AGRICULTURAL BIOLOGY,
2017, V. 52, № 3, pp. 597-606
(SEL'SKOKHOZYAISTVENNAYA BIOLOGIYA)

ISSN 2412-0324 (English ed. Online)
ISSN 0131-6397 (Russian ed. Print)
ISSN 2313-4836 (Russian ed. Online)

Genotypes: analysis and selection

UDC 635.656:631.522/.524

doi: 10.15389/agrobiology.2017.3.597rus
doi: 10.15389/agrobiology.2017.3.597eng

PEA (*Pisum sativum* L.) CULTIVARS WITH LOW ACCUMULATION OF HEAVY METALS FROM CONTAMINATED SOIL

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The authors declare no conflict of interests
Acknowledgements:
Supported by Russian Science Foundation (projects № 14-16-00137 and № 14-26-00094 for design and implementation of the experiments, and for bioinformatic processing, respectively)
Received October 21, 2016

Abstract

Heavy metals are among the most common contaminants of agricultural lands. Cleaning (remediation) of such territories is extremely difficult or impossible. A promising approach for the production of environmentally friendly products of crop industry in the contaminated soils can be a selection of varieties with reduced accumulation of heavy metals. The aim of this work was to study the variability of pea in accumulation and transport of heavy metals from shoots to seeds and to identify varieties with low accumulation of heavy metals from contaminated soils. The objects of research were 30 varieties of pea (*Pisum sativum* L.) from the collection of Federal Research Center N.I. Vavilov All-Russia Institute of Plant Genetic Resources (St. Petersburg). The pot experiment was carried out in summer in a greenhouse with natural light and temperature (All-Russian Research Institute of Agricultural Microbiology, St. Petersburg). Pea seeds were surface-sterilized and scribbled with concentrated H_2SO_4 for 30 minutes and germinated for 3 days at 22 °C in Petri dishes with wet filter paper. The seedlings were planted in pots (5 seedlings per pot, 3 pots for each genotype) containing 5 kg of sod-podzolic fallow soil. Ten days before seed sowing the soil was enriched with heavy metals in the form of chlorides (mg/kg): Cd — 5, Co — 25, Cr — 60, Cu — 10, Ni — 15, Pb — 100, Sr — 50, Zn — 50. At the same time, fertilizers were applied (mg/kg): NH_4NO_3 — 15, KNO_3 — 200, KH_2PO_4 — 200, $MgSO_4$ — 30, $CaCl_2$ — 20, H_3BO_3 — 3, $MnSO_4$ — 3, $ZnSO_4$ — 3, Na_2MoO_4 — 1.5. The plants were grown until the seed maturing phase, dried and ground to a powder. Samples (separately shoots and seeds) were digested in a mixture of concentrated nitric acid and 38 % H_2O_2. The content of heavy metals and nutrients was determined using ICPE-9000 spectrometer (Shimadzu, Japan). The studied samples differed significantly in the content of heavy metals in shoots and seeds that indicated a high variability of pea in the accumulation of heavy metals and their transport from vegetative to reproductive organs. The variability values for shoots and seeds were comparable in magnitude, but did not correlate with each other. The shoots or seed contents of various heavy metals, as well as nutrients, in many cases positively correlated, which could be due to the diversity of molecular transport channels in plants and their low specificity. There was positive correlation between the content of elements in shoots and seeds for Cd, Co, Cr, Ni, P, Sr, and negative was found between the shoot and seed contents of Zn and K. The results indicate specific mechanisms of transport of individual elements from shoot to seed and the barrier for abiogenic metal transport from vegetative to reproductive organs. The effectiveness of these mechanisms depends significantly on the plant genotype. The possibility of selection of pea varieties with a low content of many heavy metals simultaneously is shown. Pea varieties k-188, k-1027, k-1250, k-2593, k-3445, k-4788, k-5012, k-6468, k-8093 and k-8543 are recommended for use in selection programs for obtaining ecologically safe crop production.

Keywords: biodiversity, pea, soil contamination, heavy metals, environmentally friendly

products

Environmentally friendly and energy-saving approaches for developing sustainable agriculture and providing with quality food products is becoming especially important because of growing anthropogenic pollution of the environment. Heavy metals (HM) (Cd, Co, Cr, Cu, Ni, Pb, Zn) of the highest class of hygienic hazard are among the most common soil pollutants. The total area of HM-contaminated agricultural land in Russia is about 150 thousand hectares [1]. Basically, these are soils with medium or low HM contamination, which does not have a toxic effect on plant growth, but leads to exceeding the maximum permissible content of HM for agricultural products. The remediation of such territories is extremely difficult, expensive or impossible. The selection of varieties with reduced accumulation of heavy metals [2-4] is a promising approach for obtaining environmentally friendly products, in contrast to phytoextraction technologies [5].

