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POTENTIAL OF SELECTED AROMATIC ASTERACEAE SPECIES FOR THE PHYTOREMEDIATION OF HEAVY METAL - CONTAMINATED SOILS

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Abstract

Aromatic plants of the Asteraceae family have significant potential for phytoremediation due to their rapid growth, high biomass production, and resilience in contaminated soils. This study evaluated the capacity of Artemisia absinthium, Achillea millefolium, Tanacetum balsamita, Tanacetum vulgare, and Artemisia dracunculus to accumulate heavy metals in soils contaminated by industrial activities in Bulgaria. Field experiments were conducted at contaminated sites, where soil and plant tissues (roots, stems, leaves, and flowers) were analysed for Pb, Cd, and Zn using ICP-OES. Bioconcentration (BCF) and translocation (TF) factors were calculated to assess metal uptake and distribution from roots to aboveground biomass. The results demonstrate considerable accumulation of Pb and Zn, with A. absinthium and A. millefolium exhibiting the highest BCF and TF values, indicating their suitability as the most effective species for phytoextraction. T. balsamita and T. vulgare displayed moderate accumulation with limited translocation, suggesting their potential for phytostabilisation, whereas A. dracunculus showed minimal uptake. These findings provide important insights into metal accumulation and translocation in Asteraceae species and identify the most promising species for the sustainable management of industrially contaminated soils.

Key words*: Asteraceae, aromatic plants, heavy metals, phytoremediation, bioaccumulation, soil contamination.*

INTRODUCTION

Soil contamination with heavy metals represents one of the most pressing environmental challenges resulting from industrialisation, mining, metallurgical activities, and intensive agriculture. Among the most prevalent soil pollutants are lead (Pb), cadmium (Cd), and zinc (Zn), which are highly persistent in the environment because they are not subject to biological degradation and can remain in soils for extended periods. Accumulation of these elements in soil ecosystems can reduce soil fertility, disrupt plant growth and development, and exert toxic effects on soil microorganisms. Furthermore, heavy metals can enter the food chain, posing a serious risk to human health (Raskin & Ensley, 2000; Terry & Banuelos, 2000; Ali et al., 2013; Yan et al., 2020).

Conventional remediation methods, such as excavation, soil washing, and chemical stabilisation, are often associated with high costs, substantial technical resources, and significant disruption of soil structure and ecosystem functions. Consequently, in recent decades, there has been growing interest in phytoremediation as an environmentally friendly and cost-effective technology for restoring contaminated sites. Phytoremediation employs plants to extract, stabilise, or transform contaminants in soil and water and is considered a sustainable alternative to conventional cleanup methods (Terry & Banuelos, 2000; Angelova, 2023; Angelova & Ihtyarova, 2023; Angelova, 2025; Bhat et al., 2025). Depending on the mechanism, phytoremediation may involve phytoextraction, phytostabilisation, rhizofiltration, or phytovolatilisation, each of which differs in how plants interact with contaminants (Bhat et al., 2025).

The effectiveness of phytoremediation largely depends on selecting suitable plant species. Ideal plants should exhibit rapid growth, high biomass production, well-developed root systems, and tolerance to elevated contaminant concentrations. Recently, there has been increasing scientific interest in using medicinal and aromatic plants for phytoremediation. These plants typically show high resilience to abiotic stress and can thrive on margminal or degraded soils. Moreover, their economic value associated with bioactive compounds, enables

the integration of environmental and economic benefits (Deng et al., 2024; Yadav et al., 2025). Particular attention has been given to species from the Asteraceae family, which are widely distributed and well-adapted to diverse environmental conditions. Many members exhibit high ecological plasticity, rapid growth, and substantial biomass production - key traits for successful phytoremediation. Genera such as Achillea, Artemisia, and Tanacetum include species used in traditional medicine and the production of pharmaceutical products. Studies indicate that these plants can accumulate significant amounts of heavy metals in various organs while maintaining resilience in contaminated environments (Salt et al., 1998; Sharma et al., 2023; Zhang et al., 2024; Bhat et al., 2025).

Despite growing interest in using aromatic plants for phytoremediation, several aspects remain underexplored. Most research has focused on classical hyperaccumulator or energy crop species, while the potential of aromatic plants, particularly Asteraceae, remains relatively poorly investigated. Information on the distribution of heavy metals among different plant organs and the efficiency of translocation from roots to shoots under naturally contaminated conditions is limited.

This knowledge gap is especially relevant for regions with long-term industrial and mining activities, where soils are often heavily contaminated with Pb, Cd, and Zn. In Bulgaria, numerous industrial and mining areas face significant environmental challenges from heavy metal accumulation, underscoring the need for sustainable, effective remediation strategies.

