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BIOACCUMULATION AND DISTRIBUTION OF HEAVY METALS, MACRO- AND MICROELEMENTS IN *ODONTARRHENA CHALCIDICA* FROM BULGARIAN SERPENTINE SOILS

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Abstract

Comparative research has been carried out to determine the accumulation of heavy metals, macro, and microelements in the vegetative organs of Odontarrhena chalcidica, collected from serpentine soils from the Eastern and South Rhodopes Mountains (Bulgaria). The content of metals in the plant varies depending on the sampling location and, above all, on the content of their mobile forms in the soil. In Odontarrhena chalcidica plants, the maximum concentrations of Ni were up to 873.1 mg/kg in roots, 924.9 mg/kg in shoots, 8317 mg/kg in leaves, and 6693 mg/kg in flowers. Ca/Mg ratio in plant tissues were up to 6.2 (roots), 7.4 (stems), 10.2 (leaves), and 7.4 (flowers). There is a distinct pattern in the accumulation of heavy metals in the vegetative organs of Odontarrhena chalcidica. Most of the Ni, Ca and Mg accumulate in the leaves and flowers, K and P in the flowers. There is no clear trend for Pb, Zn, Cu Fe, Mn, Cr and Co. This study shows that Odontarrhena chalcidica from serpentine soils of Bulgaria appears as a strong Ni hyperaccumulator and can be used for phytoextraction purposes.

Key words*: serpentine soils, nickel hyperaccumulator, heavy metals, Odontarrhena chalcidica, Bulgaria.*

INTRODUCTION

Serpentine soils are widespread in various parts of the world (Cuba, New Caledonia, Australia, Turkey, Brazil, China, etc.) (Brooks, 1987). In Europe, they are found mainly in the Balkans (Bani et al., 2010). They exist as large blocks or as small outcrops separated by other geological formations in central Bosnia and western and central Serbia, central and south-eastern parts of Albania, the regions of Epirus and Thessaly in Greece.

Small amounts of serpentine rocks are typical in the southwestern, southern, and central parts of Bulgaria, mainly in the Central and East parts of the Rhodope Mountains (Pavlova, 2001a; 2001b). Serpentine soils originate from serpentine rocks, which are usually shallow, and have specific physical and chemical properties, such as low nutrient status, cation imbalance, moisture stress, soil instability, high surface temperature and high metal concentrations. Fe, Mg, Si, Ni, Cr, and Co are present in large amounts, while N, P, Ca, K, and B are generally deficient (Shallari et al., 1998). Mn content may also be higher compared to other soil types. The Mg/Ca ratio is high because soils are rich in Mg and poor in Ca (Proctor, 1999). Plants growing on serpentine soils have elevated Ni and Co contents compared to the same plants on other soil types. Extremely high concentrations of Ni (known as Ni hyperaccumulators) have been found in the aerial parts of some plants growing on serpentine soils. The species Alyssum (family Brassicaceae) is endemic to serpentine soils in the Mediterranean and can uptake Ni >1000 mg/kg in its tissues without showing symptoms of toxicity (Van der Ent et al., 2013). Significant variability in the Ni content of plants has been found (Reeves and Adgüzel 2008), with the highest values found in A. murale (7-34690 mg/kg) and A. heldreichii (1440-32040 mg/kg) (Bani et al., 2010). The Ni-enriched biomass can be considered raw material for Ni production, and the whole process is called phytomining (Sheoran et al., 2009; Van der Ent et al., 2015). With phytomining technologies, Ni-contaminated soils can be cleaned, and high purity Ni metal can be recovered (Chaney et al., 1999; Li et al., 2003a; Li et al., 2003b; Nkrumah et al., 2016).

The present work aims to conduct a comparative study that will allow us to determine the uptake of heavy metals, macro, and microelements in the vegetative organs of

Odontarrhena chalcidica collected from serpentine soils and establish the potential for Ni phytoextraction.