It is known that many crops, including legumes [6-8], oilseeds [7-8] and cereals [9-11], differ significantly in HM accumulation. A high intraspecific polymorphism in HM content in several crops, including legumes, was also described. Significant varietal differences have been shown in soybean [6, 12], peanut [6] and beans [6, 13] for Cd accumulation, in soybeans [14] for Zn accumulation, and in beans [13] for Pb and Zn accumulation from contaminated soil. However, many experiments compared a limited number of varieties (from 2 to 20) that did not reflect the diversity, domestication and history of cultivation of the species, which reduces the value of such studies in terms of trait polymorphism.

We showed for the first time a significant intraspecific variability of garden pea (*Pisum sativum* L.) in the accumulation of HM in shoots by comparing 99 samples (mostly primitive and local varieties) from VIR collection of (N.I. Vavilov All-Russia Institute of Plant Genetic Resources, St. Petersburg), grown on soil enriched with a mixture of heavy metals (Cd, Cr, Cu, Ni, Pb, Sr, Zn) [15]. It was found that the accumulation of these metals in the shoots differed multiply depending on the plant genotype. As a result, samples with a low content of several HM in the shoots were detected, which were involved in the presented study.

The choice of initial pea seed material for selection of varieties tolerant to accumulation of heavy metals in biomass on contaminated soils was carried out in this work for the first time.

Our goal was to study the intraspecific variability of garden pea according to accumulation and transport of heavy metals from the shoot to the seeds and to identify the relationship of these processes to the consumption of nutrients by the plants.

Technique. In the study, 30 samples of garden pea (*Pisum sativum* L.) from VIR collection were involved, some of which (k-188, k-1027, k-1250, k-1693, k-2593, k-3445, k-4788, 5012, k-6468, k-6883, k-7131, k-8093, k-8543) were characterized by low accumulation of HM from contaminated soil [15]. In addition, varieties and lines from different countries with valuable agronomic traits (high productivity and protein content, fruit abounding, etc.) were selected based on VIR collection evaluation databases, i.e. k-6935, k-8861, k-8862, k-9283, k-9384, k-9385, k-9386, k-9389, k-9465, k-9509, k-9510, k-9526, k-9540 and k-9566. Control samples with high HM content in shoots when growing on contaminated soil were k-1658, k-1930, and k-8274 [15].

The pot experiment was carried out in summer in a greenhouse under natural light and temperature (All-Russian Research Institute for Agricultural Microbiology, St. Petersburg). Pea seeds were surface-sterilized and scarified with concentrated H_2SO_4 for 30 min, after which they were germinated for 3 days at 22 °C in Petri dishes with wet filter paper. The seedlings were planted in pots (5 seedlings per pot, 3 pots per genotype) containing 5 kg of sod-podzolic fallow soil (C_{com} 2.34±0.05%, N_{com} 0.18±0.1%, N_{NO} 1.5±0.2 mg N/100 g, P_{mob} 7.7±0.6 mg P/100 g, K_{mob} 13.5±0.9 mg K/100 g; pH_{KCl} 6.6±0.1). The agrochemical soil parameters were determined by standard methods [16]. Ten days before sowing, the soil was enriched with heavy metals (as chlorides): Cd (5 mg/kg), Co (25 mg/kg), Cr (60 mg/kg), Cu (10 mg/kg), Ni (15 mg/kg), Pb (100 mg/kg), Sr (50 mg/kg), and Zn (50 mg/kg). Simultaneously, fertilizers were applied, i.e. NH_4NO_3 (15 mg/kg), KNO_3 (200 mg/kg), KH_2PO_4 (200 mg/kg), $MgSO_4$ (30 mg/kg), $CaCl_2$ (20 mg/kg), H_3BO_3 (3 mg/kg), $MnSO_4$ (3 mg/kg), $ZnSO_4$ (3 mg/kg), Na_2MoO_4 (1.5 mg/kg). The soil moisture was maintained at 60-70 % of the total moisture capacity during the experiment by adding water (to the same weight of vessels). The plants were grown until seed maturation, dried and ground to a powder; samples (separately shoots and seeds) were burned in a mixture of concentrated nitric acid and 38 % H_2O_2 at 70 °C in a DigiBlock graphite furnace (LabTech, Italy). The content of heavy metals and nutrients was determined using an ICPE-9000 spectrometer (Shimadzu, Japan) according to the manufacturer's protocol.

