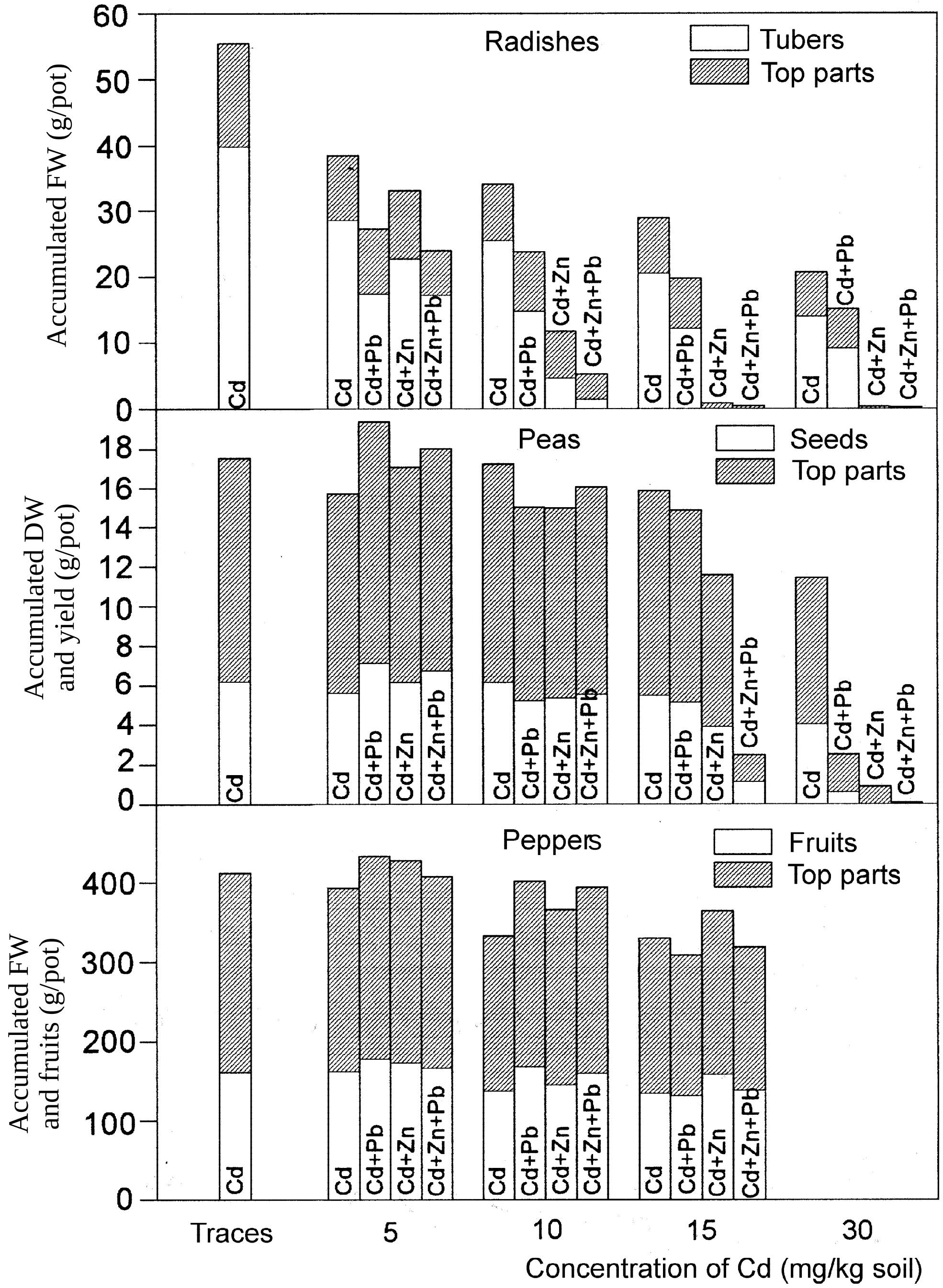

Fig. 1. Influence of the level of single and combined contamination of soil with Cd, Pb and Zn on the growth and yield of radish, pea and pepper plants

of growth and yield inhibition on $Cd_{10}Zn_{500}$ and $Cd_{10}Pb_{500}$ levels. The triple combination alleviates unfavourable effect of CdZn and CdPb. The next contamination levels: $Cd_{15,30}$, $Zn_{1000,2000}$, $Pb_{1000,2000}$ have the same effect on pea as on radish plants. The combination CdZn is more phytotoxic than CdPb, the effect of triple combination is additive.