MATERIALS AND METHODS

Plant and soil samples were collected for analysis in May and June of 2020 and 2021 from 9 locations in Eastern and South Rhodopes Mountains (Bulgaria). Table 1 shows the coordinates and sampling sites.

Five plants were collected from each site. Simultaneously, three soil samples were collected at 0-20 cm depth from each site.

The soils were air-dried and ground. *Odontarrhena chalcidica* plants were washed with water, separated into their parts (roots, stems, leaves and flowers), and dried at 45oC. The contents of heavy metals and micro and macroelements in the plant material (roots, stems, leaves and flowers) were determined by microwave mineralization. The total content of heavy metals in soils was determined in accordance with ISO 11466. The mobilizable heavy metals contents in soils, considered a "potentially bioavailable metal fraction", were extracted by a solution of DTPA (ISO 14870). The quantitative measurements were carried out with inductively coupled plasma emission spectrometry (ICP) (Jobin Yvon Emission - JY 38 S, France).

Table 1. Sampling sites

Sampling sites	Site code	Geographical coordinates	
		Latitude (N)	Longitude (E)
Eastern Rhodopes Mt			
Avren	Av	41°20'616"	25°41'8.1"
Goljamo Kamenjane	GK	41°24'1.4"	25°42'58.1"
Chernichevo	Ch	41°20'42.5"	25°45'45.8"
Kazak	K	41°24' 42.7"	25°53'2.0"
Kardzali	Kd	41°33'15.0"	25°33'24.5"
Dobromirzi	D	41°23'2.3"	25°12'28.6"
Djuliza	Dju	42°22'35.8"	25°19'23.3"
Central Rhodopes Mt			
Parvenetz	Pz	42°3'55.9"	24°39'28.3"
Gornoslav	G	41°54'38.5"	24°57'20.1"

RESULTS AND DISCUSSIONS

Soil characteristics

The contents of heavy metals and macro and microelements in the studied serpentine soils are presented in Table 2. The soils had a neutral to slightly alkaline reaction (pH 6.4 to 7.6) and a medium to high organic matter content.

Serpentine soils from all locations are characterized by elevated metals Ni, Cr, Co, and Mn levels, which is typical of such soils (Table 2). The total Ni content in the study areas ranged from 1269.9 to 2281 mg/kg, while DTPA extracted Ni ranged from 6.1 mg/kg to 99.4 mg/kg. All concentrations were much higher than those considered toxic to normal plants by Allen et al. (1974) and Kabata-Pendias (2011). In serpentine soils, Ni and Cr concentrations are known to reach several g/kg typically and reach more than 10 g/kg (Proctor, 1999; Nkrumah et al., 2016). The obtained values are similar to Bani et al. (2010) results for serpentine soils from Bulgaria, Greece and Albania, with values exceeding 3.0 g/kg Ni in some soils from Albania.

The Cr content of the soils ranged from 327.9 to 1876.8 mg/kg. All exceed the upper limit given for normal soils by Allen et al. (1974) and Brooks (1987) (500 mg/kg) except for the soils from Dobromirzi. The values we obtained are similar to those found by Karataglis et al. (1982) for northern Greece and Bani et al. (2010) for Albania.

Cobalt in soils ranged from 200.4 to 314.4 mg/kg and was within the normal range for serpentines. Cobalt's relatively easy interaction with all metals geochemically or biochemically associated with Fe significantly influences its behaviour in soils and its phytoavailability (Kabata Pendias, 2011).

The Fe content in serpentine soils is high and ranges from 40704 to 72964 mg/kg, typical for the Balkan Peninsula's serpentine soils (Salihaj and Bani, 2018, Pavlova 2001b).

Mn content ranges from 787 to 2019 mg/kg and is characteristic of serpentine soils from Albania, Greece and Bulgaria (Bani et al., 2010).

