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Identification and ecological assessment of plant species with reported bioaccumulation and phytoremediation potential in recreation areas of Aliağa (İzmir) industrial districts

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Abstract
Purpose: This study aims to evaluate plant species in urban recreation areas under pressure from intensive industrial activities in the Aliağa district of İzmir in terms of their reported bioaccumulation and phytoremediation potential. The study seeks to contribute to plant design decisions in industry-focused cities being made not only for aesthetic reasons but also in line with ecological functions.
Method: Within the scope of the study, eight recreational areas located near industrial facilities, port activities, and transportation networks were examined on-site, and the existing plant species in these areas were identified. The identified species were analyzed in terms of their life forms, area-based distribution, proportion within the total number of species, and the plant organs (leaves, roots, branches) reported in the literature to accumulate heavy metals, and were classified according to their potential phytoremediation roles.
Findings: The data obtained showed that the proportion of species with reported bioaccumulation and phytoremediation potential within the total number of species ranged from 3.23% to 39.29% depending on the area. In contrast, it was determined that the representation (prevalence) rates of these species within the population ranged from 21.67% to 81.87%, which were higher levels. Furthermore, according to literature data, heavy metal accumulation in the relevant species was most frequently reported in leaf tissue (20 species), followed by root (7 species) and branch (6 species) organs.
Conclusion: Research findings reveal that high species diversity in recreational areas alone does not necessarily reflect environmental improvement potential. The ecological improvement potential is largely related to the representation level (density) of species with literature-reported phytoremediation potential within the area. In this context, promoting species identified in the literature as having pollutant retention potential in plant designs for cities under industrial pressure is critically important for ecological sustainability. One of the main limitations of this study is the absence of direct heavy metal analyses on plant tissues or soil samples, and therefore the results should be interpreted as a literature-based potential assessment.

Keywords: bioaccumulator plants; phytoremediation; heavy metal pollution; urban recreation areas; plant design; Aliağa

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Aliağa (İzmir) sanayi ilçelerindeki rekreasyon alanlarında biyobirikim ve fitoremediasyon potansiyeli bildirilen bitki türlerinin tanımlanması ve ekolojik değerlendirilmesi

Özet
Amaç: Bu çalışma, İzmir Aliağa ilçesinde yoğun sanayi faaliyetlerinin baskısı altındaki kentsel rekreasyon alanlarında bulunan bitki türlerinin, biyobirikim ve fitoremediasyon potansiyelleri açısından değerlendirilmesini amaçlamaktadır. Çalışma, sanayi odaklı kentlerde bitki tasarım kararlarının sadece estetik nedenlerle değil, ekolojik işlevlerle de uyumlu olarak alınmasına katkıda bulunmayı hedeflemektedir.
Metod: Çalışma kapsamında, endüstriyel tesisler, liman faaliyetleri ve ulaşım ağlarının yakınında bulunan sekiz rekreasyon alanı yerinde incelenmiş ve bu alanlardaki mevcut bitki türleri belirlenmiştir. Belirlenen türler, yaşam formları, alan bazlı dağılımları, toplam tür sayısı içindeki oranları ve literatürde ağır metalleri biriktirdiği belirtilen bitki

