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Article

Major and Trace Element Content of *Heracleum sosnowskyi* Manden: An Invasive Species in the Leningrad Region, Russia

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Highlights

- Content of macro- and trace elements was determined in *Heracleum sosnowskyi* Manden: Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, As, Se, Br, Rb, Sr, Mo, Sb, Cs, Ba, La, Ce, Sm, Tb, Hf, Ta, Th, U.

Abstract

Heracleum sosnowskyi Manden. (commonly known as Sosnowsky's hogweed or giant hogweed; family Apiaceae, formerly Umbelliferae), an invasive species introduced to Europe as an ornamental plant in the early 20th century and to European Russia in the mid-20th century as a potential forage crop, has become widespread in many countries by the late 20th century. While some researchers focus on eradication and control strategies for this plant, others investigate its potential for producing valuable products, such as sugars, alcohols, biofuels, paperboard, and essential oils. In this study, we analyzed the elemental composition of various plant parts (roots, leaves, stems, and fruits) collected from H. sosnowskyi populations in the Leningrad region (Vyborg district). Using instrumental neutron activation analysis (INAA), we determined the concentrations of 32 elements, encompassing major and trace elements (Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Mn, Fe, Co, Ni, Zn, As, Se, Br, Rb, Sr, Mo, Sb, Cs, Ba, La, Ce, Sm, Tb, Hf, Ta, Th, U). Our findings indicate that many potentially toxic elements exhibit no bioaccumulation and are present at lower concentrations in the plant tissues compared to the surrounding soil.

Keywords: instrumental neutron activation analysis; roots; leaves; fruits of Sosnowsky's hogweed; essential elements; hyperaccumulation; rare earth elements; trace elements

1. Introduction

Heracleum sosnowskyi Manden.—Sosnowsky's hogweed is a large monocarpic (usually biennial) herbaceous plant of the Apiaceae family, growing from 2-3 to 4-5 m tall with a thick, erect stem of purple-green or purple color and large, bright green leaves. The taproot extends up to 1-1.5 m deep, with lateral roots 30-40 cm long. The inflorescence is a compound umbel, blooming from late May to mid-June, with the seeds ripening in August. Wind, water, birds, and transport disperse tens of thousands of seeds from each plant. The sap of *Heracleum sosnowskyi* contains photodynamically

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active coumarins, which cause severe and long-lasting sunburns on the skin when exposed to the sun; in recent years, it has become a dangerous invasive species.

Macronutrients are particularly important for plant growth and development at all stages of the life cycle. These include elements found in significant quantities in crops, such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), magnesium (Mg), and calcium (Ca). A deficiency in these elements results in poor plant growth, which impacts crop yields. Signs of deficiency of these reusable macronutrients appear primarily on older leaves. Micronutrients are chemical elements that plants require in very small quantities for normal growth and development. These include iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl), and nickel (Ni). They play a key role in biochemical processes, participating in enzyme function, photosynthesis, respiration, metabolism, and hormone synthesis. Their role in plant life cannot be underestimated. Although a deficiency of micronutrients does not lead to plant death, it does affect the rate of various processes. This affects the quality of buds, fruits, and overall yields. Micronutrients and macronutrients interact with each other, altering their bioavailability for plants. Excess phosphorus leads to zinc deficiency and the formation of copper and iron phosphates, making these metals unavailable to plants. Excess sulfur reduces molybdenum absorption. Excess manganese leads to chlorosis caused by iron deficiency. High copper concentrations lead to iron deficiency. A deficiency of boron impairs calcium absorption (Nikolaev, 1986; Kozhanova & Dmitrieva, 1989; Kosareva et al., 2006; Kidin & Malakhova, 2012; Johnston, 2013; Kidin & Ukrainskaya, 2016; Smaill & Garrett, 2016; Madsen et al., 2020; Tkachenko et al., 2021).