The Fe content of the studied soils shows typical values for serpentine soils and ranges from 4.1% to 7.3%, which is in agreement with published data by other authors (2.43-6.28%, Bani et al., 2010). The high pH of soils (6.4-7.6) causes poorly soluble oxides of Fe, Mn, and Cr, resulting in these metals being unavailable to plants (Babalonas et al., 1984).

The Cu content ranged from 4 to 120.6 mg/kg, while Zn ranged from 42.6 to 392 mg/kg.

These values fall within limits for normal soils (Allen et al., 1974; Kabata-Pendias, 2011).

Serpentine soils are rich in Mg but low in Ca. The Mg content ranges from 3.9 to 23.7% and Ca from 0.14 to 0.52%. All soils are characterized by an extremely low Ca/Mg ratio (0.02-0.04), which can lead to Ca deficiency stress for plants.

The P content ranged from 76.2 to 442 mg/kg, while the K content ranged from 142 to 1849 mg/kg. Most of the soil samples are characterized by low nutrient (P and K) levels, a common characteristic of serpentine soils (Brooks, 1987).

The low available phosphorus in serpentine soils is related to the high affinity of soluble phosphates for serpentines (Brooks, 1987). The content of available macronutrients such as Ca and K is also very low and ranges from 94 to 1317.2 mg/kg for Ca and 13 to 50.2 mg/kg for K, which is also characteristic of serpentine soils.

The chemical composition of serpentine soils from the Eastern and Central Rhodopes is similar to serpentine soils from the Balkan Peninsula (Brooks, 1987; Bani et al., 2010), with high metals such as Ni and Cr relatively low Ca/Mg ratios. The Ca and Mg levels found in these Bulgarian serpentine soils are typical of such soils from other areas (Brooks, 1987). The total Ni content of the soils is similar to that of Italian (Vergnan Gambi et al., 1982), Greek (Babalonas et al., 1984) and Albanian (Shallari et al., 1998; Bani et al., 2010) serpentine zones.

Chemical composition of plant material

The contents of heavy metals, and macro and nicroelements in different parts of *Odontarrhena chalcidica* are presented in Tables 3, 4, 5 and 6.

In all *Odontarrhena chalcidica* plants tested from serpentine soils, the highest Ni values were recorded in the leaves, up to ten times higher than in the stems. The Ni content ranged from 108.8 to 924.9 mg/kg in stems, 1444 to 8285 mg/kg in leaves, and 870 to 6084 mg/kg in flowers.

Leaves and flowers are the main Ni storage organs. From the roots and the conducting system, Ni moves and accumulates in the leaves and flowers. The results confirm the findings of Broadhurst et al. (2004a; 2004b, 2009) that leaves contain the most Ni of all Ni hyperaccumulator organs, and Ni is highly concentrated in vacuoles of epidermal cells and epidermal villi (trichomes). The values found for Ni are significantly lower than the data published by Bani et al. (2014), who found more than 20,000 mg/kg Ni in plant leaves from serpentine soils in Albania and Greece. According to Bani et al. (2010), the highest Ni concentrations in leaves collected from serpentine soils in Bulgaria (Rhodope Massif) range from 5,000 mg/kg (Kardzali) to 15,100 mg/kg (Kazak), while in Serbia the Ni content in leaves ranges from 700 to 13,000 mg/kg (Tumi et al., 2012). No correlation between soil pH and Ni uptake in *Odontarrhena chalcidica* has been found from serpentines in the Balkans (Bani et al., 2010). According to the authors, the Ni content of this species strongly depends on the site of sample collection (Bani et al. 2010, 2013, 2015a, 2015b). No relationship between Ni levels in plant leaves and those in soil was found. This is probably due to the wide variability of the sites from which the plants were collected, and differences in their physical and chemical properties, climate and altitude.

Despite the high Cr content of the soil, the amounts of Cr taken up by *Odontarrhena chalcidica* reach up to 0.5 mg/kg in the stems, 11.5 mg/kg in the leaves and 6.0 mg/kg in the flowers. According to Brooks (1987), plants from serpentine soils typically contain <15 mg/kg Cr.