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organları (yapraklar, kökler, dallar) açısından analiz edilmiş ve potansiyel fitoremediasyon rolleri doğrultusunda sınıflandırılmıştır.
Bulgular: Elde edilen veriler, toplam tür sayısı içindeki biyobirikim ve fitoremediasyon potansiyeline sahip türlerin oranının, bölgeye bağlı olarak %3.23 ile %39.29 arasında değiştiğini göstermiştir. Buna karşılık, bu türlerin popülasyon içindeki temsil (yaygınlık) oranlarının %21.67 ile %81.87 arasında değiştiği ve daha yüksek seviyelerde olduğu belirlenmiştir. Ayrıca, literatür verilerine göre, ilgili türlerde ağır metal birikimi en sık yaprak dokusunda (20 tür), ardından kök (7 tür) ve dal (6 tür) organlarında bildirilmiştir.
Sonuç: Araştırma bulguları, rekreasyon alanlarındaki yüksek tür çeşitliliğinin tek başına çevresel iyileştirme potansiyelini yansıtmadığını ortaya koymaktadır. Ekolojik iyileştirme potansiyeli büyük ölçüde, alandaki literatürde fitoremediasyon potansiyeli bildirilen türlerin temsil düzeyi (yoğunluğu) ile ilgilidir. Bu bağlamda, endüstriyel baskı altındaki şehirler için bitki tasarımlarında literatürde kirletici madde tutma potansiyeline sahip olarak tanımlanan türlerin teşvik edilmesi, ekolojik sürdürülebilirlik için son derece önemlidir. Bu çalışmanın başlıca sınırlamalarından biri, bitki dokularında veya toprak örneklerinde doğrudan ağır metal analizlerinin yapılmamış olmasıdır ve bu nedenle sonuçlar, literatüre dayalı bir potansiyel değerlendirmesi olarak yorumlanmalıdır.

Anahtar kelimeler: biyokümülatör bitkiler; fitoremediasyon; ağır metal kirliliği; kentsel rekreasyon alanları; bitkisel tasarım; Aliağa

1. Introduction

Rapid industrialization and urbanization processes place significant pressure on the urban environment, particularly in areas with concentrated heavy industrial activity [1]. Industrial facilities, port operations, and intensive transportation networks have been shown to disrupt the functioning of urban ecosystems by contributing to the accumulation of heavy metals in soil, air, and plant matrices [2, 3]. This situation poses critical risks to urban residents in terms of environmental quality, ecosystem balance, and long-term public health. Heavy metals such as nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn) are among the most common pollutants in urban environments, with well-documented toxic effects on biological systems [4].

Urban green spaces and recreation areas, beyond their aesthetic and social functions, are vital ecological components that can alleviate these environmental pressures [5]. The plant species chosen for these areas can play an active role in bioaccumulation and phytoremediation processes due to their potential to accumulate or remove heavy metals from the environment [6, 7]. However, in practice, plant selection is often based on criteria such as aesthetic concerns, ease of maintenance, and intensity of use; the environmental improvement capacities of plants are frequently overlooked [8, 9]. This situation can lead to landscape design decisions lacking a scientific ecological basis, especially in cities under intense industrial pressure [10].

This study aims to address this deficiency by identifying plant species in urban recreation areas in the Aliağa district of İzmir province, which is under the influence of intense industrial activities, and evaluating the literature-reported heavy metal accumulation potential of these species. The species identified in the study were analyzed in terms of their organs reported in the literature as heavy metal accumulation sites and the types of metals previously documented to be accumulated by these species; area-based ratios of species reported to have potential bioaccumulation and phytoremediation relevance were determined. The research aims to provide an ecological perspective to plant design decisions in industrial areas by offering a literature-based potential assessment grounded in the existing plant presence. While this study does not include direct experimental analyses, the results should be considered as a preliminary assessment, highlighting the need for future experimental studies to validate the ecological contributions of these species.

2. Materials and methods

This research was conducted between February 2026 and Mart 2026 in the open-green areas used for urban recreation in Aliağa district, İzmir province, where intensive industrial activities create environmental pressure. Due to its industrial character, Aliağa is considered a high-risk area in terms of heavy metal accumulation in urban soils [11]. Considering their proximity to industrial facilities, main traffic roads, and urban activity areas, eight recreation areas heavily used by the public were selected as the study area. The list of study areas is shown in Table 1, and their locations are shown in Figure 1.

The study consists of three stages. In the first stage, all plant species in the study areas were examined in situ and identified using standard flora references and taxonomic keys [13]. Species descriptions were provided by the authors. Sample specimens could not be collected. This was accepted as a limitation of the study, and the identifications were based on diagnostic features observable in the field and supported by relevant taxonomic sources.

