Journal of Elementology ISSN 1644-2296

Rahmonov, O., Środek, D., Pytel, S., Kupka, T. and Makieieva, N. (2023)
'Accumulation of heavy metals in soil and *Chelidonium majus* L.
in the urban environment',
Journal of Elementology, 28(4), 1329-1351,
available: https://doi.org/10.5601/jelem.2023.28.4.3147

RECEIVED: 8 October 2023
ACCEPTED: 21 December 2023

ORIGINAL PAPER

Accumulation of heavy metals in soil and *Chelidonium majus* L. in an urban environment*

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Abstract

Urban park ecosystems are an integral part of the natural environment, and form a mosaic of habitats resulting from the diversity of soil cover for the growth of plants with different ecological requirements. The study was conducted in six urban parks in the Upper Silesia region (Poland) and investigated the chemical properties, the content of heavy metals (HMs) in the soils and in the underground (UP) and aerial parts (AP) of *Chelidonium majus* as an essential medicinal plant. Soil samples were taken directly beneath the *Ch. majus* clumps in the rhizosphere zone, the average thickness of which was about 12-15 cm. The reaction of soil can be described as slightly acidic (5.3±0.2-6.7±0.1 in KCl) to alkaline (7.1±0.1-7.5±0.3 in H_2O). The organic carbon (OC) content at all sites was high, ranging from 3.6±0.4 to 12.5±0.76%, with the highest total nitrogen (N_t) content of 0.66±0.01%. The average content of total phosphorus (P_t) in all samples is 549 mg kg^{-1} (and its range: 303±4.7-955±10.5 mg kg^{-1}), indicating its anthropogenic origin. The concentrations of HM in the topsoil and plant samples are varied. The highest contents of Zn (1363±1.6 mg kg^{-1}), Pb (527±0.8 mg kg^{-1}) and Cd (13.6±0.3 mg kg^{-1}) in the soil were confirmed in 3 locations and exceeded the permissible standards. Environmental indicators, such as the geo-accumulation index, the enrichment factor, and the potential ecological risk index, showed that the analysed soils are strongly contaminated with HMs. In plant material, the highest concentrations of HMs were found in UP and AP, respectively. Zn showed the highest values among the elements tested in soil and plant tissues. Pb and Cd generally dominated in the underground parts, while As, Hg and Cr dominated in the aerial parts. The identification of HM levels in the plant-soil system will provide valuable information on the behaviour of HMs, which is important in the context of the sustainable development of urbanized areas.

Keywords: environmental indicators, traces elements, soil properties, urban environment, medicinal plant

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* This research was funded by the Institute of Earth Sciences, Faculty of Natural Sciences, University of Silesia in Katowice (statutory research – InoZ-ZB-22).

INTRODUCTION

Chelidonium majus L., known as greater celandine, is a medicinal plant species from the *Papaveraceae* family. Plants from this family are rich in specific alkaloids, some of which are important in medicine. As for greater celandine, alkaloid-rich, orange-coloured latex issues from broken stems and roots of this plant. On drying, the plant loses the alkaloids it contains. Dried latex is available in the herbal trade, and products made with this substance as an ingredient are sold in pharmacies for internal and external use and in cosmetic shops for external use (Szentmihályi et al. 2006). *C. majus* grows as a weed in lowlands and foothills, in deciduous forests, brush woods, parks, gardens, on roadsides and around buildings, and it often occupies anthropogenic habitats. It grows wild in whole Europe and almost everywhere in Asia, but nowadays it is found even in North America (Szentmihalyi, Then 2007).

The species has a long tradition of being used mainly in folk medicine. It has been used in herbal medicine since the time of Dioscorides and Pliny the Elder, i.e. 1st century AD (Migas, Heyka 2011, Zielińska et al. 2018). *Ch. majus* is a herbal plant highly praised for its therapeutic potential in western phytotherapy and traditional Chinese medicine and in European countries (Gilca et al. 2018). Both crude extracts of *C. majus* and purified compounds derived from it exhibit a wide array of biological activities, which are in concordance with the traditional uses of *Ch. majus*. This species exhibits multiple biological properties, such as antiviral, antitumor, antibacterial, antifungal effects, antiprotozoal, anti-inflammatory and antispasmodic influences (Monavari et al. 2012, Zielińska et al. 2018), and contains different alkaloids in its various parts (Maji, Banerji 2015). The main use of greater celandine is externally against warts and corns, and internally for healing liver and gallbladder diseases. Bioactive components of the plant extracts have a wide range of effects, including antioxidant, spasmolytic, anti-inflammatory, antimicrobial, antiviral, antifungal, and cytotoxic properties (Maji, Banerji 2015). More than 70 compounds have been isolated and identified from this species, including alkaloids, flavonoids, saponins, vitamins, mineral elements, sterols, acids and their derivatives (Szentmihalyi et al. 2012, Jyoti 2013).

Besides effective bioactive alkaloid components (coptisine, chelidonine, chelerythrine, sanguinarine, berberine, protropine, etc.), greater celandine contains flavonoids, chelidonine acid, resin, fruit acids, vitamin C, volatile oil (Colombo, Bosisio 1996, Seidler-Łozykowska et al. 2016) and macro- and micro-elements as well as heavy metals (Sárközi et al. 2005, Szentmihalyi, Then 2007, Szentmihalyi et al. 2012, Rahmonov et al. 2023*a*).

The elemental content of herbs may depend on a degree of soil pollution, the soil type or air pollution (Li et al. 2018). In the last centuries, and particularly in the last few decades, human activity has continuously increased the level of heavy metals (HMs) circulating in the environment. Therefore, because of their negative impact on the functioning of ecosystems, environmental contamination with trace elements has become an important topic of investigations. This concerns mainly urban areas, which are characterised by an increased content of HMs, especially in the surface layer of the ground (Darko et al. 2017, Rodríguez-Seijo et al. 2017, Ciupa et al. 2020). There is large spatial variation of metal content, mainly arising from the way urban environments develop and function (Bosiacki et al. 2022).

The organic composition and main bioactive ingredients of greater celandine are generally well known, but the elemental composition and concentration of individual elements are mostly unknown. The beneficial properties of plants may originate from their organic agents and inorganic mineral elements. Measurement of the content of trace and major elements in plant drugs may be relevant in view of human health, animal health and the environment (Lesko et al. 2002, Szoke and Kéry 2003, Szentmihályi et al. 2005, Sagiroglu et al. 2006, Szentmihályi et al. 2006, Riaz et al. 2012).