The statistical processing was carried out by dispersion methods, correlation and cluster analysis using Statistica 8.0 software (StatSoft Inc., USA) and DIANA software [17]. The cluster analysis of standardized values (SV) of elements content was carried out using the Ward method with squares of Euclidean distances. The heavy metal content index was calculated as the average of the standardized content values of all heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Sr, Zn) in shoots and seeds.

Results. The studied pea samples (Table 1) differed significantly in the content of heavy metals in the shoots (Table 2).

1. Samples of garden pea (*Pisum sativum* L.) estimated for accumulate and transport of heavy metals from shoots to seeds (VIR collection, N.I. Vavilov All-Russia Institute of Plant Genetic Resources, St. Petersburg)

№ in VIR catalog	Name	Origin	Use
k-188	Mahorg	Pamir	Fodder
k-1027	Untitled	Germany before1986	Fodder
k-1250	Local	Tajikistan, Pamir, Yarchych	Fodder
k-1658	Weibull	Sweden	Fodder
k-1693	Untitled	United Kingdom	Vegetable
k-1930	Local	Italy	Grain
k-2593	Local	Cyprus	Grain
k-3445	Untitled	Azerbaijan	Grain
k-4788	Untitled	Mongolia	Fodder
k-5012	Ojo negro especial	Argentina	Grain and vegetable
k-6468	Local	Sudan	Grain
k-6883	Local	Uzbekistan	Fodder
k-6935	Preclamex	France	Vegetable
k-7131	Local	Tunisia	Vegetable
k-8093	Telephone	Madagascar	Vegetable
k-8274	Vendevil	France	Grain and vegetable
k-8543	Fillbaskit	Sri Lanka	Grain and vegetable
k-8861	Effulgent	Russia, the Kirov region	Grain
k-8862	Agate	Belarus	Fodder
k-9283	Nikolka	Russia, the Tyumen region	Fodder
k-9384	Falcon mustachioed	Russia, the Kirov region	Grain
k-9385	Boreas	Russia, the Kirov region	Fodder
k-9386	G-16992	Russia, the Kirov region	Grain
k-9389	D-13560	Russia, the Kirov region	Fodder
k-9465	Tyumenets	Russia, the Tyumen region	Grain
k-9509	Vlad	Belarus	Vegetable
k-9510	Azure	Belarus	Grain
k-9526	Azur	Germany	Grain
k-9540	ID 29001914	Australia	Fodder
k-9566	Kazar	France	Vegetable

The samples k-1027, k-4788 and k-9540 showed the minimum values of this index for Cd, Co and Cr, respectively. Low content of Co, Cr, Ni, Sr, Zn was characteristic of k-1027, and low Pb was found in k-4788. In the shoots of k-3445, Cu, Ni, Pb, Sr, Zn amounts were minimal, and Cd, Co, Cr were low. In k-6468 Cd, Cu and Sr content was low, in k-8093 Cu, Ni, Pb and Zn were low. The minimum and maximum levels of heavy metals in the shoots differed 12-fold for Cd (in k-1027 and k-9389), 2.5-fold for Co (in k-1027 and k-6935), 2.5-fold for Cr (in k-1027 and k-6935), 7.3-fold for Cu (in k-3445 and k-9385), 2.8-fold for Ni (in k-3445 and k-6935), 3.9-fold for Pb (in k-3445 and k-9566), 2.9-fold for Sr (in k-3445 and k-9566), 4.3-fold for Zn (in k-3445 and k-9566) (Table 2). The obtained results are consistent with data of a high variability of garden pea on HM accumulation in shoots [15]. The samples (k-1658, k-1930, k-8274), taken as control, showed a high content of heavy metals in shoots, but it was slightly lower or close to that in the samples k-6935, k-9389, k-9566.