The present study addresses this gap by systematically evaluating the phytoremediation potential of selected aromatic Asteraceae species grown on industrially contaminated soils in Bulgaria. By analysing Pb, Cd, and Zn concentrations in roots, stems, and leaves and calculating bioconcentration (BCF) and translocation (TF) factors, the study provides a comprehensive assessment of these species' capacity to accumulate and translocate heavy metals.

The objectives of this study are: (i) to determine Pb, Cd, and Zn concentrations in different plant organs (roots, stems, leaves, flowers); (ii) to evaluate the species' ability to accumulate and translocate metals through BCF and TF calculations; and (iii) to identify species with the highest potential for application in the phytoremediation of heavy metal-contaminated soils.

The results will contribute to a better understanding of the mechanisms of metal accumulation and translocation and support the development of sustainable strategies for the management and restoration of industrially contaminated soils.

MATERIALS AND METHODS

The study was conducted on soils located in the vicinity of a major industrial pollution source - the Non-Ferrous Metal Works near Plovdiv, Bulgaria. The sampling sites are situated at approximately 0.5 km from the emission source, where long-term industrial activity has resulted in significant accumulation of trace metals in the surface soil layer.

This site has been extensively investigated in previous studies focused on plant-based phytoremediation (Angelova, 2020; Angelova & Ihtyarova, 2023; Angelova & Ihtyarova, 2025), and is therefore considered a well-characterised system for assessing heavy metal behaviour under field conditions.

Seedlings of selected medicinal plants - costmary (*Tanacetum balsamita* L.), tansy (*Tanacetum vulgare* L.), yarrow (*Achillea millefolium* L.), wormwood (*Artemisia absinthium* L.), and tarragon (*Artemisia dracunculus* L.) - were obtained from a commercial nursery and planted in spring. Plant samples were collected during the flowering stage in the second and third years after planting and dried at room temperature to a constant air-dry mass.

Pseudo-total metal content in the soil was determined following ISO 11466. At the same time, concentrations of Pb, Zn, and Cd in plant organs (roots, stems, leaves, and flowers) were analysed after microwave-assisted acid digestion. Quantitative measurements were performed using inductively coupled plasma optical emission spectrometry (ICP-OES; Jobin Yvon Emission JY 38 S, France), with analytical accuracy validated using apple leaves as a certified reference material (SRM 1515, NIST).

Phytoremediation potential was evaluated using quantitative indices describing metal uptake, translocation, and accumulation in plant tissues (Raskin & Ensley, 2000; Terry & Banuelos, 2000). The phytoremediation assessment focused on three key indicators: the bioconcentration factor (BCF), the translocation factor (TF), and the aboveground accumulation factor (BAF). These parameters are widely applied in studies of heavy metal uptake and phytoextraction efficiency (Yoon et al., 2006; Kabata-Pendias, 2011; Ali et al., 2013). BCF quantifies root uptake relative to soil concentrations (BCF = Croot/Csoil). TF evaluates internal metal mobility and is calculated for individual organs (TF_stem = Cstem/Croot; TF_leaf = Cleaf/Croot; TF_flower = Cflower/Croot) as well as a total value (TF_total = Caboveground/Croot). BAF represents the accumulation of metals in the aboveground biomass relative to soil concentration (BAF = Caboveground/Csoil).

Together, these metrics provide a concise evaluation of metal uptake, translocation, and accumulation efficiency. BCF reflects the efficiency of metal uptake by roots relative to soil concentrations; values >1 indicate effective extractors, whereas values <0.1 denote stabilisers or metal excluders. TF characterises internal metal translocation, with TF_total summarising transport from roots to all aboveground tissues; TF_total >1 indicates efficient translocation, while TF_total <1 suggests predominant root retention and potential for phytostabilisation. BAF integrates uptake and translocation into a direct indicator of phytoextraction potential. Together, these metrics enable robust classification of species as accumulators, intermediates, stabilisers, or excluders, supporting their targeted application in sustainable soil remediation strategies.

RESULTS AND DISCUSSIONS

Soil Contamination Characteristics

Soils at the investigated site show markedly elevated concentrations of heavy metals as a result of long-term industrial activity in the region. The measured concentrations of Zn, Pb and Cd considerably exceed commonly accepted guideline values for agricultural soils reported in the literature, indicating severe contamination (Kabata-Pendias, 2011).