Studies on *Ch. majus* have mainly focused on its medicinal properties and effects based on the alkaloids which the species biosynthesises (Maji, Banerji, 2015). In addition to organic compounds, soluble mineral substances of herbs (in this case, greater celandine) may also play a role in treatment. The content of selected metals has been measured directly from dried plant material and from different extracts derived from *Ch. majus* (Then et al. 2000, Buzuk et al. 2001, Szentmihályi et al. 2021). Some research has dealt with the toxic effects of HMs on the germination and growth of *Ch. majus* seedlings in urban areas (Dojczeva 2021).

The physical and chemical properties of the soil influence the growth of plant species. However, no studies are available comparing the HM content of *Ch. majus* and the chemical composition of the soil in which the plant grows. The chemical composition of plants is also modified by the chemical composition of the soil material. Based the chemical composition of plants, the content of selected elements in the soil can be predicted at least indirectly, as has been repeatedly demonstrated in the case of hyperaccumulators (Sagiroglu et al. 2006). This type of research in areas of high anthropogenic intensity is important for gaining an insight into the level of contamination in residential areas (Rahmonov et al. 2019).

Therefore, the present study attempts to recognize relationships of the chemical composition in the plant-soil system. We suppose that plants growing on anthropogenic soils containing HM may accumulate these metals in plant tissues. Thus, the aim of this study is to determine the heavy metal content of the underground and aerial parts of *Ch. majus* and in the soil in urban park areas.

MATERIALS AND METHODS

Study area

The research was carried out in urban parks in Sosnowiec and Dąbrowa Górnicza, situated in the macro-region of the Silesian Upland. Shöen Park (PSh-I, PSh-II: 50°17′57.99″N 19°08′20.76″ E), Zielona Park (PZ-III: 50°20′41.79″ N 19°10′56.63″ E), Leśna Park also called Kuronia Park (PK/L-IV, PK/L-V: 50°18′01.05″ N 19°14′29.87″ E) and Sielec Park (PS-VI: 50°16′59.08″ N 19°08′34.82″ E) were selected for the study (Figure 1).

Fig. 1. Location of study sites in Poland and in Silesian Voivodeship

These parks vary in age, surface area, and degree of management of the greens. They are urban parks located in the industrial impact zone, and are intensively used by the local population for sports and recreational purposes. They have ecological, sport and recreational, economic, cultural and entertainment functions, and are a regional element of the ecological corridors in the area.

The parks represent a wide range of habitats in terms of plant occurrence, from seminatural habitats (PZ-III) to completely transformed habitats associated with park infrastructure. The analysed species grows mainly at the edge of parks, on the anthropogenic soil, where it is accompanied by nitrophilous species (Rahmonov et al. 2023).

Plant and soil sampling

Soil samples for chemical analyses were taken from the root zone of *Ch. majus* by shaking off the soil from the plant roots. This was mainly soil from the humus horizon (of anthropogenic origin), whose thickness ranged from 15 to 30 cm, with an average of 20-25 cm. In the laboratory, air-dried samples were sieved (mesh size: 1 mm) and analysed, following the standard procedures: pH was measured potentiometrically in H_2O and in 1N KCl using a glass electrode (soil:water:1/2.5), hydrolytic (H_h) – the Kappen method and exchangeable acidity (H^+, Al^{3+}) by the Sokołowa method, loss on ignition at 550°C, total organic carbon (OC) according to the Tiurin method, total nitrogen (N_t) content using the Kjeldahl method (in plant samples also), and total phosphorus (P_t) by the Bleck method as modified by Gebhardt, the available phosphorus (Pav.) and available potassium (Kav.) by the Egner-Riehm method, and magnesium (Mgav.) according to PN-R-04023/23 (Bednarek et al. 2004).

The plant material composed of leaves, stems (referred to as aerial parts/AP), and roots (rhizome/underground/UP) was sampled at the end of the growing season, in late September/early October. At each site, material was collected from 5 plants to form 1 composite sample. This material was submitted to analyses. The preliminary preparation of the samples for analyses involved washing of the plant material with distilled water, drying at room temperature for two weeks, and then at 105°C for 4 h, followed by homogenisation.

The total content of Pb, Cd, Zn, Fe, Mn, Cr, Cu, Ni, As, and Hg in plant material and soil was measured using ICP-OES after wet mineralisation in *aqua regia* ($3HCl + HNO_3$). The analyses were performed in the ACME Laboratory (Vancouver, Canada) using AQ250_EXT (soils) and VG105_EXT (plant tissues) procedures and 5 g samples. All plant and soil samples were analysed in triplicate for all the parameters being investigated, and mean values were calculated.

Estimating pollutant impact

To demonstrate the HM concentration, its enrichment in soil, and potential contamination level, we calculated chemical indexes used in similar studies (Solgi et al. 2012, Okedeyi et al. 2014, Napoletano et al. 2021), i.e. the geoaccumulation index (Igeo), enrichment factor (EF), contamination factor (CF), pollution load index (PLI), and potential ecological risk index (RI).

Index of geo-accumulation (Igeo)

The Igeo index shows the degree of HM contamination in soil. It was calculated from the formula (Okedeyi et al. 2014):

$$Igeo = log_2\left(\frac{C_n}{1.5B_n}\right)$$

where C_n is the content of the element in the studied sample and B_n is the concentration of the same element in the upper continental crust. We used the chemical composition of the upper continental crust as a standard reference point, as it is employed in calculating chemical indexes in various kinds of environmental studies (Chien et al. 2019, Gruszecka-Kosowska et al. 2020). We assigned seven contamination classes based on the increasing value of the geo-accumulation index, following Ho et al. (2010):

Igeo < 0 – unpolluted,

0 ≤ Igeo < 1 – unpolluted to moderately polluted,

1 ≤ Igeo < 2 – moderately polluted,

2 ≤ Igeo < 3 – moderately to strongly polluted,

3 ≤ Igeo < 4 – strongly polluted,

4 ≤ Igeo < 5 – strongly to very strongly polluted,

5 ≤ Igeo – very strongly polluted.