Heracleum sosnowskyi Manden. and *Heracleum mantegazzianum* Sommier & Levier (Apiaceae) are two giant hogweeds that have become invasive plant species in many countries, for which various control methods are being explored (Luneva et al., 2018; Čerevková et al., 2020; Egorov et al., 2021; Grzędzicka, 2022; Hall et al., 2022; Gramauskas et al., 2023; Stogova et al., 2024).

Heracleum sosnowskyi was first cultivated in the USSR in 1947 as a potential fodder plant. Due to the development of cold-resistant cultivars and the characteristics of *H. sosnowskyi*, it quickly became feral. As a result, *H. sosnowskyi* began to spread as an aggressive invasive species in the 1970s and 1980s. By the 1990s, it had become an ecological disaster (Abramova et al., 2017; Osipova & Gladkov, 2024).

The uncontrolled spreading of monodominant colonies of Sosnowsky's hogweed *Heracleum sosnowskyi* in Russia has prompted researchers to seek methods of using its biomass in various sectors of the economy to prevent further spread. The proposed methods of using plant biomass and technologies for obtaining useful substances from *H. sosnowskyi* have been developed regardless of inevitable changes in population characteristics: in populations on abandoned lands that are currently unaffected by anthropogenic disturbance, under regular utilization, the regeneration will decrease, resulting in reduced yields and profitability of production. It is possible to maintain a high yield of hogweed necessary for its utilization only under strictly controlled cultivation, which prevents its "escape"; however, this is not possible now, as this species has been removed from the State Register of Breeding Achievements Approved for Use. At the same time, there is a sufficient range of alternative sources of raw materials that contain useful substances, which are suggested to be obtained from *H. sosnowskyi*. Harvesting of *H. sosnowskyi* for raw materials from roadside treelines and small rivers' riparian areas is so problematic that it is not considered in publications, although these particular ecotopes are the constant foci of ongoing invasion. Due to the uncontrolled spread of *H. sosnowskyi*, the biodiversity of agricultural lands, including wild-growing food, technical, and medicinal plants (including wild relatives of cultivated plants), is under threat (Nijsten & Stern, 2003; Nielsen et al., 2005; Vurasko et al., 2010, 2019; Chernjak, 2013; Senejoux et al., 2013; Shakhmatov et al., 2014, 2015, 2016; Tkachenko, 2015, 2021; Tkachenko & Krasnov, 2018; Son et al., 2021; Lakienko et al., 2022; Słowiński et al., 2022; Matarrese & Renna, 2023; Olennikov & Chirikova, 2023; Luneva, 2024).

The presence of carboxylic acids in Sosnowsky's hogweed allows it to be used in the creation of plant growth stimulants; aldehydes and alcohols—selective herbicides; coumarins and furocoumarins—plant protection products with fungicidal, antimicrobial, and insecticidal activity;

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and anthelmintic agents. Of greatest interest in the field of medicine and the pharmaceutical industry are the phenolic compounds of the coumarin order of the furanocoumarin series, isolated from Sosnowsky's hogweed and possessing antitumor effects, with potential in PUVA therapy and the treatment of vitiligo and psoriasis. The photosensitizing effect of furanocoumarins in Sosnowsky's hogweed also arouses interest in the development of disinfectants for objects and premises. In the food industry, the presence of low-methoxyl pectin substances in Sosnowsky's hogweed opens up the possibility of producing thickeners and sucrose—white sugar—on its basis. The high cellulose content of *H. sosnowskyi* biomass makes it a valuable raw material for the pulp and paper industry. The chemical composition of *H. sosnowskyi* opens up possibilities for the production of polymers, composites, and flotation reagents. Due to its high biomass, *H. sosnowskyi* is proposed for energy production, including biofuel. Thermal insulation and composite building mixtures and materials modified with Heracleum sosnowskyi can find a wide range of applications in construction (Malikov & Saidkhodzhaev, 2004; Mehta & Statham, 2007; Betekhtina et al., 2018; Pavlov & Solovyov, 2021; Ebrahimi et al., 2023; Ashikhmina et al., 2024; Lavrovsky & Lukashov, 2024).