Pepper plants respond to the level and kind of contamination more like peas than radishes. Fresh biomass at the highest level of contamination decreases 28%, yield – only 14%. Under conditions of double treatments – CdPb and CdZn, Pb^{2+} and Zn^{2+} have protective effects on growth and yield of pepper in comparison to the same level of single treatments. Pb^{2+} ions are more effective at lower levels, Zn^{2+} at the highest.

The interaction of Cd^{2+} with Zn^{2+} in plants is based on the substitution of Cd^{2+} with Zn^{2+} and the decrease of Cd^{2+} below its phytotoxic concentration in tissues (Purvis, 1985; Kabata-Pendias and Pendias, 1989; Fergusson, 1991). Under the levels studied Zn^{2+} even at Zn_{250} have more pronounced phytotoxic effect on radish tubers than Cd_5 (unpublished data). Wallace (1982) reports similar effect by barley plants grown on single and combined contamination with Li, Zn, Cu, Co, Ni and Cd.

Single and combined Cd, Pb and Zn contaminations affect much more Cd content than growth and yield of radish, pea and pepper plants. Cadmium is an extremely toxic element. There is no agreement about the uptake of Cd in plants. Fergusson (1991) divides the plants by their relative uptake of Cd and other heavy metals into three groups: low, middle and high. According to this arrangement peas belong to the group middle–low while radishes to low–middle.

From the dose response curve of single soil Cd contamination —> Cd content of radishes and peas is obvious that accumulated amounts of Cd are similar to soil level Cd_{15} (Fig. 2). At the highest level Cd_{30} pea plants have 2 times more Cd than radishes: 3 ppm radishes, 6.15 ppm peas. The pepper fruits in corresponding levels have over 10 fold higher Cd content. On uncontaminated soil radishes have only traces, pepper fruits – 0.2 ppm and pea plants accumulate 0.7 ppm Cd. The level of contamination, type of sowing area (Dimov, 1991) and cultivated plant have a hardly predictable effect on the Cd content of plants studied (Page, 1981; Purves, 1985; Kabata-Pendias and Pendias, 1989; Fergusson, 1991). The most probable explanation is that by relatively low levels of industrial contamination Cd is immobilized on the cell walls of the roots, stems and leaves and is impenetrable into the plant reproductive organs.

Pepper fruits at level Cd_5 accumulate much Cd – 14.4 ppm. The double contamination Cd_5Pb_{250} slightly reduces Cd content, meaning that Pb^{2+} at low levels act as a poor antagonist of Cd^{2+}. Zinc ions are more effective and reduce pepper fruit Cd content 2.2 times, while Cd content at triple contamination is intermediate (Fig. 3). At level $Cd_{10}Pb_{500}Zn_{500}$ the relation between Cd^{2+} and Pb^{2+} in double contamination changes from antagonistic to synergistic and the Cd content of pepper increases 12% compared to Cd_{10}. At double treatment $Cd_{10}Zn_{500}$ the relation does not change, Zn^{2+} ions act as antagonists again and Cd content decreases about 43%. Cd content of tri-