<u>Enrichment factor (EF)</u>

The degree of metal enrichment in the soil was estimated by calculating the EF. This method normalises the content of metals with respect to a sample reference metal (Lizárraga-Mendiola et al. 2008). We used Fe as the reference metal, which is a recommended procedure for such studies (Ghrefat et al. 2011, Antić-Mladenović et al. 2019). We calculated the EF using the equation:

$$EF = \frac{\left[\frac{C_{metal}}{C_{normalizer}}\right] soil}{\left[\frac{C_{metal}}{C_{normalizer}}\right] control}$$

where C_{metal} is the content of the examined metal and $C_{normalizer}$ is the selected normaliser concentration in soil and the control sample (Okedeyi et al. 2014). The five classes of the *EF* can be separated (Środek, Rahmonov 2022):

EF < 2 – deficiency to minimal enrichment,

2 ≤ EF < 5 – moderate enrichment,

5 ≤ EF < 20 – significant enrichment,

20 ≤ EF < 40 – very high enrichment,

40 ≤ EF – extremely high enrichment.

<u>Contamination factor (CF)</u>

The CF index was obtained using the formula (Uriah, Shehu 2014):

$$CF = \frac{C_n}{B_n}$$

where C_n is the element content in tested soil, and B_n is the same element concentration in the continental crust (Okedeyi et al. 2014). It shows a degree of contamination related to the average composition of the continental crust. *CF* can be classified as:

CF < 1 – low contamination factor,

1 ≤ CF < 3 – moderate contamination factor,

3 ≤ CF < 6 – considerable contamination factor,

6 ≤ CF – very high contamination factor.

Pollution load index (PLI)

The PLI index was calculated using the contamination factors according to the equation:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times \ldots \times CF_n}$$

where n is the number of the contamination factors. To calculate PLI, we used the five highest values following Napoletano et al. (2021). This index allows for assessing HM contamination, and it can assume values <1 (absence of pollution) or 1< (presence of pollution).

Potential ecological risk index (RI)

The *RI* allows evaluating the heavy metal impact on the environment. It is calculated from the equation:

$$RI = \sum \mathrm{E}_{\mathrm{r}}^{\mathrm{i}},$$

where E_r^i is the potential ecological risk factor of the specific element. The is derived from the equation:

$$E_r^i = T_r^i \times CF$$

where T_r^i is the toxic response factor of the metal given by Napoletano et al. (2021). The ecological risk can be classified as follows (Ahmad et al. 2020):

< 40 – low,

40 ≤ -< 80 – moderate,

80 ≤ -< 160 – considerable,

160 ≤ -< 320 – high,

320 ≤ – very high,

and the risk index can be divided into four classes:

RI <150 – low risk,

150 ≤ RI < 300 – moderate risk,

300 ≤ RI < 600 – considerable risk,

600 ≤ RI – very high risk.

Statistical analyses

The Spearman's rank-correlation coefficient was applied to verify whether there was any relationship between the concentrations of the selected elements in aerial (stem and leaves) and underground (roots) parts of *Ch. majus* and soils. This is the coefficient applied to samples that do not meet the assumptions of normality. The statistical significance of the Spearman's correlation coefficient data was determined using the Spearman's rank correlation test. The exact values of the correlation coefficient were calculated for α=0.001, 0.01 and 0.05 (Runge 2007). All statistical analyses were performed using SPSS Statistics software.

RESULTS AND DISCUSSION

In industrial regions or cities, anthropogenic influences shape soil properties more than natural processes do. The human impact leads to the loss or alteration of specific soil characteristics, such as morphological, biological and physicochemical properties resulting from natural pedogenesis. Long-term anthropogenic activity in urban areas promotes significant transformation of the soil cover, which in extreme cases devastates its natural structure and character. This results in the formation of soils with specific properties, the parameters of which depend on the intensity, direction and duration of human impact (Greinert 2003, Prokof'eva, Poputnikov 2010). The topsoil in parks and green spaces is often formed by applying artificial material transported from outside. This material usually contains a significant amount of organic matter, which affects soil properties, such as pH value, loss on ignition and content of various elements, which differ from natural conditions.

The pH range of soil samples on the tested surfaces was determined to be from slightly acidic (5.3-6.67 in KCl) to alkaline (7.1-7.4 in H_2O). A slightly acidic reaction in water was found only in sites PZ-III (6.33±0.17) and PS-VI (6.13±0.12), which corresponded to higher hydrolytic acidity (H_h) and higher content of exchangeable acid cations (Table 1). Such regularities were found at the PS-VI site, where the pH (6.13±0.12) and hydrolytic acidity values (4.74±0.01 cmol(+)/kg) are similar to ones at the PZ-III site (Table 1). These soil pH values are determined by the interaction of hydrogen and hydroxide ions in the soil solution and the $CaCO_3$ content of anthropogenic soils (Greinert 2003). The paths running through the urban parks and the walls around the gardens are made of materials containing calcium carbonate, and the dissolved ions enter the soil during rainfall. Dust and ash from neighbouring areas also contribute significantly to the alkalinisation of urban soils. The alkaline pH immobilises HM and thus limits their uptake by plant species.

Loss on ignition results indicate a high percentage of organic matter in the upper layers of this anthropogenic organic horizon. The highest values were found at the foot of the artificial embankment at the sites PS-Vl (25.2±1.02%) and PL/K-IV (20.3±0.65%). Elevated values of this indicator were observed in the remaining places (Table 1).

The OC content was high, ranging from 3.63±0.37% (PK/L-IV) to 12.53±0.76% (PS-VI). The content of N_t differed at the tested sites. The highest levels of N_t were recorded at PS-VI (0.66±0.01%) and PK/L-IV (0.60±0.00%). Significant amounts of N_t accumulated in the UP (rhizome: 2.783%) and AP (shoots, leaves: 2.626%) of *Ch. majus*, with an average of 2.7%, also indicative of the high nitrogen content of the soil.

The content of OC and N_t in soils under clumps of *Ch. majus* communities was very uneven, mainly due to the deposition of external material of mineral nature in sites located within urban boundaries (PSh-II, PS-VI) or organic sediments from flood waters or agricultural fields. The latter occurs on less disturbed land sites outside urban areas (PK/L-IV). OC and N_t content also affect the concentration of available K, Mg and Pav. Similar results were found in soils from other urban areas, especially urban green spaces (Greinert 2003, Prokof'eva, Poputnikov 2010, Charzyński et al. 2013, Rahmonov et al. 2019).