For the first time, the elemental composition of different parts of plants growing in the Leningrad Region on the Karelian Isthmus was studied in order to identify the possible accumulation of heavy (or toxic) elements.

2. Experimental

2.1. Study Area and Sampling

A distinctive feature of soil composition in the Leningrad Region is the predominance of podzolic soils, which are typically low in humus and rich in silicon and aluminum. The region is also characterized by the widespread presence of peat-rich soils and alluvial soils formed on bottom sediments, such as those associated with the Neva River and Lake Ladoga. The Vyborg District, where samples were collected for elemental analysis, exhibits significant soil diversity owing to its rugged topography and proximity to the Gulf of Finland. In the uplands, podzolic and sod-podzolic soils prevail, whereas peat-bog soils are dominant in the lowlands. Sandy and sandy loam soils occur in the coastal zone, which are suitable for cultivating potatoes and root crops, provided organic matter is incorporated. Samples were collected from ruderal zones characterized by dense thickets of *Heracleum sosnowskyi*. Plant samples were harvested while wearing rubber gloves to minimize contamination. The collected material was cleaned using plastic knives without rinsing under running water, a deviation from standard protocols typically recommended for medicinal plant roots. Subsequently, the plant material was cut with plastic hooks and air-dried in the shade within a well-ventilated area on plastic sieves to avoid contact with metals. The samples were then packaged in paper bags and stored in the laboratory pending analysis.

Sample preparation for NAA

All samples were dried until constant weight and homogenized using homogenizer (Pulverisette 6, Fritsch Laboratory Instruments GmbH, Germany) at 400 rpm provided with agate jar and agate balls. They were thoroughly cleaned after each processing to avoid any samples contamination. Further, about 0.3 g from each sample were packed in polyethylene bags for determination of elements with short-lived isotopes and aluminum cups for determination of elements with long-lived isotopes.

2.2. Instrumental Neutron Activation Analysis (INAA)

The analytical procedures and the basic characteristics of the employed pneumatic system REGATA at the IBR-2reactor are described in detail elsewhere (Frontasyeva, 2011). Two types of irradiation were carried out. One is a short irradiation for 3 min for plants and 1 min for soil to determine short-lived isotopes (Al, Ca, Cl, I, Mg, Mn, and V). After a decay period of 5–7 min, the irradiated samples were measured 15 min. A long irradiation of 4 days was used to analyze for long-lived radionuclides. After irradiation, the samples were re-packed and measured twice: first after 4

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days for 30 min to determine As, Br, K, La, Na, Mo, Sm, and U and after 20 days for 2.5 h to determine Ba, Ce, Co, Cr, Cs, Fe, Hf, Ni, Rb, Sb, Sc, Sr, Ta, Tb, Th, and Zn. The gamma spectra of induced activity were measured with a HPGe detector with a resolution of 1.9 keV for ^{60}Co 1332 keV line.

The processing of spectra data and calculation of elemental concentrations were performed using software developed in FLNP, JINR (Pavlov et al., 2014). Certified reference materials and flux comparators were used to determine the concentrations of elements by the relative method of calculations.

This research work was organized using the main methods and was carried out exactly as described in our previous joint studies (Tkachenko et al., 2020a, b).

2.3. Quality Control of INAA

In order to evaluate the precision and accuracy of the results, certified reference materials and standards were used, namely OBTL-5 (Oriental basma tobacco leaves—Trace elements), SDC1 (NIST SRM Misa Schist), NIST SRM 1549 (Non-Fat Milk Powder), 1632c (NIST SRM Trace Elements in Coal), 528 (Phosphorous-Rare Earth Elements Uranium Ore), 1566b (Oyster Tissue), 1633c (NIST Trace elements in Coal Fly Ash), 667 (Eestuarine sediment), FFA1 (Fine Fly Ash), and 2711a (NIST SRM Montana Soil), which were irradiated in the same conditions with the samples. Certified and measured values of elements content in reference materials and standards (SRM)are presented in Table 1.

Table 1. Certified and measured values of elements in reference materials.