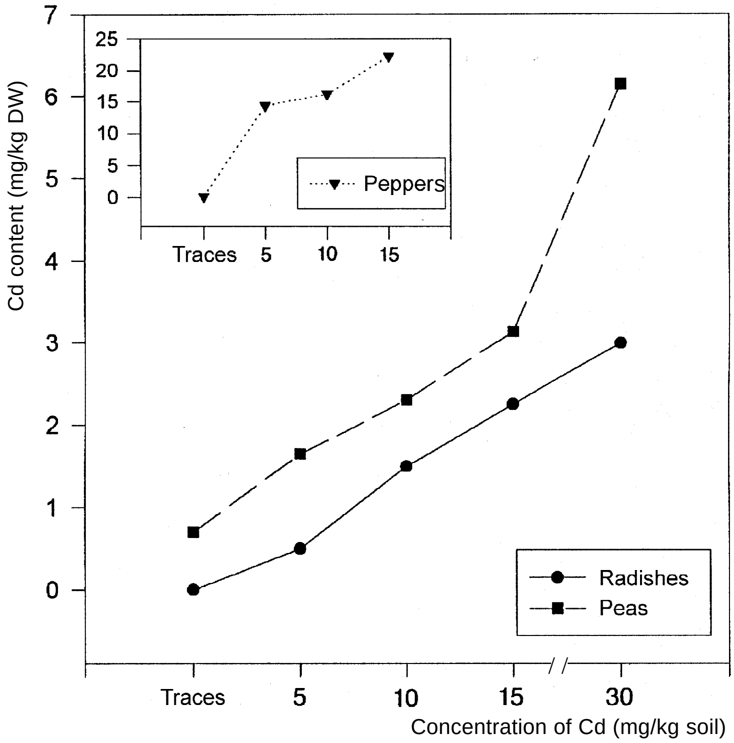

Fig. 2. Influence of the level of single soil Cd contamination on Cd content of radish tubers, pepper fruits and top parts of peas

ple contamination is intermediate. The interactions between CdZn and CdPb at the highest contamination level – $Cd_{15}Pb_{1000}Zn_{1000}$ are of the same type as the former, only the differences diminish. The relations among Cd^{2+}, Zn^{2+} and Pb^{2+} in triple contamination are antagonistic and Cd content is reduced about 30%.

Pepper fruits accumulate much Cd (Cd_5 – 14.4 ppm) if they have a dry matter content about 7% (St. Pandev personal communication), so the Cd content of fresh fruits would be about 1.08 ppm, which means 10 times more than the admissible concentration limits of Cd for food-stuffs (0.1 ppm, Bulgarian State Standard). The pepper plants should not be cultivated even on soils at low levels of Cd contamination.

Pea plants compared to pepper plants accumulate less Cd. At the level $Cd_5Pb_{250}Zn_{250}$ in double treatments Pb^{2+} and Zn^{2+} interact antagonistically to Cd^{2+} and decrease its content (Pb^{2+} – 2 times, Zn^{2+} – about 27%). Pb^{2+} ions are more effective antagonists of Cd^{2+} than Zn^{2+}. The type of interaction at the level $Cd_{10}Pb_{500}Zn_{500}$ between Cd^{2+} and Zn^{2+} changes and Cd content of pea plants increases, Pb^{2+} act like at previous level – antagonistically. On triple treatment Cd^{2+}, Zn^{2+} and Pb^{2+} interact synergistically and Cd content increases 2.52 times. At the following level $Cd_{15}Pb_{1000}Zn_{1000}$ the type of double interactions is similar to the previous level.