The content of available Mg, K and P in the study sites is shown in Table 1. The average range of Mg was 236 mg kg^{-1} (153±4.08-329±2.08 mg kg^{-1}), K – 236 mg kg^{-1} (178±2.45-304±6.60 mg kg^{-1}) and Pav. 88.7 mg kg^{-1} (12.9±0.37-146±2.13 mg kg^{-1}). The highest values of total phosphorus (P_t-955±10.5 mg kg^{-1}) of anthropogenic origin were recorded in Sielec Park (PS-VI), while the lowest content was recorded in sample PZ-III. The average Pt content in all samples is 549 mg kg^{-1} (range: 303±4.71-955±10.50 mg kg^{-1}). High levels of this element are mainly due to fertilisation of urban greenery and excrement from domestic animals, among others.

High P_t concentrations ranging from 298 to 940 mg kg^{-1} were found at all sites. According to many authors (Prusinkiewicz et al. 1998, Charzyński et al. 2013), phosphorus content of more than 300 mg kg^{-1} in the soil indicates that various human activities have led to its accumulation, and can therefore be considered an indicator of environmental anthropogenisation. The source of P_t in urban parks is related to the fertilisation and maintenance of urban greenery, the accumulation of organic waste, domestic sewage run-off, waste and domestic animal excrement, which are regular features of urban parks. It can be concluded that P_t in anthropogenic soils is related to human activities. The high P_t content positively affects the viability of *Ch. majus*, as evidenced by its morphology (Rahmonov et al. 2023*a*).

Based on the Spearman rank correlation analysis, a high statistically significant positive correlation was found between the loss-on-ignition-P_t ($r(6)$=.943), N_t-H ($r(6)$=.939), H_h-H ($r(6)$=.926) and P_{av}.-P_t ($r(6)$=.943), which corresponds to results from other urban areas reported by other researchers

Table 1

Soil properties at anthropogenic sites under *Ch. majus* clumps (*n*=3)

Sites	pH		Loss on ignition	OC	Nt	Mgav.	Kav.	Pav.	Pt	H_h	Al^{3+}	H^+
	H_2O	KCl	(%)			(mg kg^{-1})				(cmol(+)/kg)		
PSh-I	7.47±0.25	6.40±0.16	13.2±0.28	10.9±0.56	0.27±0.00	159±3.83	225±2.87	55.0±2.24	407±7.72	1.45±0.02	0.07±0.04	0.04±0.02
PSh-II	7.30±0.08	6.67±0.05	11.1±0.68	8.27±0.33	0.22±0.00	140±1.28	198±2.45	39.2±1.52	430±4.08	1.31±0.02	0.05±0.04	0.02±0.0
PZ-III	6.33±0.17	5.30±0.24	9.06±0.47	6.86±0.25	0.37±0.0	153±4.08	178±2.45	12.9±0.37	303±4.71	2.80±0.01	0.04±0.04	0.12±0.00
PK/L-IV	7.1±0.08	6.33±0.31	20.3±0.65	3.63±0.37	0.60±0.00	325±2.34	304±6.60	146±2.13	707±4.64	1.90±0.03	0.02±0.00	0.08±0.00
PK/L-V	7.43±0.29	6.53±0.21	10.9±0.47	7.37±2.15	0.29±0.01	329±2.08	298±2.65	136±1.48	513±4.22	1.39±0.04	0.05±0.04	0.04±0.0
PS-VI	6.13±0.12	5.67±0.05	25.2±1.02	12.5±0.76	0.66±0.01	307±4.74	211±2.41	144±3.26	955±10.50	4.74±0.01	0.03±0.01	0.15±0.01

Table 2

Correlation of soil characteristic under *Ch. majus*

Specification	pH_KCl	Loss on ignition	OC	Nt	M_{gav}.	K	P_{av}.	P_t	H_h	Al^{3+}	H^+
pH-H_2O	.886	.257	.371	-.058	.543	.714	.314	.200	-.086	**.828***	-.370
pH-KCl		.429	.486	.058	.829	.829	.543	.486	-.086	**.828***	-.278
Loss on ignition			.657	**.812***	.600	.600	**.886***	**.943****	.657	.000	.617
OC				.464	.371	.200	.371	.600	.543	.414	.309
N_t					.406	.348	.754	**.812***	**.928****	-.420	**.939****
$Mg_{av.}$						**.886***	**.829***	.771	.143	.414	.123
$K_{av.}$							**.829***	.657	.086	.414	.031
$P_{av.}$								**.943****	.486	.000	.525
P_t									.600	.000	.617
H_h										-.414	**.926****
Al^{3+}											-.671

*** $p<0.001$, ** $p<0.01$, * $p<0.05$

(Rodríguez-Seijo et al. 2017, Rahmonov et al. 2019, 2020, Środek, Rahmonov 2022). The other correlations are shown in Table 2.

Content of heavy metals in soil

Rapid industrialisation and urbanisation in the recent decades have dramatically affected urban soil properties and led to large discharges of pollutants, which inevitably affect the health of soils, ecosystems and human populations (Cachada et al. 2012, Li et al. 2018). Emissions in urban areas come from transport (fossil fuel combustion, attrition of parts and tyres, petrol and engine oil leaks), coal combustion (power plants and heating), industrial activities (mining, metallurgy and chemical engineering) building and waste disposal, and incineration contaminate the soil and ecosystems (Oliver 1997, Li et al. 2018).

The content of HMs at each site varied. Among these metals, Zn achieved the highest content compared to other elements (Table 3). It ranged from 394±0.79 mg kg^{-1} (PZ-III) to 1364±1.64 mg kg^{-1} (PL/K-IV), with a mean value (Zn) of 917 mg kg^{-1} for all soil samples analysed. The maximum Pb content was found at sites PSh-I (527±0.78 mg kg^{-1}), PSh-II (374±0.77 mg kg^{-1}) and PK/L-IV (346±0.83 mg kg^{-1}), and the lowest at site PZ-III (119±1.25 mg kg^{-1}).