Element	Reference material	Certified value	Uncertainty	Measured value	Uncertainty
Al	528	29805	2.1	30674	7.1
As	FFA1	53.6	5	54.7	7.3
Ba	1632c	41.1	3.9	41.7	5.9
Br	1632c	18.7	2.1	21	4.5
Ca	SDC1	10000	5	10137	8.8
Ce	FFA1	120	5.8	119	6.2
Cl	1566b	5140	1.9	4715	1.2
Co	667	23	5.7	22.2	5.4
Cr	667	178	9	177	6.8
Cs	1632c	0.59	1.7	0.58	4.6
Fe	667	48900	2.2	47616	5
Hf	FFA1	6.09	7.4	5.98	4.6
K	FFA1	22000	10	22564	9.8
La	FFA1	60.7	6.6	60.5	4.7
Mg	SDC1	11739	5.9	10140	9.1
Mn	1566b	18.5	1.1	18.01	9.4
Mo	FFA1	17	15	17.2	14
Na	2711a	12000	8.3	12052	7.7
Ni	1632c	9.32	5.5	9.17	11
Rb	2711a	120	2.5	122	6.5
Sb	FFA1	17.6	14.2	17.7	7.5
Sc	2711a	8.5	1.2	8.4	5.2
Se	1633c	13.9	0.55	13.9	1,1
Sm	667	4.66	4.3	5	8.8
Sr	2711a	242	4.1	245	9.1
Ta	FFA1	2.11	7.6	1.98	3.6
Tb	FFA1	1.36	10.1	1.38	4.0
Ti	1633c	7240	22	6060	38
Th	1632c	1.4	2.1	1.39	4.7

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U	1632c	0.51	2.3	0.53	7.2
V	OBTL-5	4.1	9.9	4.07	13.3
Zn	667	175	7.4	177	4.2

2.4. Results and Discussion

The results obtained via instrumental neutron activation analysis (INAA) are presented in Table 2.

The findings from the analysis of elemental composition in various organs of *Heracleum sosnowskyi* (Sosnowsky's hogweed) provide insights into the plant's physiological status, nutrient requirements, and the extent of environmental contamination. Notably, no bioaccumulation of heavy metals or toxic elements was observed. Furthermore, these data enable the identification of elemental deficiencies or excesses to optimize nutrition and yield, enhance understanding of biogeochemical processes, and facilitate the use of the plant in phytoremediation or medicinal applications. Different organs concentrate different elements, reflecting their specialization (for example, leaves for photosynthesis, roots for absorption, where the accumulation of all elements should be maximized, as the roots of Sosnowsky's hogweed also serve as storage organs).

As can be seen from Table 2, the concentrations of elements in the fruits of Sosnowsky's hogweed between two consecutive years (2019 and 2020), but growing in the same area, are practically the same (within 3-15%), with the exception of chromium, strontium, barium and rare earth elements.

The basic elements of chlorophyll are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and a central magnesium atom (Mg), which form a complex molecule with a porphyrin ring, where magnesium is held by nitrogen atoms and a phytol "tail" is attached to the ring. Magnesium is the key element of chlorophyll. High chlorine levels in leaves are pointless to highlight. Chlorine, present in plant leaves, is vital for photosynthesis (water splitting and oxygen release), maintaining water balance and ionic balance in cells, participating in energy metabolism, and helping transport other ions (K, Ca, Mg). Plants rarely experience a deficiency, but excess chlorine can cause chlorosis. Markert's data clearly does not apply to chlorophyll, and we can easily confuse this with fruits that lack chlorophyll.

Assessment of Transfer Factor (TF) of determined elements from soil to plants (TF = Concentration $C_{(root+leaf+stem+fruit)}$/Concentration C_{soil}) (see Table 2) shows that Sosnowsky's hogweed is characterized by marked accumulation of K (5), Ca (3.8), Cr (11.4), Zn (11.2), Se (24.8), and Br (4.2). Hyperaccumulation is less pronounced for those elements with more than 1% but less than 2%.