Zinc concentrations generally fall within the range typical for metal-impacted soils in proximity to metallurgical facilities, while lead and cadmium levels also indicate strong anthropogenic influence. Such elevated concentrations reflect the long-term accumulation of trace elements derived from emissions of the nearby Non-Ferrous Metal Works and associated industrial activities.

Similar contamination patterns for this site have been previously reported (Angelova et al., 2025), confirming that the studied soils represent a characteristic example of chronically polluted industrial areas. Under such conditions, only plant species with high tolerance to metal stress are able to persist, often developing adaptive physiological and biochemical mechanisms that enable survival in highly contaminated environments.

Measured concentrations (Table 1) further confirm that Zn, Pb and Cd levels exceed regulatory limits by several-fold. Such contamination levels are characteristic of soils affected by mining and metallurgical activities, where prolonged anthropogenic inputs lead to the accumulation of trace metals (Alloway, 2013). Elevated concentrations of Pb, Cd and Zn impose strong selective pressure on vegetation, favoring species capable of tolerating metal stress and regulating metal uptake. Plants growing under such conditions typically activate complex physiological and biochemical defense mechanisms, including metal binding, antioxidant responses and intracellular compartmentalization, which allow them to maintain metabolic function despite high soil contamination (Al-Khayri et al., 2023).

Heavy Metal Accumulation in Plant Organs

Analysis of metal concentrations in different plant organs revealed substantial interspecific and metal-specific differences. The highest concentrations of Pb, Cd, and Zn were generally observed in leaves and roots, while stems contained considerably lower amounts (Table 1). This pattern is characteristic of plants actively translocating metals to aerial tissues (Angelova, 2020; Angelova & Ihtyarova, 2023; Ihtyarova & Angelova, 2023; Angelova, 2023; Angelova, 2025). Roots serve as the primary site of metal uptake from the soil solution, after which ions are transported to aboveground tissues via the xylem, where they accumulate in

leaves and other photosynthetically active organs. In some cases, leaf metal accumulation may also result from atmospheric deposition of metal particles, especially in industrially contaminated areas (Rahman et al., 2024). Similar accumulation patterns have been documented in aromatic Asteraceae, which demonstrate enhanced metal tolerance and the ability to regulate intracellular concentrations through detoxification and compartmentalisation mechanisms (Ali et al., 2013; Kumar et al., 2016).

Table 1. Concentrations of Pb, Cd, and Zn (mg/kg) in soils and different plant organs (roots, stems, leaves, flowers) of selected Asteraceae species grown on industrially contaminated sites

Species/Element		Soils	Roots	Stems	Leaves	Flowers
Artemisia absinthium	Pb	2509.1	1913.0	123.5	4414.9	1223.3
	Cd	64.3	102.7	19.9	225.1	163.9
	Zn	2423.9	1495.2	76.1	2026.6	911.5
Achillea millefolium	Pb	2509	1000.3	230.8	405.6	1170.9
	Cd	64.3	102.6	82.7	133.0	89.8
	Zn	2423.9	506.4	196.1	737.6	1035.3
Tanacetum balsamita	Pb	2966.9	676.3	495.1	566.0	244.1
	Cd	92.0	58.4	77.1	59.7	18.4
	Zn	3196.1	500.7	395.1	664.6	159.7
Tanacetum vulgare	Pb	2966.9	237.1	71.8	425.0	310.6
	Cd	92.0	56.3	75.4	99.4	56.5
	Zn	3196.1	112.8	73.9	508.0	312.4
Artemisia dracunculus	Pb	2509.1	91.1	56.5	742.8	294.3
	Cd	64.3	3.9	15.5	39.0	35.1
	Zn	2423.9	50.9	68.5	556.1	304.6

Metal-Specific Uptake and Translocation Patterns

Artemisia absinthium exhibited the highest Pb accumulation among the studied species, with leaf concentrations exceeding 4415 mg/kg and root concentrations of around 1913 mg/kg. The high translocation factor (TF_leaf > 2) indicates effective transport to aerial parts. This is unusual, as Pb generally has low mobility and is largely retained in roots due to strong binding to cell walls and limited xylem transport (Rahman et al., 2024). Enhanced mobility may involve organic ligands, such as phenolics and terpenoids, which facilitate Pb translocation. *Achillea millefolium* also accumulated considerable Pb, particularly in flowers, suggesting active translocation to reproductive organs (Salt et al., 1998; Angelova & Ihtyarova, 2023; Yadav et al., 2025). *T. balsamita* and *T. vulgare* retained Pb mainly in roots, characteristic of phytostabilisation strategies (Ali et al., 2013; Nikolić & Stević, 2015; Angelova & Ihtyarova, 2023; Angelova, 2025). *Artemisia dracunculus* showed minimal Pb uptake (BCF = 0.04) (Table 2), indicating limited Pb accumulation under the studied conditions.