Table 3

The concentration of HMs in topsoil

Elements/ Sites	PSh-I	PSh-II	PZ-III	PK/L-IV	PK/L-V	PS-VI	Limit values for soil*
	(mg kg^{-1})						
Pb	527±0.78	374±0.77	119±1.25	346±0.83	198±1.66	247±0.82	200
Cd	8.60±0.41	7.64±0.47	3.38±0.37	13.6±0.34	7.55±0.49	7.72±0.43	2
Zn	1113±1.76	1038±1.64	394±0.79	1364±1.64	639±23.58	951±0.37	500
Mn	716±0.82	562±1.25	344±1.63	588±1.63	375±0.82	484±1.25	240**
Cu	155±0.86	75.7±1.17	21.7±0.70	46.2±0.99	29.3±0.69	50.3±1.00	200
Ni	27.2±1.22	33.6±0.79	9.47±0.33	32.5±0.82	12.8±0.53	16.5±0.53	150
Cr	25.2±0.62	23.7±0.45	17.3±0.65	17.2±0.78	18.3±0.53	13.4±0.70	200
As	22.3±0.82	22.9±1.11	8.53±0.37	18.7±0.65	8.63±0.52	18.2±0.57	25
Hg (μg kg^{-1})	309±0.82	330±0.82	112.5±0.82	198±1.25	128±1.25	254±0.82	5
Fe (%)	2.59±0.02	2.75±0.04	1.45±0.06	2.01±0.08	1.09±0.08	2.10±0.08	0.57**

* Journal of Laws (2016), ** Kabata-Pendias and Pendias (1999)

The content of Cd values ranged from 3.38±0.37 mg kg^{-1} in Park Zielona (PZ-III) to 13.6±0.34 mg kg^{-1} (PK/L-IV). Mn concentration varied f rom 344±1.63 to 716 mg kg^{-1} at site PSh-I. The lowest content of Cu (344±1.63 mg kg^{-1}), Ni (9.47±0.33 mg kg^{-1}), As (8.53±0.37 mg kg^{-1}) and Hg was found at site PZ-III. Chromium occurred within acceptable limits and was not shown as a soil contaminant, being in the range of 13.4±0.70-25.2±0.62 mg kg^{-1} (Table 3). Pb, Zn, and Cd exceeded their permissible soil concentration (Table 3). The average Fe content in the epipedons of the studied parks was about 1.99% (19 900 g kg^{-1}). The highest amounts were found in Schöen Park (PSh-I – 2.76%) and the lowest were in Leśna Park (PK/L-V – 1.07%). Iron is an essential element for soil-forming processes. It significantly influences soil properties in terms of chemistry and soil morphology, but in urban parks, it has an anthropogenic character, related to the park's infrastructure.

The total content of HMs in the soils of recreational and leisure areas is a helpful indicator of the intensity of environmental pollution used to assess the degree of their degradation (Kabata-Pendias, Pendias 1999). The topsoil horizons (humus horizon) in the parks analysed were characterised by considerable variation in the content of metals. At all the studied sites, Pb, Zn and Cd exceeded the permissible standard set to assess the pollution of the earth's surface in recreational and leisure areas, children's playgrounds, arranged parks, green squares (Journal of Laws 2016) and the content of trace elements in agriculturally used soils (Kabata-Pendias, Pendias 1999). Zn exceeded the standard almost three times (1364±1.64 mg kg^{-1}) in PK/L-IV, Pb practically three times (527±0.78) in PSh-I, Cd seven times (13.6±0.34) in PK/L-IV and four times (8.60±0.41 mg kg^{-1}) in PSh-I.

Numerous studies have confirmed significant contamination of urban surface soils with Zn, Pb and Cu (Oliver 1997, Greinert 2003, Prokof'eva, Poputnikov 2010, Charzyński et al. 2013, Li et al. 2018, Rahmonov et al. 2020, 2023*b*, Środek, Rahmonov 2022). Considering the current legislation in Poland (Journal of Laws 2016), the humus horizons of the soils of the studied parks showed permissible contents of Mn, Cu, Ni, Cr, Hg and As. Some other sources of soil contamination involve using fertilisers, pesticides, sewage sludge and organic manures (Singh et al. 2010).

Correlation between metals content

The Spearman rank correlation analysis showed very high statistically significant positive correlation between metals in most samples (Table 4): Pb-Mn (r(6)=.943), Pb-Cu (r(6)=.943), Pb-As (r(6)=.943), Cd-Zn (r(6)=.943), Zn-Mn (r(6)=.943), Fe-Hg (r(6)=.943), Cu-Hg (r(6)=.943) and Ni-As (r(6)=.943). These results are similar to other urban areas (Prokof'eva, Poputnikov 2010, Charzyński et al. 2013, Ciupa et al. 2020).

Content of heavy metals of Ch. majus

The soil's features affect plant species' viability by making nutrients available. The chemical composition of plants reflects the chemical composition of the soil material and the parent rock and their richness in nutrients.

Table 4

Correlation of topsoil heavy metal content under *Ch. majus*

Elements	Cd	Zn	Mn	Fe	Cu	Ni	Cr	Hg	As
Pb	.714	.829	**.943****	.829	**.943****	.829	.543	.886	**.943****
Cd		**.943****	.886	.429	.600	.657	-.086	.486	.600
Zn			**.943****	.543	.657	.829	.143	.600	.771
Mn				.657	.829	.771	.371	.714	.829
Fe					.886	.771	.371	**.943****	.886
Cu						.714	.486	**.943****	.886
Ni							.257	.829	**.943****
Cr								.429	.486
Hg									**.943****

*** $p<0.001$, ** $p<0.01$, * $p<0.05$

Thus, there can be differences in concentrations of the elements in the same species growing in different environments. Associations between some alkaloids (including isoquinoline) and content of such elements as Co, Cu and Zn are genetically determined in *Ch. majus* (Buzuk et al. 2001, 2003). This may also impact the content of elements in the aerial part of this species. The results of determinations of the content of HMs in the analysed parts of *Ch. majus* are presented in Table 5. The metal accumulation ratios in the different parts differed, and most metals accumulated in the roots and leaves and stems. Pb values in the rhizome ranged from 8.76 mg kg^{-1} (PZ-III) to 34.3 mg kg^{-1}; in the leaves/stems (as one mixed sample), their content ranged from 6.84 to 28.0 mg kg^{-1} (PK/L-IV). Pb generally occurred more abundantly in rhizomes (mean value: 19.9 mg kg^{-1}) than in aerial parts (mean value: 16.5 mg kg^{-1}) – Table 5.