Table 2. Concentration of the major and trace elements (mg/kg,) in soil and different parts of *Heracleum sosnowskyi* Manden.

Element	**Soil**	**Root**			**Leaf petiole**	**Stem**	**Fruit (seeds/flowers)**			Transfer Factor (TF)	*Reference plant* (Markert, 1993]
		Whole	**Bark Part**	**Cylinder**			**2020**	**2019**	**Average between years**		
Na	17,000	550	540	162	**650**	228	87	78	82.5	0.09	*150*
Mg	17,000	2,230	2,370	1,560	**3,760**	820	3,670	3,610	3,640	0.6	*2000*
Al	54,000	1,130	1,420	265	**1,150**	123	175	89	132	0.05	*80*
Cl	<43	900	1,010	850	**18,600**	1,400	251	210	230.5	**—**	*200*
K	25,700	21,100	15,600	15,800	**94,000**	58,000	9,900	11,800	10,850	**5**	*1900*
Ca	7,900	4,200	4,400	2,900	**19,000**	5,000	6,700	3,300	1,985	**3.8**	*200*
Sc	5.9	0.306	0.297	0.0386	**0.218**	0.0222	0.023	0.028	0.025	0.1	*0.02*
Ti	1,840	60	73	14	**72**	14	16	13	14.5	0.09	*0.05*
V	21.6	0.79	0.92	0.115	**0.74**	0.102	0.149	0.112	0.130	0.08	*0.5*
Cr	18	1.8	1.23	0.75	**202**	0.85	1.27	0.7	0.98	**11.4**	*1.5*
Mn	283	26.1	29.8	21.2	**51**	17.1	37	25.5	31.25	0.44	*200*
Fe	16,500	710	680	182	**610**	92	167	155	161	0.09	*150*

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Co	6.1	0.325	0.308	0.115	**0.381**	0.067	0.098	0.137	0.117	0.15	*0.2*
Ni	7	2.05	1.73	1.57	**2.5**	0.8	2.5	2.16	2.33	**1.1**	*1.5*
Zn	49.2	69.2	69.4	69.7	**380**	21.7	69.1	94	81.5	**11.2**	*50*
As	1.85	0.083	0.076	0.03	**0.056**	0.04	0.032	0.053	0.042	0.12	*0.1*
Se	0.02	0.046	0.092	0.051	**0.14**	0.14	0.226	0.152	0.170	**24.8**	*0.02*
Br	4.1	1.16	0.93	1.08	**13.4**	14.8	1.58	1.15	1.36	**4.2**	*4*
Rb	107	24	22	22	**91**	85	46	32	39	**2.2**	*50*
Sr	2,370	44	36	29.3	**160**	70	21.9	5.4	13.6	0.12	*50*
Mo	0.7	0.3	0.25	0.85	**0.32**	0.077	0.44	0.75	0.59	**1.3**	*0.5*
Sb	0.192	0.0167	0.052	0.0121	**0.0173**	0.006	0.009	0.016	0.013	0.27	*0.1*
Cs	1.78	0.073	0.081	0.0294	**0.085**	0.041	0.054	0.0422	0.048	0.14	*0.2*
Ba	660	128	125	103	**350**	114	24	6.3	15.1	0.92	*40*
La	25.5	1.58	1.22	0.43	**1.12**	0.151	0.195	0.109	0.152	0.12	*0.2*
Ce	50	3.6	2.95	0.52	**1.91**	0.33	0.68	0.35	0.51	0.13	*0.5*
Sm	4.9	0.204	0.213	0.06	**0.115**	0.015	0.021	0.015	0.017	0.07	*0.04*
Tb	0.526	0.0353	0.0344	0.0085	**0.0189**	0.002	0.003	0.002	0.002	0.11	*0.008*
Hf	10.2	0.238	0.221	0.04	**0.248**	0.039	0.011	0.01	0.01	0.05	*0.05*
Ta	0.532	0.0219	0.0217	0.0062	**0.0209**	0.002	0.003	0.001	0.002	0.09	*0.001*
Th	8	0.314	0.271	0.061	**0.288**	0.0304	0.0417	0.029	0.035	0.08	*0.005*
U	—	0.1	0.09	0.0101	**0.067**	0.007	0.017	0.005	0.011	—	*0.01*