2. Shoot biomass and heavy metal content in garden pea (*Pisum sativum* L.) shoots grown on contaminated soil (vegetation experience)

№ in VIR catalog	Dry shoot weight, g/plant	Content, mg/kg dry weight							
		Cd	Co	Cr	Cu	Ni	Pb	Sr	Zn
k-188	2.0	4.4	9.3*	7.5	29	9.8*	5.2*	449*	156
k-1027	2.2	1.1*	6.4*	6.3*	26	7.7*	5.5*	323*	108*
k-1250	2.2	6.4	9.3	7.4	25*	10.3	8.1	407*	170
k-1658[a]	2.5	6.7	12.4	7.8	29	15.0	10.5	557	239
k-1693	1.6	1.9*	7.0*	7.8	25*	9.5*	5.7*	467	169
k-1930[a]	1.1	6.9	13.3	9.1	30	11.7	10.3	561	180
k-2593	2.0	4.0	7.9*	6.7*	21*	9.4*	5.1*	392*	140
k-3445	2.2	2.0*	6.2*	6.0*	14*	6.7*	3.5*	288*	60*
k-4788	2.1	2.0*	6.0*	6.5*	26	9.8*	4.4*	411*	140
k-5012	1.5	3.5*	8.9*	6.6*	31	10.6*	6.1*	471	192
k-6468	1.8	2.5*	9.7	7.1	17*	8.8*	5.7*	326*	135*
k-6883	1.3	2.5*	8.5*	7.7	29	12.1	6.3*	440*	154
k-6935	1.5	8.5	15.9	14.6	28	18.6	9.9	680	180
k-7131	2.0	5.2	9.5	8.0	26	11.2	10.3	547	213
k-8093	1.9	2.8*	7.9*	6.5*	15*	7.6*	5.4*	375*	83*
k-8274[a]	0.8	7.8	10.8	10.6	30	11.2	7.4	674	153
k-8543	1.9	3.5*	7.6*	6.8*	26	8.9*	4.5*	320*	131*
k-8861	1.9	6.0	10.5	7.4	58	12.6	7.0	418*	143
k-8862	1.8	3.9*	11.2	9.5	36	14.4	6.8	556	99
k-9283	2.0	4.5	10.8	8.0	67	14.2	6.9	407*	191
k-9384	1.6	8.8	11.8	7.0	63	14.8	6.7	520	121*
k-9385	1.6	6.5	9.7	6.6*	74	13.5	5.9*	421*	150
k-9386	1.3	9.9	13.0	7.3	18*	15.0	7.7	657	159
k-9389	1.7	13.2	12.9	6.5*	14*	14.8	10.2	652	174
k-9465	1.5	6.6	11.2	6.2*	50	12.9	8.1	578	171
k-9509	1.9	5.6	12.6	6.6*	38	15.9	8.7	640	222
k-9510	1.8	10.2	12.2	6.4*	26	13.7	10.0	572	215
k-9526	1.1	9.4	17.3	7.7	55	16.8	10.4	734	171
k-9540	2.0	5.7	11.9	5.9*	27	11.9	7.0	550	147
k-9566	2.2	10.2	14.7	8.6	22*	18.6	13.8	827	257
Average	1.8	5.7	10.5	7.5	33	12.3	7.4	496	161
Cv, %	28	53	26	22	60	27	32	27	31
$LSD_{0.05}$	0.47	1.52	1.31	1.05	7,3	1.93	1.51	64	12,3

Note. Samples from VIR collection (N.I. Vavilov All-Russia Institute of Plant Genetic Resources, St. Petersburg): a — samples with high heavy metals content used as a control; an asterisk for each element denotes values that were less than the difference between the average for all samples and the confidence interval when analyzing the average presented in the table; *Cv* is the variation coefficient.

The analysis of element composition in seeds also showed a high variability in HM content (Table 3). The minimum amount of Cd was found in the seeds of the sample k-1693, which, however, had a near-average content of other metals. The sample k-3445 was characterized by a minimum content of Co and Cr with low Cd, Ni, Sr; the sample k-9566 had minimum content of Cu and low Pb and Zn; the sample k-188 had minimum content of Ni and low Pb and Sr; for the sample k-8274 minimum content of Pb was characteristic at low Co, Ni, Sr and Zn level. In the seeds of other samples (k-1250, k-1658, k-2593, k-6468, k-8543, k-9389), several heavy metals was also low. The minimum and maximum accumulation of heavy metals in seeds differed 9 times for Cd (samples k-1693 and k-9384), 4.2 times for Co (k-3445 and k-9283), for 10 times Cr (k-3445 and k-1693), 3.3 times for Cu (k-9566 and k-9384), 3.2 times for Ni (k-188 and k-9283), 6.8 times for Pb (k-8274 and k-9526), 4.1 times for Sr (k-8543 and k-9509), and 4.3 times for Zn (k-8861 and k-8093). Previously, high variability in heavy metal level in seeds, mainly in Cd, was noted for soybean [12], peanut [6, 18], maize [19], rice [10], wheat and barley [9].