Cd exhibited higher mobility than Pb. The highest concentrations were observed in leaves of *A. absinthium* (225.1 mg/kg) and *A. millefolium* (133.0 mg/kg), indicating efficient translocation to aboveground tissues. High Cd accumulation reflects effective detoxification mechanisms, including complexation with organic acids, amino acids, and phytochelatins (Clemens et al., 2013). Cd is relatively easily transported via the xylem to photosynthetic tissues (Tao & Lu, 2022). In *A. dracunculus*, Cd accumulated primarily in leaves and flowers despite low root concentrations, demonstrating efficient internal metal transport (Nagajyoti et al., 2010).

Table 2. Bioconcentration (BCF), translocation (TF), and aboveground accumulation (BAF) factors for Pb, Cd, and Zn in selected Asteraceae species cultivated on industrially contaminated soils

Element	BCF	TF stem	TF leaf	TF flower	TF total	BAF
T. balsamita						
Pb	0.23	0.73	0.84	0.36	1.93	0.44
Cd	0.64	1.32	1.02	0.32	2.66	1.69
Zn	0.16	0.79	1.33	0.32	2.43	0.38
T. vulgare						
Pb	0.08	0.30	1.79	1.31	3.41	0.27
Cd	0.61	1.34	1.77	1.00	4.11	2.51
Zn	0.04	0.66	4.51	2.77	7.93	0.28
A. millefolium						
Pb	0.40	0.23	0.41	1.17	1.81	0.72
Cd	1.60	0.81	1.30	0.88	2.98	4.75
Zn	0.21	0.38	1.46	2.04	3.89	0.81
A. absinthium						
Pb	0.76	0.06	2.30	0.64	3.01	2.30
Cd	1.60	0.19	2.19	1.60	3.98	6.36
Zn	0.62	0.05	1.36	0.61	2.02	1.24
A. dracunculus						
Pb	0.04	0.62	8.15	3.23	12.01	0.44
Cd	0.06	3.97	9.96	8.95	22.87	1.39
Zn	0.02	1.34	10.93	5.99	18.26	0.38

Zn is an essential micronutrient with tightly regulated uptake. The highest concentrations were observed in *A. absinthium* leaves (>2000 mg/kg). Relatively high concentrations were also detected in *A. millefolium*, especially in leaves and flowers, indicating that Asteraceae species can accumulate Zn without visible toxicity symptoms, likely through intracellular compartmentalisation (Broadley et al., 2007; Balafrej et al., 2020).

Species-Specific Phytoremediation Strategies

Artemisia absinthium demonstrated the highest capacity for heavy metal accumulation. The genus Artemisia is known for resilience to

abiotic stress, including metal contamination, activating protective mechanisms through enhanced synthesis of secondary metabolites such as terpenes and phenolics (Balafrej et al., 2020). *Achillea millefolium* also showed considerable potential for Pb, Cd, and Zn accumulation, making it promising for phytoextraction (Angelova & Ihtyarova, 2023). *T. balsamita* and *T. vulgare* exhibited moderate BCF and limited translocation, suitable for phytostabilisation (Nikolić & Stevović, 2015). *Artemisia dracunculus* showed low accumulation potential and is suitable for cultivation on moderately contaminated soils.

Morphological Determinants of Metal Uptake

Morphological traits significantly influence metal accumulation. Species with deep, branched roots, such as *A. absinthium* and *A. millefolium*, showed higher efficiency in metal ion uptake. Dense leaf trichomes enhance deposition of atmospheric metal particles, leading to higher Pb concentrations in leaves, particularly in industrial areas (Rahman et al., 2024). High transpiration rates facilitate transport of mobile metals such as Cd and Zn to aerial organs (Tao & Lu, 2022).