The highest values of Cd (3.6 mg kg^{-1}) and Zn (409 mg kg^{-1}) were found in the UP, while the Cd content in the AP was 2.34 mg kg^{-1}. Zn values varied in the AP part of the species from 149 (PZ-III) to 525 mg kg^{-1} in PSh-II (Table 3). Its average content in all samples is 270 (UP) and 282 mg kg^{-1} (AP).

The Mn values ranged from 62-365 in aerial and 47-183 mg kg^{-1} in UP, and their ratio was 1.05. The copper concentrations showed similarities in both UP and AP samples. Higher Cu contents were found in Sielec Park (PS-VI: 19.7 mg kg^{-1}) and in the PSh-I sample (19.8 mg kg^{-1}). Ni ranged from 1.5 to 3.3 in the roots and from 0.90 to 9.1 mg kg^{-1} in the aerial parts of *Ch. majus*. Its average values were 2.33 and 2.91 mg kg^{-1}, respectively. The range of Cr varied in the tissues analysed, with the higher content recorded more often in the AP (from 3.7 to 18 mg kg^{-1}) than in roots (Table 3).

Higher Hg values were found in the AP of greater celandine (PK/L-V-64 ppb and PSh-I/II-56 μg kg^{-1}) than in the UP. The opposite situation was observed for As (Table 3). The average Fe content in roots was 0.17%

Table 5

The mean value of heavy metal content of the underground (UP) and aerial parts (AP) of *Ch. majus*

Elements	Plant parts/ sites	PSh-I	PSh-II	PZ-III	PK/L-IV	PK/L-V	PS-VI	Limit value for edible plants*
		(mg kg^{-1})						
Pb	UP	34.3	25.5	8.76	27.9	11.2	11.9	0.43
	AP	24.8	12.6	6.84	28.0	15.5	11.4	
Cd	UP	2.50	3.60	2.03	2.27	1.70	3.00	0.3
	AP	1.23	2.34	0.81	1.84	1.14	0.90	
Zn	UP	278	409	236	234	179	284	27.4
	AP	263	525	149	324	156	275	
Mn	UP	183	78.0	108	81.0	70.0	47.0	2
	AP	365	95.0	100	105	83.0	62.0	
Cu	UP	17.2	16.6	11.8	10.6	7.66	19.7	3
	AP	19.8	12.5	10.9	13.5	10.8	13.6	
Ni	UP	3.10	3.30	1.50	2.00	2.50	1.60	1.63
	AP	2.50	9.10	0.90	2.00	2.10	0.90	
Cr	UP	3.40	4.30	2.70	3.00	3.20	2.40	0.02
	AP	5.10	18.0	3.70	4.60	6.60	3.60	
As	UP	2.80	1.30	0.80	2.60	0.90	1.70	no data
	AP	1.60	0.90	0.20	2.10	1.10	0.80	
		(µg kg^{-1})						
Hg	UP	39.2	27.0	18.0	18.0	19.0	26.0	no data
	AP	56.0	56.0	31.0	48.0	64.0	45.0	
		(%)						
Fe	UP	0.23	0.20	0.13	0.18	0.12	0.16	20
	AP	0.23	0.11	0.10	0.19	0.13	0.14	

* According to the FAO/WHO Guidance Note (Jabeen et al. 2010).

(i.e. 1700 g kg^{-1}) and 0.15% in AP (1500 g kg^{-1}). The content of the analysed HMs (Pb, Cd, Zn, Mn, Fe, Cu, Ni and Cr) in tissues of *Ch. majus* exceeded (Table 3) several times the values allowed for food and medicinal plants according to FAO/WHO guidelines (Jabeen et al. 2010).

The results obtained from some sites (PSh-I and PZ-III) correspond with the results obtained by other authors (Szentmihályi et al. 2006, 2021) for medicinal plants, e.g. Cr (4.35 mg kg^{-1}), Zn (57.3 mg kg^{-1}), Cu (15.9 mg kg^{-1}) in aerial parts of plants. Detailed analysis of the mineral composition of *Ch. majus* plants growing in an area unaffected by human activity was carried out by Sárközi et al. (2005), who analysed the plant specimens and divided them into two parts; the herbal part and the root, corresponding to the underground and aerial parts in our study. The cited authors obtained similar results to ours (Table 5) in the case of Cu (18.1 herb, 14.3 rhizome mg kg^{-1}), Mn (22.4 herb, 31.02 rhizome mg kg^{-1}) and Ni (1.42 herb, 2.51 rhizome mg kg^{-1}). Zn per rhizome in this work reaches the maximum of 409 mg kg^{-1}, nearly three times as much as 141 mg kg^{-1} determined in the study by Sárközi et al. (2005). Our results regarding the content of HMs (Table 3) are several times higher than those obtained by Riaz et al. (2012) and for medicinal plants. The concentrations of Pb, Cd, Zn, Mn, Fe, Cu and Cr exceeded the limit values for edible and medicinal plants (in the case of Pb, Cd) recommended by FAO/WHO (Jabeen et al. 2010).

Heavy metal concentrations in the soil, aerial (AP) and underground (UP) part *Ch. majus*

A study of the relationship between HM content in soil, AP and UP was also carried out (Table 6), where a very high statistically significant positive correlation was found between heavy metal content in soil (S) and underground plant parts (UP): PbS-Pb/UP (r(6)=.943), Cd/S-Pb/UP (r(6)=.943), Zn/S-Pb/UP (r(6)=. 943), Fe/S-Cd/UP (r(6)=.943), Cu/S-Hg/UP (r(6)=.899), Cr/S-Cr/UP (r(6)=. 943), Hg/S-Cd/UP (r(6)=.886), As/S-Fe/UP (r(6)=.886). Such high correlations are due to the higher content of these elements in the soil and their accumulation in the roots of *Ch. majus* compared to results from other areas (Szentmihályi et al. 2006, 2021). Analyses of the bioaccumulation and translocation factors showed that *Ch. majus* generally does not accumulate or transport HMs from the rhizomes to the plant's aerial parts (Rahmonov et al. 2023*a*).