It is known that the Co content rarely reaches 10 mg kg in plants from both normal soils and serpentine soils. The values we obtained confirm that this level is not exceeded, except in plants from Kardjali (11.4 mg/kg). In their study, Bani et al. (2010) found unusually high Co values in Ni hyperaccumulators (15-100 mg/kg).

Ca content ranged from 11652 to 34822 mg/kg in leaves and 10744 to 36199 mg/kg in flowers. It is noteworthy that the Ca uptake by *Odontarrhena chalcidica* is significant, although the Ca content of serpentine soils is low. According to Proctor (1971), Ca is one of the elements influencing lowering the toxicity of heavy metals. Probably *Odontarrhena chalcidica* growing on serpentine soils absorb more Ca to compensate for the toxic action of various toxic metals. Karataglis et al. (1982) suggested that the plants have a mechanism to assimilate significant amounts of Ca. Bani et al. (2010) found that Ca and Ni can be antagonists. The higher Ca and the lower Ni concentrations can explain the content in the leaves of *Odontarrhena chalcidica*. In all *Odontarrhena chalcidica* plants tested, the Ni: Ca ratio was lower than unity (0.07-0.4), while the Ni: Mg ratio was higher than unity (2.4-19.0). Broadhurst and Chaney (2016) reported the exceptional Ca uptake in the leaves of hyperaccumulator species (and the genus Alyssum). This is probably an adaptive ability of this genus (Odontarrhenae) to Ca deficiency in serpentine soils. The reason for the high leaf Ca content is the density of trichomes and the nodules of $CaCO_3$ covering the trichome surface (Broadhurst and Chaney, 2016)

The Ca content in the leaves of species of the genus Alyssum is very high, despite the low Ca values in the soil. This property of species of the genus Alyssum from serpentine soils has also been noted by other authors (Reeves & Adigüzel, 2008). High Ca concentrations have been recorded for A. murale from the Thessaloniki region (3.98%), and up to 4.3% in Albania. No correlation was found between Ca and Ni values in leaves of *Odontarrhena chalcidica*. Still, there was a significant negative correlation between Ni in leaves of *Odontarrhena chalcidica*, and the total Ca content of the soil. Extremely high Ca uptake is essential for Ni-hyperaccumulator physiology (Broadhurst et al., 2004; Chaney et al., 2008). Walker et al. (1955) suggested that serpentine plants survive because they uptake greater Ca than Mg.

However, the hydrometallurgical method must consider the significant amounts of Ca in the leaves and flowers when phytoextracting Ni from the plant.

Although the Mg content of soils is high, Mg is accumulated to a significantly lesser extent by *Odontarrhena chalcidica* compared to Ni and Ca. The highest Mg content was in leaves and flowers, where it ranged from 1147 to 8317 mg/kg (leaves) and from 1452 to 6693 mg/kg (flowers). The Mg content is significantly lower in stems and roots. According to Bani et al. (2010), the average Mg content for Alyssum species is 0.43-0.83%.

Brooks and Yang (1984) found a negative correlation between Mg content and the content of other nutrients such as Fe, Co, and Mn. The results suggest that Mg uptake leads to less uptake of other nutrients. Brooks and Young (1984) suggested that elevated Mg levels in serpentine soils and antagonism with other elements may be the most critical factor in plant survival in serpentine soils.

There are conflicting opinions on the relationship between Ni and Mg uptake in Alyssum species (Kazakou et al., 2008). According to Robinson et al. (1999), it is possible that Mg also limits Ni accumulation by the plant and that there is a negative correlation between Ni and Fe. It was found that an antagonistic relationship may exist between Ni and Mg, similar to the relationship between Mg and Fe.

The Ca/Mg ratio in all plant samples was > 1. *Odontarrhena chalcidica* from serpentine soils can maintain a ratio greater than one despite minimal Ca levels in the soils. It is suggested that plants have very efficient uptake systems or the ability to exclude Mg despite high soil contents.