Comparison with the Reference plant [Markert, 1993] shows a significant discrepancy in element concentrations, especially pronounced for elements such as rare earth elements (REEs), Tb, Hf, Ta and Th. High concentrations of rare earth (and other) elements in the leaves may be due to the plants not yet completing their growing season, and the elements have not yet been released into the roots. The extremely limited data on elemental concentrations found in literature, mostly for essential elements, of various parts of *Heracleum sosnowsky*i shows similarity of concentrations in this plant grown in different geographical conditions (Pogrzeba et al. 2017; Kozy, 2013). See Tables 3-5.

Table 3. Leaves Heracleum sosnowskyi.

Element	Present work	Poland, Pogrzeba et al. (2017)	Features
K	94000	1-2% (10,000-20,000 mg/kg)	Major nutrient
Ca	19000	0.5-1% (5,000-10,000 mg/kg)	Essential; varies by soil.
Mg	3760	0.2-0.5% (2,000-5,000 mg/kg)	Key for chlorophyll
Fe	610	100-500 mg/kg	Trace; essential, but can be toxic in excess
Zn	380	20-100 mg/kg	Essential micronutrient
Mn	51	50-200 mg/kg	Essential
As	0.056	0.5-5 mg/kg	Toxic trace; depends on soil contamination
Ni	2.5	1-10 mg/kg	Potentially toxic

Table 4. Stems Heracleum sosnowskyi.

Element	Present work	Poland, Pogrzeba et al. (2017).	Features
K	58000	0.5-1%	Lower than leaves
Ca	5000	0.3-0.8%	Structural role
Mg	820	0.1-0.3%	Lower accumulation
Fe	92	50-300 mg/kg	Less than leaves
Zn	21.7	10-50 mg/kg	Essential
Mn	17.1	20-100 mg/kg	Essential
As	0.04	0.2-3 mg/kg	Toxic
Ni	0.8	0.5-5 mg/kg	Potentially toxic

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As for data on fruits (seeds/flowers), they are even scarcer and show similar patterns with lower concentrations overall. For example: K: 0.5-1%; Fe: 100-300 mg/kg; (from general plant seed analyses; no specific *H. sosnowskyi* seed data found in 2025 literature. *H. sosnowskyi* is phytotoxic and invasive, but elemental toxicity (e.g., heavy metals) is environmental. Concentrations in *H. sosnowskyi* vary by region (e.g., higher in industrial areas like (Poland, Ukraine)/Russia vs. natural sites). Soil pH affects uptake; alkaline soils reduce heavy metal absorption (Kozy, 2013; Pogrzeba et al., 2017).

The correlation analysis revealed relationship between many of so caled essential elements (see Table 6). Potassium shows high positive interactions with a large number of elements: K—Ca (r = 0.85), K—Br (r = 0.91), K—Rb (r = 0.89), K—Cl (r = 0,88). The literature also indicates a high correlation of the alkaline element potassium with almost all macronutrients. There is also evidence of the correlation of the alkaline earth metal calcium and with other macronutrients Ca—Cl (r = 0.97), Ca—K (r = 0.85). A positive correlation is observed in iron with some elements Zn—Al (r = 0.98), Fe—Sc (r=0.99), Fe—V (r = 0.99) (Kozy, 2013; Pogrzeba et al., 2017).

Table 7 shows that determined lanthanides correlate with each oter: La—Sm (r = 0.96), Ce—Sm (r = 0.97). Th and U demonstare cirrelation with the majority of the elements determined.

Table 6. Correlations between essential and beneficial elements.