3. Seeds weight and heavy metal content in garden pea (*Pisum sativum* L.) grown on contaminated soil (vegetation experience)

№ in VIR catalog	Seed dry weight, g/plant	Content, mg/kg dry weight							
		Cd	Co	Cr	Cu	Ni	Pb	Sr	Zn
k-188	1.3	0.50	2.8	0.35	23	3.4*	0.54*	16*	14
k-1027	1.1	0.37*	2.5*	0.56	25	4.1*	0.67*	24	20
k-1250	1.8	0.64	2.1*	0.24*	19	5.8*	0.57*	17*	15
k-1658[a]	1.5	0.49*	1.9*	0.23*	16*	6.7	0.83	21	13
k-1693	1.2	0.22*	3.0	0.89	26	7.2	1.55	36	13
k-1930[a]	1.2	0.89	2.8	0.28	28	5.5*	0.36*	22*	13*
k-2593	1.3	0.65	2.3*	0.18*	23	5.1*	0.47*	17*	23
k-3445	1.8	0.36*	1.5*	0.09*	20	5.2*	0.79	12*	31
k-4788	1.4	0.36*	1.9*	0.40	21	6.7	1.28	16*	9
k-5012	1.4	0.40*	2.8	0.30	16*	7.0	0.99	32	18
k-6468	1.0	0.28*	1.8*	0.21*	15*	5.8*	1.02	19*	25
k-6883	1.0	0.43*	2.5*	0.38	21	4.4*	0.68*	20	15
k-6935	1.2	1.12	4.8	0.61	24	8.3	1.27	88	12*
k-7131	1.1	0.41*	3.0	0.44	23	7.8	0.64*	28	16
k-8093	1.2	0.35*	2.6*	0.49	22	8.7	0.83	25	26
k-8274[a]	0.9	0.73	2.0	0.58	18	3.9*	0.29*	16*	12*
k-8543	1.1	0.32*	2.0	0.23*	20	5.2*	1.10	11*	15
k-8861	2.0	0.61	2.7	0.31	14*	7.5	0.89	31	6*
k-8862	2.1	0.99	3.9	0.36	18	7.3	1.09	39	10*
k-9283	1.6	0.86	5.3	0.54	24	10.9	1.33	47	14
k-9384	1.5	1.99	5.7	0.54	39	8.4	1.76	70	14
k-9385	1.7	0.98	4.2	0.31	22	6.3	0.95	37	10*
k-9386	1.1	0.57	3.7	0.28*	17*	8.1	0.82	30	9*
k-9389	1.9	0.87	3.2	0.18*	14*	6.3	0.69	23*	9*
k-9465	1.7	0.49*	4.1	0.27*	15*	7.4	1.35	33	8*
k-9509	1.6	0.63	5.3	0.32	17*	7.9	0.87	45	13
k-9510	1.5	0.44*	4.4	0.27*	18	8.0	1.10	35	17
k-9526	1.3	0.69	5.0	0.26*	20	6.9	1.98	25	12*
k-9540	2.0	0.67	3.9	0.25*	14*	6.9	1.31	28	9*
k-9566	1.4	1.21	3.1	0.28	12*	7.3	0.69*	34	8*
Average	1.4	0.65	3.2	0.36	20	6.7	0.96	30	14
Cv, %	23	56	38	51	27	24	42	56	43
$HCP_{0.05}$	0.54	0.150	0.81	0.096	6.1	1.83	0.32	7.8	3.6

N o t e. Samples from VIR collection (N.I. Vavilov All-Russia Institute of Plant Genetic Resources, St. Petersburg): a — samples with high heavy metal content used as a control; an asterisk for each element denotes values that were less than the difference between the average for all samples and the confidence interval when analyzing the average presented in the table; *Cv* is the variation coefficient.

The variability in the content of elements in pea seeds was higher or comparable to that of shoots, as evidenced by high coefficients of variation (Tables 2, 3). However, we did not find a correlation between *Cv* in shoots and seeds. This indicated the differences in the mechanisms of transport of metals from shoots to seeds in the studied samples. The content of heavy metals in seeds was several times less than in shoots, which is consistent with the description of legumes as species with low metal translocation in the root—shoot—seed system [2, 5, 7, 20].

A negative correlation was found between shoot biomass and the content of Cd (r = –0.44; P = 0.015), Co (r = –0.51; P = 0.004), Cr (r = –0.40; P = 0.026), Ni (r = –0.41; P = 0.024) and Sr (r = –0.63; P = 0.001), which probably was due to the dilution of the metal with biomass at limited accessibility from pots. However, the observed effect could also be due to the peculiarities of the samples, since the shoot weight did not correlate with the accumulation of other heavy metals (Cu, Zn) and nutrients (P, K, Fe, Mn), and we also failed to detect correlations between seed weight and HM or nutrient levels.