P and K contents are highest in flowers and range from1273 to 4361 mg/kg for P and from 2928 to 11460 mg/kg for K. K is a crucial plant nutrient whose most important role in the maintenance of plant water balance (osmore-gulation). Although K in serpentine soils is low, K accumulates in leaves and flowers.

No trends in Fe accumulation were found in the plants tested. In plants from the Kazak, Dulitsa and Parvenetz areas, Fe accumulated in the leaves, whereas in plants from Avren, Chernichevo, Kardzali, Gornoslav and Golyamo Kamenyane, it accumulated in the roots. Fe is also essential for many plant functions as it is a constituent of some enzymes and proteins and plays a role in energy transfer in the plant. Similar values for the Fe content in the aboveground mass of *O. Chalcidica* have also been found by other authors (Bani et al., 2014; Broadhurst and Chaney, 2016; Xhaferri et al., 2018). According to Bani et al. (2010), the Fe content is usually below 1000 mg/kg, confirmed by results from this study. Higher values indicate contamination of foliar samples by serpentine soil or dust, which is difficult to remove by washing samples before analysis.

No trends in Mn accumulation were detected either. Most of the Mn accumulated in the leaves in plants from Avren, Chernichevo, Kazak, Kardzali and Parvenetz, in the roots (Golyamo Kamenene and Dulitsa), and plants from Dobromirtsi, no significant difference in concentration was found between roots, stems, leaves and flowers. According to Broadhurst et al. (2004b, 2009), Alyssum accumulates a significant Mn in the same vacuole cavities. That contains Ni. Ni hyperaccumulators accumulate less Mn and Co than other transition metals such as Fe, Cr, or Cu (Broadhurst and Cheeney, 2016). According to Broadhurst et al. (2009) and Ghaderian et al. (2015), there is a specific relationship between Mn accumulation and Ni hyperaccumulation rather than Mn uptake and storage associated with enhanced Ca uptake in trichomes (McNear and Kupper, 2013).

Similar results were obtained for Cu, Zn, Pb and Co.

Zn uptake is similar to that observed in normal soils. This is not surprising as Zn concentrations in serpentine soils are not unusual.

The bioaccumulation coefficients (ratio of metal concentrations in the aboveground mass and soil) and the translocation factor (ratio of metal concentrations in the aboveground mass and roots) were used to estimate plant uptake of Ni. In hyperaccumulators, the values of both factors are usually above 1 (Baker and Whiting, 2002).

The translocation factor (TF) provides information on the ability of plants to uptake heavy metals through the roots and move them to the aboveground mass (leaves). Hyperaccumulators usually contain fewer heavy metals in the roots than the aboveground mass. (Baker et al., 1994). TF in hyperaccumulators can reach values > 1, indicating that the heavy metal content in the aboveground mass is higher than that in the below-ground parts (roots). The obtained values ranged from 5.7 to 40 (Figure1).

The bioconcentration factor also determines the efficiency of phytoextraction. It measures the plant's ability to absorb and move metals to the aboveground mass that can be readily harvested. In hyperaccumulators, the bioconcentration factor is higher than one and, in some cases, can reach 50-100. The results indicate that Ni in the aboveground mass of *O. chalcidica* is 1 to 10 times higher than in soil. Values were lower in Gornoslav, Parvenetz and Dulitsa (slightly above 1), intermediate in Kazak, Golyamo Kamenyane and Dobromirtsi (2.8-5.3), and highest in Avren, Kardzali and Chernichevo (above 9). The tested plant *Odontarrhena chalcidica* is a hyperaccumulator and can be used for Ni phytoextraction.

There is a distinct pattern in the accumulation of heavy metals and micro and macro elements in the vegetative organs of *Odontarrhena chalcidica*. Most of the Ni, Ca and Mg accumulate in the leaves and flowers, K and P in the flowers. There is no clear trend for Pb, Zn, Cu Fe, Mn, Cr and Co.