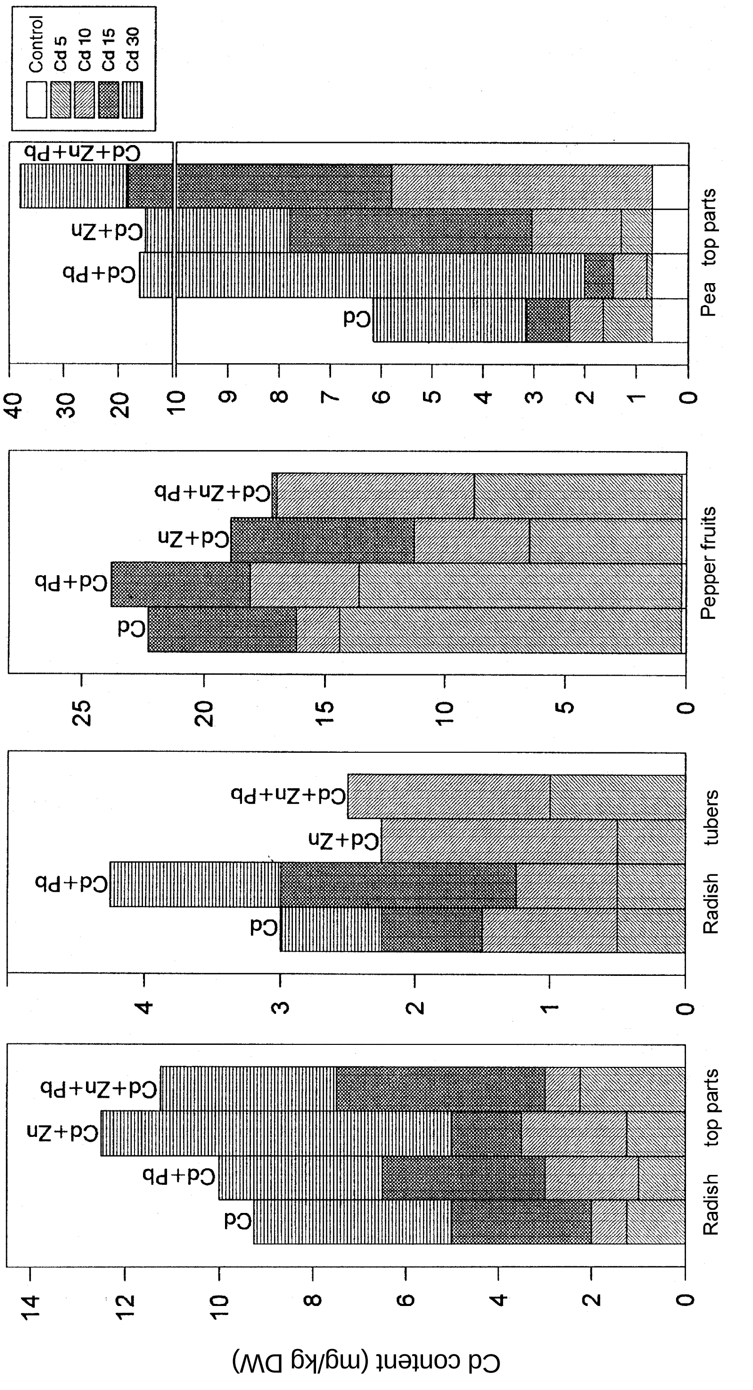

Fig. 3. Influence of the level of single and combined soil contamination with Cd, Pb and Zn on Cd content of top parts and tubers of radish and pepper fruits and top parts of pea plants

The synergistic effect among these three ions is very strong and Cd content increases over 5 times. At the last level of contamination Cd^{2+}, Pb^{2+} and Zn^{2+} also interact synergistically – Cd content increases: CdPb 2.6, CdZn 2.43 and in the triple treatment Cd content is over 6 fold. Pb^{2+} is a more effective antagonist of Cd^{2+} than Zn^{2+} in top parts of peas at levels of contamination $Cd_{5,10,15}$, only at Cd_{30} Pb^{2+} and Cd^{2+} interact synergistically. Cd^{2+} and Zn^{2+} interact synergistically at all levels except Cd_5Zn_{250}. The combined triple contamination of peas is exceptionally dangerous, because the three ions at all levels of combined contamination interact synergistically and increase Cd content of the top parts, the combined effects are higher than the sums of Cd^{2+}, Pb^{2+} and Zn^{2+}.

The tubers and top parts of radishes cultivated on uncontaminated soils in comparison with peppers and peas accumulate the least Cd. At the lowest level of combined contamination ($Cd_5Pb_{250}Zn_{250}$), Zn^{2+} and Pb^{2+} do not exert any influence on the Cd content of tubers, only the triple combination on the base of synergistic interaction increases Cd content.

At the next level ($Cd_{10}Pb_{500}Zn_{500}$) in combination CdPb, Pb^{2+} insert an antagonistic effect on Cd^{2+} and Cd content decreases 20%, while Zn^{2+} act synergistically and increase Cd content 50%. The triple combination is also synergistic and Cd content increases 66%. It can be speculated that the presence of Zn^{2+} eliminate the antagonism between Cd^{2+} and Pb^{2+}. The interaction between Cd^{2+} and Pb^{2+} at the higher levels of contamination ($Cd_{15}Pb_{1000}$ and $Cd_{30}Pb_{2000}$) is also synergistic. Probably at higher levels plants can not cope with enhanced concentration of Cd^{2+} and Pb^{2+} in soil solution and protect tubers against accumulation of Cd. It is obvious that the same type of interaction is created by different causes. At the levels $Cd_{15}Pb_{1000}Zn_{1000}$ and $Cd_{30}Pb_{2000}Zn_{2000}$ the tubers are formed only in the presence of Pb^{2+}, the interaction is synergistic and the Cd content is increased 33% and 42% respectively.