In many cases, there was a positive interdependence between the accumulation in the shoots of various heavy metals, as well as nutrients (Table 4), for example, Cd, Co, Mg, Ni, Pb, S, Sr and Zn. The same pattern was manifested in seeds (see Table 4). Thus, the amount of Sr in seeds correlated with the content of all elements, with the exception of B, Fe, S. The presence of such correlation was first discovered by us [15]. This paper confirms this phenomenon and supplements it with a description of the correlation relationships for Co and nutrients, the content of which has not previously been measured. The obtained results are consistent with the data of W. Cheng et al. [10], which found a positive correlation between the content of As, Cd, and Pb; As and Zn; Cr and Ni in grain in different varieties of rice grown on contaminated soils. Probably, this phenomenon is connected with the variety of molecular transport mechanisms and their low specificity in plants (the same channels provide transportation of both nutritional elements and HM) [21-23].

4. Correlation coefficients between the chemical element content in seeds (1) **and shoots** (2) **of garden pea (*Pisum sativum* L.) grown on contaminated soil** (vegetation experience)

2 \ 1	B	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Ni	P	Pb	S	Sr	Zn
B		0,30	0,13	0,11	0,45*	0,44*	0,30	–0,05	0,10	0,19	–0,01	0,19	0,07	0,17	0,26	0,12
Ca	0.32		0.61*	0.65*	0.46*	0.47*	–0.24	0.51*	0.36*	0.64*	0.58*	–0.42*	0.47*	–0.09	0.97*	–0.10
Cd	0.30	0.77*		0.57*	0.11	0.40*	–0.41*	0.46*	0.15	0.20	0.29	–0.46*	0.21	0.06	0.65*	–0.36*
Co	0.45*	0.81*	0.81*		0.24	0.28	–0.49*	0.87*	0.49*	0.45*	0.68*	–0.46*	0.58*	–0.04	0.75*	–0.37*
Cr	0.48*	0.45*	0.23	0.46*		0.53*	0.05	0.15	0.59*	0.23	0.22	0.11	0.25	0.30	0.46*	–0.11
Cu	0.49*	0.03	0.14	0.19	–0.03		0.23	–0.07	0.56*	0.40*	0.07	0.41*	0.24	0.27	0.38*	0.21
Fe	0.17	–0.27	–0.30	–0.18	0.32	0.01		–0.63*	–0.05	0.29	–0.33	0.69*	–0.30	–0.16	–0.36	0.64*
K	–0.41*	–0.25	–0.38*	–0.32	–0.06	–0.37*	–0.09		0.34	0.34	0.75*	–0.66*	0.53*	–0.16	0.65*	–0.52*
Mg	0.39*	0.88*	0.71	0.75*	0.52*	0.06	–0.05	–0.24		0.44*	0.40*	0.26	0.20	0.10	0.37*	0.02
Mn	–0.13	0.14	–0.05	–0.05	0.19	–0.26	0.47*	0.08	0.32		0.56*	–0.06	0.38*	–0.39*	0.55*	0.32
Ni	0.55*	0.72*	0.75*	0.88*	0.46*	0.34*	–0.03	–0.46*	0.68*	–0.08		–0.43*	0.53*	–0.23	0.63*	–0.21
P	–0.28	–0.23	–0.45*	–0.36	0.03	–0.11	0.28	0.52*	0.01	0.58*	–0.48*		–0.35	0.20	–0.52*	0.64*
Pb	0.26	0.79*	0.75*	0.81*	0.37*	–0.02	–0.09	–0.29	0.79*	0.27	0.76*	–0.25		–0.12	0.48*	–0.20
S	0.20	0.74*	0.43*	0.52*	0.47*	–0.01	–0.26	0.03	0.68*	0.12	0.40*	0.07	0.44*		–0.03	–0.22
Sr	0.29	0.94*	0.78*	0.85*	0.44*	0.01	–0.29	–0.29	0.81*	0.06	0.83*	–0.35	0.83*	0.64*		–0.27
Zn	0.17	0.61*	0.50*	0.54*	0.20	0.04	0.02	–0.14	0.57*	0.31	0.62*	–0.17	0.78*	0.36*	0.62*	

* Statistically significant correlation coefficients (r) (for $r > 0.35$ $P \leq 0.05$; for $r > 0.45$ $P \leq 0.01$; for $r > 0.56$ $P \leq 0.001$; $n = 30$).