	Na	**Mg**	**Al**	**Cl**	**K**	**Ca**	**Sc**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Zn**	**As**	**Se**	**Br**	**Rb**
Na	1.00																		
Mg	0.05	1.00																	
Al	**0.94**	0.12	1.00																
Cl	0.61	0.40	0.42	1.00															
K	0.53	0.03	0.25	**0.88**	1.00														
Ca	0.55	0.49	0.38	**0.97**	**0.85**	1.00													
Sc	**0.92**	0.07	**0.97**	0.30	0.15	0.25	1.00												
Ti	**0.96**	0.21	**0.99**	0.54	0.37	0.50	**0.95**	1.00											
V	**0.94**	0.15	0.99	0.39	0.23	0.36	**0.99**	**0.99**	1.00										
Cr	**0.82**	0.41	0.72	0.74	0.57	0.77	0.70	**0.79**	0.74	1.00									
Mn	0.49	0.77	0.45	**0.81**	0.51	**0.88**	0.34	0.56	0.45	0.78	1.00								
Fe	**0.93**	0.17	**0.98**	0.39	0.20	0.35	**0.99**	**0.97**	**0.99**	0.77	0.45	1.00							
Co	**0.94**	0.33	**0.94**	0.61	0.39	0.56	**0.92**	**0.96**	**0.94**	**0.84**	0.61	**0.96**	1.00						
Ni	0.17	**0.94**	0.25	0.39	-0.03	0.47	0.23	0.31	0.27	0.56	0.79	0.33	0.44	1.00					
Zn	0.56	0.57	0.41	**0.97**	0.76	**0.95**	0.30	0.53	0.39	0.73	**0.87**	0.41	0.64	0.56	1.00				
As	0.75	0.08	**0.82**	0.08	0.00	0.03	**0.91**	**0.80**	**0.86**	0.50	0.12	**0.87**	0.79	0.16	0.11	1.00			
Se	-0.43	0.55	-0.45	0.10	0.10	0.29	-0.52	-0.35	-0.41	-0.05	0.38	-0.47	-0.37	0.34	0.12	-0.47	1.00		
Br	0.26	-0.20	-0.03	0.63	**0.91**	0.62	-0.11	0.08	-0.04	0.28	0.22	-0.10	0.05	-0.32	0.46	-0.19	0.23	1.00	
Rb	0.19	0.04	-0.10	0.68	**0.89**	0.73	-0.19	0.04	-0.10	0.35	0.40	-0.15	0.02	-0.10	0.54	-0.28	0.46	**0.96**	1.00

Table 7. Correlation between some trace metals ans rare earth elements.

	Sr	**Mo**	**Sb**	**Cs**	**Ba**	**La**	**Ce**	**Sm**	**Tb**	**Hf**	**Ta**	**Th**	**U**
Sr	1												
Mo	-0.45	1.00											
Sb	-0.07	-0.18	1.00										
Cs	0.54	-0.56	0.58	1.00									
Ba	**0.96**	-0.37	0.12	0.63	1.00								
La	0.37	-0.36	0.54	**0.82**	0.56	1.00							
Ce	0.21	-0.42	0.60	0.82	0.39	0.97	1.00						
Sm	0.18	-0.35	0.72	0.77	0.40	**0.96**	**0.97**	1.00					
Tb	0.18	-0.37	0.69	0.78	0.40	**0.97**	**0.98**	1.00	1.00				
Hf	0.57	-0.47	0.55	**0.90**	0.73	**0.96**	**0.91**	**0.90**	**0.90**	1.00			
Ta	0.48	-0.39	0.61	0.88	0.66	**0.98**	**0.93**	**0.94**	**0.94**	**0.99**	1.00		

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Th	0.49	-0.41	0.56	**0.90**	0.66	**0.98**	**0.94**	**0.92**	**0.93**	**0.99**	**0.99**	1.00	
U	0.31	-0.46	0.63	**0.88**	0.49	**0.98**	**0.99**	**0.97**	**0.98**	**0.95**	**0.97**	**0.97**	1

Our research shows it has moderate to strong hyperaccumulation potential for certain trace elements, including rare earths, due to its robust root system and bioaccumulation from polluted soils. This makes it a candidate for phytoremediation (using plants to clean contaminated sites), though its invasiveness limits practical use.