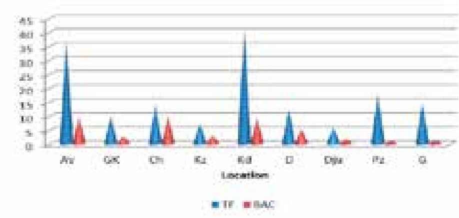

Figure 1. Translocation |TF| and bioconcentration (BAC) factors

Table 2. Content of heavy metals, micro and macroelements (mg/kg) in serpentine soils

	Pb	Zn	Cu	Fe	Mn	P	Cr	**Ni**	Ca	Mg	K	Co
Av	2.8	45.1	5.3	59175.3	1075	149.2	1335	1439	1372	38676	895.6	200.4
GK	6.7	43.5	37.0	67230.3	1295	179.5	1630	2123	2821	40729	968.9	233.7
Ch	11.1	48.3	120.6	72963.5	1702	442	672.9	1270	4529	66630	1357	228.3
Kz	19.9	67.5	8.0	67442.8	2019	266.3	1877	1481	2768	63513	999.5	314.4
Kd	71.1	130.8	10.9	64373.5	1419	209.5	1456	1709	5171	139254	1849	222.2
D	439.2	392	55.8	56187.4	1187	215.5	327.9	1276	3363	52935	1117	239.3
Dju	81.7	73.6	4.0	63847.2	1239	209	1610	1678	1775	85769	931.2	250.0
Pz	17.7	48.4	16.8	40704.2	787	76.2	562	2281	2159	236569	142.6	226.6
G	9.7	42.6	22.2	49919.1	1473	88.2	1069	2228	1419	216708	550.5	308.4

Table 3. Content of heavy metals, micro and macroelements (mg/kg) in roots of *Odontarrhena chalcidica*

	Pb	Zn	Cu	Fe	Mn	P	Cr	**Ni**	Ca	Mg	K	Co
Av	0.83	21.9	2.3	1413	112.4	341.1	9.2	352.8	1464	3732	879.8	12.6
GK	2.7	48.5	4.8	4684	92.5	566.8	37.8	589.2	3893	4657	967.4	22.2
Ch	1.1	65.4	3.4	1443	42.97	1077	13.2	873.7	4109	1821	7750	7.5
Kz	0.14	116	2.3	239.1	12.1	1608	3.7	603.2	2879	654	7600	1.8
Kd	0.2	80.3	2.2	232.5	26.7	840.3	1.5	327.1	1516	421.7	2381	1.5
D	2.8	56.5	11.2	2817	54.9	660.2	22.9	556.2	4003	1856	1411	3.6
Dju	92.6	169.7	4.2	599.2	27.8	1476	2.5	512.8	3479	1683	6182	32.9
Pz	0.63	56.3	0.89	39.5	6.7	112.4	0.09	133.1	1989	235	884.5	0.54
G	50.9	168.7	7.1	1174	36.3	349.6	6.1	216.2	3792	2132	914.6	4.9

Table 4. Content of heavy metals, micro and macroelements (mg/kg) in stems of *Odontarrhena chalcidica*

	Pb	Zn	Cu	Fe	Mn	P	Cr	Ni	Ca	Mg	K	Co
Av	0.03	10.3	0.91	20,3	8,1	326	0.01	328.6	2958	399.8	3254	0.44
GK	0.49	20.2	1.7	102.7	11.4	321.5	0.34	387.7	5237	433.2	1396	1.4
Ch	0.64	25	2.5	41.8	10.3	630.2	0.01	924.9	7272	1571	6871	0.85
Kz	0.52	11.2	1.1	22.9	6.8	776.7	0.03	304.8	3036	451.9	5493	0.30
Kd	0.04	26.4	1.8	115.3	18.8	2070	0.54	441.6	2152	906.9	10320	0.79
D	0.24	24.6	2.1	69.7	10.2	730.6	0.23	336.5	3832	702.0	5347	1.49
Dju	7.1	52.2	1.7	32	3.3	433.6	0.01	152.7	2244	290.4	5032	0.29
Pz	1.3	11.3	0.84	44.2	9.6	278.2	0.1	108.8	3629	627.2	2370	0.54
G	2.1	51.7	1.6	82.9	5.1	583.1	0.53	159.4	3567	526.0	5693	0.62