Top parts of radishes accumulate over 2 times more Cd than tubers. At the lowest level of double contamination Cd_5Pb_{250} and Cd_5Zn_{250}, Pb^{2+} interact antagonistically to Cd^{2+} and decrease Cd content 25%, CdZn does not affect Cd content. Cd^{2+}, Pb^{2+} and Zn^{2+} in triple treatments interact synergistically and Cd content increases about 2 times. At the higher levels of multiple contamination the interactions are synergistic, the differences among Cd contents of treatments with increasing Cd concentration of soil solution become smaller.

It is typical for radish and pea plants that at the triple contamination at all levels studied the type of interaction is synergistic and Cd contents increase from 0.2 to 6.2 times. The tissue concentrations of Cd in comparison with Pb and Zn are relatively low, but Cd is more dangerous because its effect is rather more pronounced on the quality than on the growth and development of plants. The consequences for human beings and animals using foods with high Cd content pose a serious health risk.

On Table 1 are shown statistically significant effects of single and multiple contamination of the soil solution with Cd concerning the growth, yield and Cd contents

Table 1. Statistically significant effects of Cd and its interactions with Pb and Zn on some basic indices of pepper, pea and radish plants

Plants	Treatment Indices	Control	Cd				Cd+Pb				Cd+Zn				Cd+Pb+Zn			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Peppers	Accumulated FW	1	0.92	0.66 *	0.66 *		1.02	0.93	0.71 *		1.02	0.88	0.82		0.90	0.93	0.42	
	Yield fruits	1	1.00	0.85	0.83		1.10 *	1.04	0.81 *		1.07 *	0.90	0.98		1.03	0.99	0.86 **	
	Cd content	1	72 ***	81 ***	111 ***		0.94	1.12 *	1.07 *		0.45 ***	0.70 **	0.85		0.61 **	1.05	0.77 *	
Peas	Accumulated DW	1	0.89	0.98	0.91	0.65 **	1.08 *	0.86	0.85 *	0.16 ***	0.96	0.85 *	0.67 **	0.08 ***	0.99	0.99	0.12 ***	0.01 ***
	Yield seeds	1	0.91	0.99	0.89	0.65 **	1.15 **	0.84 *	0.83 *	0.11 ***	0.99	0.86 *	0.63 **		1.08 *	0.89	0.19 ***	
	Cd content	1	2.36 ***	3.28 ***	4.49 ***	8.78 ***	0.48 ***	0.63 ***	0.64 ***	2.60 ***	0.79 *	1.33 ***	2.48 ***	2.44 ***		2.52 ***	5.81 ***	
Radishes	Accumulated FW leaves	1	0.55 ***	0.55 **	0.53 ***	0.43 ***	0.62 **	0.57 ***	0.49 ***	0.38 ***	0.67 ***	0.45 ***	0.05 ***	0.02 ***	0.43 ***	0.25 ***	0.03 ***	0.02 ***
	tubers	1	0.64 **	0.64 **	0.52 ***	0.35 ***	0.44 ***	0.37 ***	0.30 ***	0.23 ***	0.57 ***	0.12 ***			0.43 ***	0.03 ***		
	Accumulated DW leaves	1	0.54 ***	0.54 ***	0.53 ***	0.40 ***	0.96	0.51 ***	0.52 ***	0.42 ***	0.54 ***	0.22 ***	0.09 ***	0.04 ***	0.45 ***	0.29 ***	0.05 ***	0.04 ***
	tubers	1	0.50 ***	0.50 ***	0.37 ***	0.36 ***	0.43 ***	0.11 ***	0.36 ***	0.28 ***	0.39 ***	0.03 ***			0.39 ***	0.03 ***		
	Cd content leaves	1	1.25 ***	2.00 ***	5.00 ***	9.25 ***	0.80	1.50 ***	1.30 ***	1.08 *	1.00	1.75 ***	1.00	1.35 ***	1.80 ***	1.50 ***	1.50 ***	1.22 ***
	Cd content tubers	1	0.50 ***	1.50 ***	2.25 ***	3.00 ***	1.00	0.83	1.33 ***	1.42 ***	1.00	1.50 ***			2.00 ***	1.66 ***		