The samples were grouped into clusters. The individual clusters included those that had a low content of Cd, Co, Cr, Cu, Ni, Pb, Sr, Zn HM and B, Ca nutrients in the shoots (Fig. 1, A, cluster № 3), low heavy metals Cd, Co, Ni, Pb, Sr and Ca, K nutrients in seeds (Fig. 1, B, cluster № 3), low Cr, Cu, Zn in seeds (Fig. 1, B, cluster № 3). The composition of clusters that combined samples with a low content of most heavy metals was similar in shoots and seeds. This was consistent with a positive correlation of metal amount in shoots and seeds for Cd ($r = +0.55$, $P = 0.002$), Co ($r = +0.57$, $P = 0.001$), Cr ($r = +0.41$; $P = 0{,}023$), Ni ($r = +0.48$, $P = 0.007$), Sr ($r = + 0.37$, $P = 0.048$), and also for the nutrient P ($r = +0.67$, $P < 0.001$). At the same time, we found a negative correlation between the accumulation of the element in shoots and seeds for Zn ($r = –0.45$; $P = 0.012$) and K ($r = –0.59$; $P < 0.001$). In the control samples k-1658, k-1930 and k-8274, HM content in shoots was high (see Table 2), in the seeds it was low (see Table 3), and they were grouped in cluster № 3 (see Fig. 1, B). Samples that were included in clusters with low HM accumulation in shoots or seeds had a high content of K and P or Fe, P and Zn, respectively. The obtained results testify to the specificity of the mechanisms ensuring transport of individual elements from shoot to seeds, and a barrier for the transport of abiogenic metals from the vegetative organs to the reproductive ones. The effectiveness of these mechanisms also depends significantly on the plant genotype. Such biodiversity and wide practical use of peas (fodder, grain and vegetable varieties) indicate the need to take into account the heavy metal content simultaneously in shoots and seeds when implementing breeding programs.