Table 5. Content of heavy metals, micro and macroelements (mg/kg) in leaves of *Odontarrhena chalcidica*

	Pb	Zn	Cu	Fe	Mn	P	Cr	**Ni**	Ca	Mg	K	Co
Av	3.2	37.3	4.2	1079	137.5	1102	3.6	6952	21868	5866	8604	29.9
GK	0.61	19.3	2.5	567.9	46.3	1021	3.1	2922	25519	1549	4634	12.4
Ch	4.2	34.9	4.7	341.6	67.7	904	2.8	5184	34822	3372	9727	15.1
Kz	0.33	10.1	0.86	78.8	21.4	536	0.73	2421	11652	1147	3679	6.4
Kd	1.5	35.7	4.4	1405	221.5	2181	11.5	8285	20241	8317	11460	41.4
D	2.4	24.6	3.9	382.5	47.2	1474	3.2	3526	21143	2332	9323	18.7
Dju	4.8	87.8	1.7	869.3	14.5	462	0.52	1444	12876	1712	2928	5.9
Pz	2.0	28.7	2.3	316.2	73.6	1455	1.7	1553	22047	4981	10641	42.4
G	3.6	29.8	1.4	178.6	26.4	552	0.76	1779	27100	1427	3182	6.5

Table 6. Content of heavy metals, micro and macroelements (mg/kg) in flowers of *Odontarrhena chalcidica*

	Pb	Zn	Cu	Fe	Mn	P	Cr	Ni	Ca	Mg	K	Co
Av	0.82	29.9	3.8	196.4	95.0	4361	0.29	5808	19960	4502	19777	8.7
GK	0.28	22.1	2.5	110.2	34.8	1832	0.94	2475	22782	1612	9057	4.8
Ch	0.67	36.4	7.1	138.4	85.1	3548	0.01	6068	36199	4187	14957	8.2
Kz	0.49	27.7	2.0	99.1	33.5	1947	0.02	1744	19748	1452	9166	2.1
Kd	1.33	31.1	7.1	868.4	165.3	4266	6.0	4558	14596	6693	18060	11.4
D	0.68	25.9	4.7	249.6	44.6	3968	2.1	2945	19959	3664	14776	9.6
Dju	0.92	48.5	1.8	160.3	13.1	1644	0.05	1322	13110	2180	8731	2.1
Pz	0.5	18.95	1.6	67.5	29.0	1778	0.01	870.1	10744	3484	9877	5.6
G	1.8	36.1	2.1	89.8	29.6	1273	0.04	1210	20273	1548	9402	2.2

CONCLUSIONS

Based on the results obtained, the following conclusions can be drawn:
1. The chemical composition of serpentine soils from the Eastern and Southern Rhodopes is similar to serpentine soils from the Balkan Peninsula, and is characterized by high contents of Ni (1270-2281 mg/kg), Cr (32.7-1877 mg/kg), and Mg (38676-236569 mg/kg).
2. The content of metals in *Odontarrhena chalcidica* varies depending on the sampling location and, above all, on the content of their mobile forms in the soil.
3. There is a distinct pattern in the accumulation of heavy metals and micro and macro elements in the vegetative organs of *Odontarrhena chalcidica*. Most of the Ni, Ca and Mg accumulate in the leaves and flowers, K and P in the flowers. There is no clear trend for Pb, Zn, Cu, Fe, Mn, Cr and Co.
4. The tested hyperaccumulator plant *Odontarrhena chalcidica* can be used for Ni phytomining.

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