Bioconcentration and Translocation Factors

Bioconcentration and Translocation Factors BCF indicates a plant's ability to extract metals from soil, while TF reflects the efficiency of transport to aboveground tissues (Yoon et al., 2006). *A. absinthium* and *A. millefolium* exhibited BCF > 1 for Cd and Zn, along with high TF values (Table 2), confirming their phytoextraction potential (Angelova & Ihtyarova, 2023). In the case of Pb, although BCF values in *A. absinthium* were moderate, the high TF_leaf and TF_total values indicate efficient translocation from roots to aboveground tissues. This results in enhanced accumulation in leaves, which may exceed soil concentrations and reflects the strong accumulator behaviour of the species. As shown in Table 2, although the BCF value (0.76) indicates moderate uptake from soil, the translocation factors, particularly TF_leaf (2.30) and TF_total (3.01), demonstrate highly efficient transport of Pb from roots to aboveground tissues. In addition, the BAF value (2.30) indicates significant accumulation in the aerial biomass. This combination of moderate uptake and strong translocation results in the enrichment of Pb in leaves, leading to concentrations exceeding those in soil. Therefore, this behavior confirms the classification of *Artemisia absinthium* as an accumulator species rather than indicating an inconsistency. Furthermore, the contribution of atmospheric deposition in industrially affected areas may also enhance Pb levels in leaves. *T. balsamita* and *T. vulgare* had lower BCF and TF, typical of stabilisers (Nikolić & Stevović, 2015). A. dracunculus showed low BCF and TF, confirming limited metal uptake.

Implications for Phytoremediation

The results indicate that aromatic Asteraceae species can be integrated into sustainable strategies for managing metal-contaminated soils. High-accumulating species, such as *A. absinthium* and *A. millefolium*, are suitable for phytoextraction, whereas moderately accumulating species may serve in phytostabilisation (Ali et al., 2013; Nikolić & Stevović, 2015; Angelova, 2020; Angelova & Ihtyarova, 2023). An integrated analysis of BCF, TF_total, and BAF revealed clear differences among species. *A. absinthium* and *A. millefolium* showed the highest potential for Cd and Zn extraction, with elevated BCF, TF_total > 1, and BAF > 1 (Table 3). *T. balsamita* and *T. vulgare* exhibited moderate or partial extraction, while *A. dracunculus* displayed typical excluder behavior with low uptake but maintained internal translocation, suitable for stabilisation. These findings demonstrate the differentiated phytoremediation potential of *Asteraceae* species, indicating their promise as sustainable, multifunctional crops that combine metal tolerance with high aboveground biomass production.

From a practical perspective, the utilization of the resulting biomass depends on the level of metal accumulation and the target element. For species with high accumulation in aboveground tissues, such as *A. absinthium* and *A. millefolium*, direct use for food, feed or medicinal purposes is not recommended due to the risk of metal transfer. However, the biomass can be directed toward non-food applications, such as bioenergy production or essential oil extraction, where metals are not transferred into

the distilled product. In contrast, low-accumulating species such as *A. dracunculus* may be suitable for controlled use in moderately contaminated soils.

Table 3. Phytoremediation classification of selected Asteraceae species for Pb, Cd, and Zn, based on metal accumulation and translocation patterns.

Species	Pb	Cd	Zn
Artemisia absinthium	Accumulator	Strong accumulator / Hyperaccumulator	Accumulator
Achillea millefolium	Intermediate accumulator	Strong accumulator	Accumulator
Tanacetum balsamita	Intermediate accumulator	Accumulator	Intermediate accumulator
Tanacetum vulgare	Mixed behavior	Accumulator	Mixed
Artemisia dracunculus	Metal excluder	Mixed behavior	Metal excluder

Note: Classification is based on BCF, TF_total, and BAF values. Species with BCF > 1 and TF_total > 1 are considered potential phytoextractors, whereas species with BCF > 1 but TF_total < 1 are classified as phytostabilisers. Species with BCF < 1 are considered metal excluders. "Mixed" indicates species exhibiting contrasting behaviour depending on the metal or showing inconsistent BCF and TF patterns.

CONCLUSIONS

The present study demonstrates clear interspecific differences among Asteraceae species in their capacity for heavy metal uptake, accumulation, and translocation under conditions of severe industrial soil contamination. *Artemisia absinthium* and *Achillea millefolium* exhibited the highest phytoextraction potential, characterised by efficient accumulation of Pb, Cd, and Zn and effective translocation to the aboveground biomass. In contrast, *T. balsamita* and *T. vulgare* showed moderate metal accumulation and limited translocation, indicating a phytostabilisation-oriented strategy. *Artemisia dracunculus* displayed minimal metal uptake and typical excluder behaviour, suggesting its suitability for cultivation on moderately contaminated soils rather than for active phytoextraction.

Morphological traits, particularly a well-developed root system, leaf surface characteristics, and high transpiration capacity, appear to play a critical role in regulating metal uptake and internal transport within plant tissues. Overall, the findings highlight the significant potential of aromatic Asteraceae species as multifunctional crops for the sustainable management of metal-contaminated soils. Their capacity to combine metal tolerance with productive aboveground biomass supports their inclusion in future phytoremediation strategies aimed at the ecological restoration of industrially impacted landscapes.

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