Level of significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

1. Cd_5
2. Cd_{10}
3. Cd_{15}
4. Cd_{30}
5. Cd_5Pb_{250}
6. $Cd_{10}Pb_{500}$
7. $Cd_{15}Pb_{1000}$
8. $Cd_{30}Pb_{2000}$
9. Cd_5Zn_{250}
10. $Cd_{10}Zn_{500}$
11. $Cd_{15}Zn_{1000}$
12. $Cd_{30}Zn_{2000}$
13. $Cd_5Pb_{250}Zn_{250}$
14. $Cd_{10}Pb_{500}Zn_{500}$
15. $Cd_{15}Pb_{1000}Zn_{1000}$
16. $Cd_{30}Pb_{2000}Zn_{2000}$

of pepper fruits, radish and pea plants. Statisticaly significant reduction of dry matter production of pepper plants was observed at relatively high level of Cd contamination (Cd_{10}) and the same effect on yield (Cd_{15}), irrespectively of the high Cd content in pepper fruits.

If we analyse the relationship Cd content of pepper fruits —> growth and yield under conditions of multiple contamination, the most interesting influence from an agricultural point of view has the combination Cd_5Pb_{250} – there is a decrease in the Cd content —> an increase of the yield as compared to single Cd contamination. At the higher level of soil contamination Pb^{2+} ions increase Cd content and decrease yield. The combination CdZn also decreases Cd content as well as yield. Nevertheless the combination CdZn decreases more effectively the Cd content of fruits, there is also a reduction in yield.

Lead is stronger antagonist of Cd^{2+} than Zn^{2+} in pea plants and decreases more effectively Cd content. The synergistic interaction between Cd^{2+} and Pb^{2+} exists only at the highest combined level ($Cd_{30}Pb_{2000}$). Between Cd^{2+} and Zn^{2+} antagonistic interaction was observed at the lowest level (Cd_5Zn_{250}). At the triple combination dominates the influence of Zn^{2+}. Cd content in top parts of peas is as higher as lower the accumulated dry matter is. At triple combination the summed toxic effect of Cd^{2+}, Pb^{2+} and Zn^{2+} in pea plants is demonstrated at higher levels than $Cd_{10}Pb_{500}Zn_{500}$. Pepper plants respond similarly.

The ability of radish plants to accumulate Cd is similar to that of peas. The double interaction CdPb resembles that in peppers – it is antagonistic at level Cd_5Pb_{250} and synergistic at higher levels. The double interaction CdZn is also similar to that in pea plants – Cd content is increased at all levels of contamination. Under condition of triple contamination Cd content is also increased. The type of interaction is additive. Radish plants accumulate more Pb and Zn and less Cd in comparison to pepper and pea plants, therefore it could be expected that growth and yield would not be reduced so much, but opposite to the expectation at initial three levels they decrease 2 times. As a result, the interaction between Pb^{2+} and Zn^{2+} alleviates the phytotoxic effect of Cd^{2+} only at Cd_5Pb_{250} and Cd_5Zn_{250} levels.

In higher plants, Cd^{2+} in comparison to Pb^{2+} and Zn^{2+} appear to be highly mutagenic.

Conclusions

The susceptibility to soil Cd concentration depends on plant species, level of contamination and plant tissue ability to tolerate Cd. In the three plant studied the toxic content of the tissues is different. Double combination CdZn for pepper, pea and radish plants is more phytotoxic than CdPb. The type of interaction among Cd^{2+}, Pb^{2+} and Zn^{2+} depends on plant species and level of contamination. Pepper fruits accumulate high amount of Cd, they tolerate high concentration of Cd in the soil and the tissues without a corresponding reduction of yield. The opposite is true for radishes. Pea plants occupy an intermediate position. It is assumed that phytotoxicity of Cd depends more on free Cd^{2+} ions than on the total Cd content of plant tissues. Pepper plants should not be cultivated even on low Cd contaminated soils.

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