In the soil-aerial parts systems, the Spearman rank correlation also showed high, statistically significant positive correlations between the Cd/S-Pb/AP (r(6)=.829), Zn/S-Pb/AP (r(6)=.829), Zn/S-As/AP (r(6)=.829), Mn/S-Fe/AP (r(6)=.829), Ni/S-Cd/AP (r(6)=. 943), Ni/S-Zn/AP (r(6)=.943), Cr/S-Ni/S (r(6)=. 928) and As/S-Cd/AP (r(6)=.886 Table 6). Similar results from urban areas have been presented in several other studies (Dąbkowska--Naskręt et al. 2016, Solgi, 2016, Gąsiorek et al. 2017).

The level of heavy metal contamination in soil

The Igeo index calculated according to the content of HMs in the studied soils reveals that the most significant impact on soil contamination in all studied areas was produced by Cd, Pb, and Zn (Table 7). On this basis, the studied soil could be classified from extremely heavily (Cd) to very heavily polluted (Pb and Zn). The moderate to heavy pollution of As and moderate contamination of Hg in all the sampled soils can be noted (Table 7). The Igeo index obtained for Mn, Fe, Ni, and Cr indicates that these elements did not affect the level of contamination in the studied soils.

Table 6

Correlations between heavy metal content in soil, AP and UP parts of *Ch. majus*

Plant/Soil		Soil (S)									
		Pb	Cd	Zn	Mn	Fe	Cu	Ni	Cr	Hg	As
Plant aerial parts (AP)	Pb	.600	**.829***	**.829***	.771	.086	.371	.543	.543	.257	.486
	Cd	.771	.771	.771	.714	.600	.600	**.943****	.657	.714	**.886***
	Zn	.657	.714	.714	.600	.714	.600	**.943****	.200	.771	**.829***
	Mn	.486	.543	.543	.600	.200	.257	.257	.543	.086	.314
	Fe	.657	.771	.771	**.829***	.257	.600	.371	.314	.371	.429
	Cu	.714	.657	.657	.771	.657	.771	.429	.143	.600	.543
	Ni	.725	.435	.435	.551	.551	.638	.667	**.928****	.696	.783
	Cr	.429	.200	.200	.257	.257	.314	.486	**.829***	.429	.543
	Hg	.406	.232	.232	.319	.058	.348	.319	.754	.348	.406
	As	.600	**.829***	**.829***	.771	.086	.371	.543	.543	.257	.486
Plant under-ground parts (UP)	Pb	**.943****	**.943****	**.943****	1.000	.657	**.829***	.771	.600	.714	**.829***
	Cd	.657	.429	.429	.486	**.943****	.771	.714	.143	**.886***	.771
	Zn	.486	.143	.143	.257	**.886***	.657	.486	.086	.771	.600
	Mn	.314	.257	.257	.371	.143	.143	.029	.486	-.029	.143
	Fe	**.943****	.771	.771	**.886***	**.886***	**.886***	.771	.600	**.829***	**.886***
	Cu	.429	.143	.143	.314	.714	.657	.200	-.086	.600	.371
	Ni	.771	.486	.486	.600	.600	.714	.714	**.886***	.771	**.829***
	Cr	.657	.371	.371	.486	.486	.543	.600	**.943****	.600	.714
	Hg	.754	.290	.290	.551	.754	**.899***	.435	.638	**.841***	.696
	As	**.829***	**.886***	**.886***	**.943****	.543	.771	.600	.371	.600	.657

*** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table 7

The Igeo of HMs for the examined soils

Sites	Pb	Cd	Zn	Mn	Fe	Cu	Ni	Cr	Hg	As
PSh-I	4.37	5.81	3.84	-0.14	-0.84	2.86	-0.04	-1.06	1.88	2.89
PSh-II	3.88	5.64	3.73	-0.49	-0.75	1.82	0.27	-1.15	1.97	2.93
PZ-III	2.22	4.47	2.34	-1.20	-1.68	0.02	-1.56	-1.60	0.39	1.51
PK/L-IV	3.76	6.47	4.13	-0.43	-1.20	1.11	0.22	-1.61	1.25	2.64
PK/L-V	2.95	5.62	3.03	-1.08	-2.09	0.45	-1.12	-1.52	0.63	1.52
PS-VI	3.28	5.66	3.61	-0.71	-1.14	1.23	-0.76	-1.97	1.57	2.60

The resulting EF (Table 8) is consistent with the Igeo index. All the studied samples were characterised by extremely high Cd enrichment and very high Pb and Zn enrichment. Only the sample collected from the PZ-III site had significant Pb and Zn enrichment. The calculated EF for As indicated significant enrichment in all sites (Table 8). Moderate to significant Hg enrichment could be observed in the studied soils. The factor calculated for Cu indicated mostly moderate enrichment, with significant enrichment at the PSh-I site. The EF for Mn, Ni, and Cr showed deficiency to minimal enrichment. Similar results for the I-geo and EF were obtained from other ecologically transformed areas in southern Poland (Środek, Rahmonov 2022, Rahmonov et al. 2023*a*,*b*).

Contamination factors indicated a very high pollution level for Cd, Pb, and Zn in all sites. The CF of Cu varied between moderate (PZ-III, PK/L-V), considerable (PSh-II, PK\L-IV, PS-VI), and very high contamination (PSh-I). The CF for Hg showed that this element was causing moderate to considerable contamination. The CF values obtained for As lay between considerable and very high class (Table 9). The potential ecological risk index (PLI) for all the studied sites showed the existence of pollution.