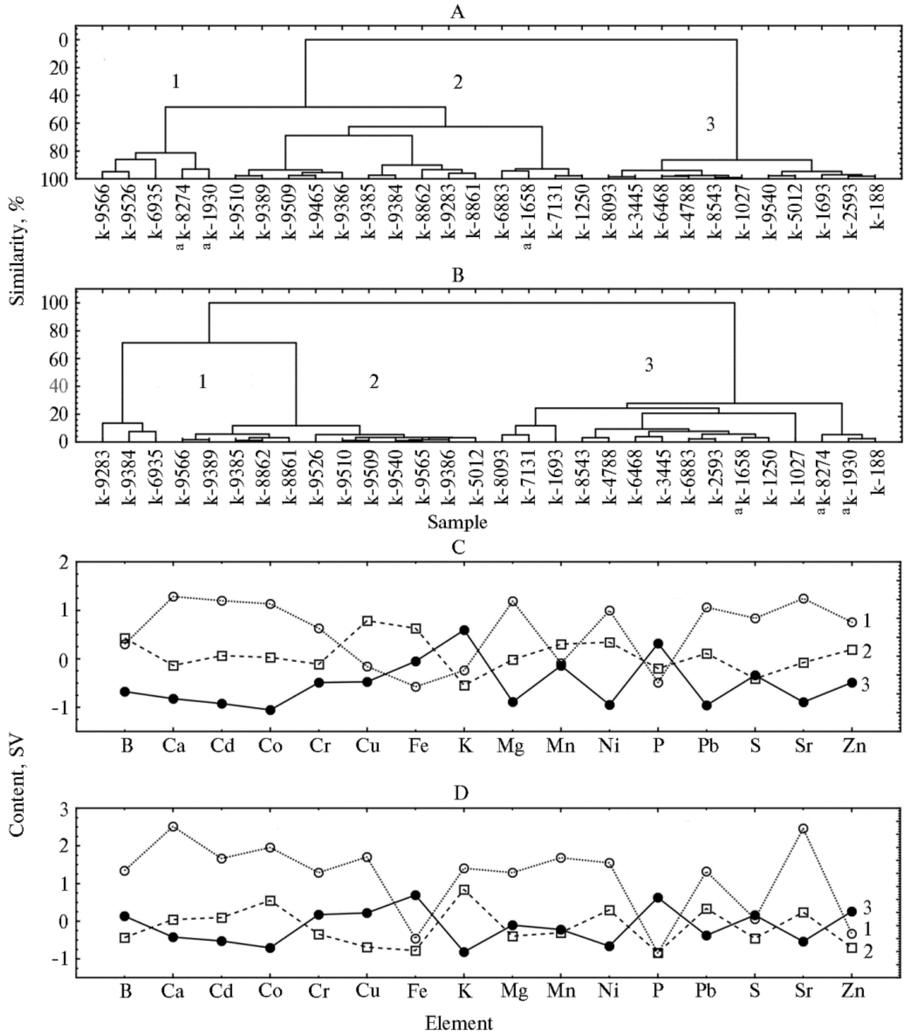

Fig. 1. Cluster diagrams showing the grouping of the samples of garden pea (*Pisum sativum* L.), grown on contaminated soil by the content of heavy metals and nutrients in shoots (A) **and seeds** (B), **as well as the mean values of element abundance in shoots** (B) **and seeds** (D)**:** 1 — cluster 1, 2 — cluster 2, 3 — cluster 3; a — samples with a high heavy metals content used as a control, SV — standardized values of the content of elements (vegetation experiment).

To generalize the obtained results, the index was calculated of the content of all heavy metals in shoots and seeds, which made it possible to reveal samples with minimum average values of this parameter (Fig. 2). Most samples with a low index were related to previously characterized forms with low accumulation of heavy metals in shoots [15], i.e. k-188, k-1027, k-1250, k-2593, k-3445, k-4788, k-5012, k-6468, k-8093, and k-8543. They were old local varieties, and their comparison with modern varieties and lines showed that the latter actively accumulate heavy metals in shoots and transport them to seeds. This may be the result of selection for intensive technologies with large yield gain at a high agricultural background (that is, effectively using mineral fertilizers). Probably, intensive assimilation and transport of nutrition mineral elements predetermine active accumulation of abiogenic elements.

It should be emphasized that many heavy metals (Co, Cu, Ni and Zn) are necessary for the plant in low concentrations. In our experiment, they were introduced in doses exceeding the MAC for agricultural use soils. However, these concentrations turned out to be lower than those for peas, as the plants developed normally and showed no signs of injury. In addition, there was a positive correlation between the content of certain nutrients (Ca, K, Mg, P and S), HM of biogenic nature (Co, Cu, Ni, Zn) and abiogenic elements (Cd and Pb) in shoots and/or seeds (see Table 4).

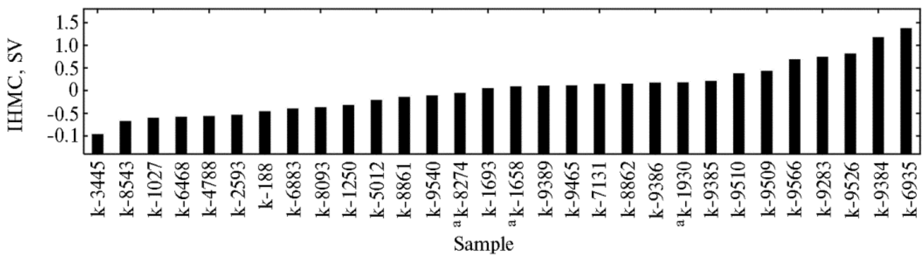

Fig. 2. The index of heavy metals content (IHMC) **in shoots and seeds of *Pisum sativum* L., grown on contaminated soil:** a — samples with a high heavy metals content used as a control, SV — standardized values of elements content (vegetation experiment).

Thus, valuable information on pea plant polymorphism on accumulation of heavy metals has been obtained and correlations between the content of various elements (nutrient macro-, micro- and abiogenic elements) in shoots and/or seeds have been found. The results demonstrate the complexity and multicomponent mechanisms and processes of nutrient and toxic elements consumption by plants, as well as high intraspecific variability of peas according to these features. It is shown that the parameters characterizing the activity of plants nutrient intake can serve as additional criteria for the search for genotypes with a reduced content of heavy metals. It should be taken into account that selection for the effective use of mineral nutrition elements can enhance the accumulation of toxic elements by plants on contaminated soils. At the same time, it is possible to select for low simultaneous accumulation of many heavy metals. For these, the old local varieties of peas from VIR collection (N.I. Vavilov All-Russia Institute of Plant Genetic Resources, St. Petersburg) k-188, k-1027, k-1250, k-2593, k-3445, k-4788, k-5012, k-6468, k-8093, k-8543, and also the modern selection material (lines) k-9386, k-9389 (Kirov region) and k-9465 (Tyumenets, Tyumen region) are prospective.

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