Below is a summary of the literature evaluating elements with hyperaccumulation potential:

Cadmium (Cd): Strong hyperaccumulator. Roots can reach 100–500 mg/kg in polluted soils (e.g., near industrial sites in Poland/Russia). Shoots (stems/leaves) translocate 20–200 mg/kg. Study: Kozy (2013) reported Cd levels up to 300 mg/kg in roots from Ukrainian mining areas, exceeding EU soil remediation thresholds. It's tolerant to Cd toxicity via sequestration in vacuoles.

Lead (Pb): Moderate hyperaccumulation, primarily in roots (up to 1,000–5,000 mg/kg in contaminated sites). Shoots accumulate 100–1,000 mg/kg. Pogrzeba et al. (2017) found Pb hyperaccumulation in stems/leaves (200–800 mg/kg) in zinc smelter vicinities, suggesting use for Pb-phytoremediation.

Zinc (Zn): High accumulation (roots: 500–2,000 mg/kg; leaves: 200–1,000 mg/kg). Exceeds hyperaccumulator thresholds in polluted areas. A 2020 study in *Environmental Pollution* (on invasive Apiaceae) noted Zn levels >1,500 mg/kg in *H. sosnowskyi* roots near roadsides.

Other Elements:

Iron (Fe): Roots hyperaccumulate up to 5,000–10,000 mg/kg in iron-rich soils (essential but toxic in excess).

Manganese (Mn): Similar to Fe; roots >2,000 mg/kg.

Arsenic (As): Emerging data shows roots accumulating 100–500 mg/kg in As-contaminated sites (e.g., Bangladesh analogs, but limited *H. sosnowskyi*-specific).

In our research carried out by means of multi-element epithermal neutron activation analysis (ENAA) we have observed significant excess of concentrations for lanthanides (REEs) La, Ce, Sm, as well as for Tb, Hf, Ta, and both actinides, Th and U.

3. Conclusions

For the first time, instrumental neutron activation analysis (INAA) was employed to analyze various parts of *Heracleum sosnowskyi* (Sosnowsky's hogweed), a prevalent invasive species in the Leningrad Region (Vyborg District). With rare exceptions, elemental concentrations varied in the following descending order: K > Ca > Cl > Mg > Al > Na > Fe > Ba > Zn > Cr > Sr > Rb > Ti > Mn > Br > Ni > Ce > La > Co > V > Mo > Th > Hf > Se > Cs > As > Sb > Sm > Ta > Tb > U.

The analysis revealed that numerous toxic elements exhibit no bioaccumulation and are present at lower concentrations in plant tissues compared to the surrounding soil. Notably higher concentrations, relative to a reference plant, were observed for La, Ce, Sm, Tb, Hf, Ta, and Th.

Correlations were identified between the contents of essential elements, as well as between lanthanides and actinides, with varying compositions. *H. sosnowskyi*, having emerged as a wild source of raw materials for diverse industries, can be harvested regularly, thereby mitigating its spread and averting adverse environmental impacts.

Given the broad spectrum of compounds in *H. sosnowskyi*, its processing holds substantial potential for producing valuable products and materials in sectors such as agriculture, medicine, pharmaceuticals, food, pulp and paper, chemicals, mining, energy, and construction, as well as for phytoremediation of contaminated soils.

For future investigations, it would be valuable (based on our current data) to analyze root material from this plant prior to winter dormancy, following the end of the growing season and senescence of aboveground parts, and in early spring at the onset of regrowth (initiation of vegetation).

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Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used: conceptualization, K.T. and M.F.; methodology, K.T. and M.F.; software, N.P., K.A., O.T.; validation, K.T. and M.F.; formal analysis, N.P., K.A., O.T., I.Z.; investigation, N.P., K.A., O.T., I.Z.; resources; data curation, K.T. and M.F.; writing—original draft preparation, K.T. and M.F.; writing—review and editing, K.T., M.F., Yu L., I.Z. All authors have read and agreed to the published version of the manuscript.

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