Table 8

Enrichment factor (EF) values of HMs for the studied sites

Sites	Pb	Cd	Zn	Mn	Fe	Cu	Ni	Cr	Hg	As
PSh-I	36.9	100.6	25.5	1.62	1.00	13	1.74	0.86	6.60	13.3
PSh-II	24.8	84.1	22.4	1.20	1.00	5.95	2.03	0.76	6.62	12.9
PZ-III	14.9	70.6	16.3	16.2	1.00	3.24	1.08	1.05	4.18	9.09
PK\L-IV	31.3	204	40.3	1.72	1.00	4.97	2.69	0.76	5.49	14.4
PK\L-V	32.9	210	34.8	2.05	1.00	5.81	1.95	1.48	6.58	12.2
PS-VI	21.4	111	26.9	1.35	1.00	5.17	1.31	0.56	6.57	13.4

Table 9

Contamination factors (CF) for heavy metals and the pollution load index (PLI)

Sites	Pb	Cd	Zn	Mn	Fe	Cu	Ni	Cr	Hg	As	PLI
PSh-I	31	84.3	21.4	1.36	0.84	10.9	1.46	0.72	5.54	11.1	23.2
PSh-II	22.1	74.9	20	1.07	0.89	5.30	1.80	0.68	5.89	11.5	18.6
PZ-III	6.98	33.1	7.58	0.65	0.47	1.52	0.51	0.49	1.96	4.27	6.81
PK\L-IV	20.4	133	26.2	1.12	0.65	3.23	1.75	0.49	3.57	9.36	18.8
PK\L-V	11.6	74	12.3	0.71	0.35	2.05	0.69	0.52	2.32	4.32	10.11
PS-VI	14.5	75.7	18.3	0.92	0.68	3.52	0.89	0.38	4.46	9.09	15.2

The highest potential ecological risk was obtained for Cd (Table 10), hence this metal could be considered as an element with a very high potential ecological risk. The values of the factor calculated for Pb and As differed between moderate and considerable risk. Also, the results obtained for Hg varied between considerable and high risk classes.

The potential ecological risk index calculated for the study sites (Table 10) indicated the presence of contaminants in all study areas. The highest risk

Table 10

Potential ecological risk factor and potential ecological risk index (RI)

Specification	Pb	Cd	Zn	Mn	Fe	Cu	Ni	Cr	Hg	As	RI
T_r^i *	5	30	1	1	1	5	5	2	40	10	
PSh-I	155	2529	21.4	1.36	0.84	54.3	7.30	1.44	221	111	3104
PSh-II	110	2247	19.9	1.07	0.89	26.5	9.02	1.35	236	115	2767
PZ-III	34.9	994	7.58	0.65	0.47	7.60	2.55	0.99	78.6	42.7	1170
PK\L-IV	102	3988	26.2	1.12	0.65	16.2	8.74	0.98	143	93.6	4380
PK\L-V	58.1	2220	12.3	0.71	0.35	10.3	3.45	1.04	92.9	43.2	2443
PS-VI	72.7	2270	18.3	0.92	0.68	17.6	4.44	0.77	179	90.9	2655

categories – considerable to very high – were associated with Cd and Hg. The RI, which assesses the contamination level, showed that most of the soils studied could be classified as having a considerable risk of HM impact. Previous studies have shown that Ch. majus does not accumulate HMs in aerial tissues (Rahmonov et al. 2023a). More significant amounts of HMs were found in the rhizomes of this plant (Rahmonov et al. 2023a), which indicates that this species has phytostabilising properties in relation to soil contamination. However, it has been noted that heavy metals, particularly Hg and Cr, are translocated from the rhizomes to the leaves (Rahmonov et al. 2023*a*). Therefore, the plant should not be harvested for medicinal purposes from heavily polluted areas.

The calculated environmental indices suggest that the soil analysed is contaminated, which may be due to its location in a city centre with numerous sources of pollution. Often, these are soils formed on post-mining waste, and results in this respect have been presented previously from Poland (Spychalski, Gilewska 2007) and other countries, such as China (Li et al. 2017). The calculated chemical indices show that all the studied soils are contaminated by HMs, especially Cd, Zn, Pb and Hg. The presence of these elements is linked to urbanisation and causes soil degradation and contamination. The source of Cd is most probably due to industrialisation, mining, coal combustion, or the use of phosphate fertilisers (WHO 1992), hence their contribution to the soil pollution.

The soils in urban areas, in addition to their function as a carrier of the city's infrastructure, also significantly impact the development of urban greenery and the quality of the city's water and air. Their degradation, besides the negative transformation of other elements of the urban environment, results in the deterioration of the population's living conditions. Therefore, continuous monitoring of the city's natural components, including the soil environment, should be pursued. Currently, the study of urban soils is not only of cognitive or scientific importance but is also legally sanctioned (Journal of Laws 2016). In most EU member states, the knowledge of the properties of soils is a requirement before soil management can be undertaken, with the ultimate aim being the development of soil maps for cities. Urban soils underlie urban green spaces, such as parks and gardens, where they act as a repository for contaminants, and it is in such places that people have more direct contact with soil.

CONCLUSIONS

1. As a nitrophilous species, Ch. majus grows at the edges of parks and on open slopes in loose soil with good aeration and does not tolerate compacted soils. The substrates for Ch. majus are mainly alkaline and contain significant amounts of OC, Nt and Pt.

2. The concentration of heavy metals in the topsoil of the parks analysed varies in all locations. The maximum contents of Zn, Pb and Cd were confirmed in 3 sites and exceeded acceptable soil standards for recreational areas and cultivated land; among these, Zn had the highest content.

3. The concentration of HMs in the tissues of Ch. majus is diverse. The highest concentrations of HMs were generally in the rhizomes and aerial parts, respectively. Zn showed the highest values among the analysed elements. Lead and cadmium generally predominate in underground plant parts, while As, Hg and Cr predominate in aerial parts. Specimens growing on highly contaminated soils are not recommended for medicinal purposes

4. The relationship among the concentration of HMs in the tissues of the studied species and in the soil is varied and is related to the chemistry of the initial anthropogenic parent rock in the individual research sites. Determining the content of elements in plants and soil will provide information about the presence of HMs in the environment and their uptake by plants from the soil. Regularly conducting research in this direction on permanent surfaces facilitates monitoring the circulation of HMs.

5. The environmental indicators used facilitated the determination of the degree of heavy metal contamination: the Igeo shows that Cd, Pb and Zn have the greatest impact on soil contamination in all study areas. The samples are characterised by extremely high Cd enrichment, very high Pb, Zn enrichment, significant As enrichment and moderate to significant Hg enrichment.

Author contributions

O.R., D.Ś., T.K., N.M. – conceptualization, O.R. – data curation, O.R., D.Ś., S.P – methodology, O.R. and S.P, D.Ś – formal analysis, O.R. – investigation, methodology, O.R. – project administration, D.Ś., S.P. – software, O.R. – supervision, visualization, O.R. – original draft preparation, O.R., D.Ś., S.P., T.K and N.M. – review & editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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