Table 1. List of study areas

Recreation Area	Area Code
Aliağa Municipality Green Park	A
Aliağa Municipality Rock Park	B
Aliağa Municipality City Park	C
Avcı Ramadan Park	D
Gazi Mustafa Kemal Atatürk Park	E
Ege University Aliağa Vocational School	F
Petkim Atilla Uzun Sports Hall	G
Binali Yıldırım Maritime Park	H



Figure 1. Location of study areas [12]

In the second stage, plant species identified in the field that have been reported in the literature to accumulate one or more heavy metals (e.g., Pb, Cd, Zn, Cu, Ni, Cr, etc.) or that are considered potential candidate species for phytoremediation were determined based on published sources. In the third stage, the data obtained were analyzed using IBM SPSS 27 statistical software. Within the scope of descriptive statistics, percentage and frequency values were calculated to determine the life form ratio of plant species reported in the literature to have bioaccumulation and phytoremediation potential and the ratio of their reported heavy metal-accumulating organs for all areas and area-based. In these calculations, the denominator was defined as the total number of species identified in each study area. After the descriptive analysis, evaluations were made, recommendations were developed, and suggestions were made for future studies.

3. Results

A total of 86 plant species belonging to 76 genera and 39 families were identified in the study areas. The identified plants are shown in Table 2.

Literature reviews were conducted using databases such as Web of Science, Scopus, and Google Scholar, with keywords including plant species, heavy metal accumulation, bioaccumulation, and phytoremediation. Species were considered to have bioaccumulation or phytoremediation potential if at least one relevant peer-reviewed study reported such properties. At least one literature record was deemed sufficient for inclusion. Table 3 presents the types of heavy metals reported in the literature to be accumulated in specific plant organs by the identified species. Species not included in Table 3 were not necessarily considered to lack heavy metal accumulation capacity; rather, no relevant information was found within the scope of the literature search. Since no experimental heavy metal analyses were conducted in this study, the findings should be interpreted as a literature-based potential assessment, not as direct measurements in the study areas.

Table 2. Plant species, life forms, and the locations where they were identified in the study areas

Plant Species	Family	Life Form	Area where It was Detected
Abelia grandiflora (Rovelli ex André) Rehder	*Caprifoliaceae*	Bush	A, E, F
Acacia dealbata Link	*Fabaceae*	Tree	A, B
Acer platanoides L.	*Sapindaceae*	Tree	C, E, G, H
Acer pseudoplatanus L.	*Sapindaceae*	Tree	C
Agave americana L.	*Asparagaceae*	Bush	A, B
Ailanthus altissima (Mill.) Swingle	*Simaroubaceae*	Tree	E, F, G
Albizia julibrissin Durazz.	*Fabaceae*	Tree	C, E, G
Archontophoenix cunninghamiana (H.Wendl.) H.Wendl. & Drude	*Arecaceae*	Tree	B, C, D, H
Atriplex halimus L.	*Amaranthaceae*	Bush	A, B, C, D
Berberis thunbergii DC.	*Berberidaceae*	Bush	C, E, F, H
Bougainvillea spectabilis Willd.	*Nyctaginaceae*	Climber	B, E
Buxus sempervirens L.	*Buxaceae*	Bush	A, B, C, E, F
Casuarina equisetifolia L.	*Casuarinaceae*	Tree	E, F, G
Cedrus deodara (Roxb. ex D.Don) G.Don	*Pinaceae*	Tree	A, B, E, F, G
Cercis siliquastrum L.	*Fabaceae*	Tree	A, C, E, H
Chaenomeles japonica (Thunb.) Lindl. ex Spach	*Rosaceae*	Bush	A, C, E
Chamaerops excelsa Thunb.	*Arecaceae*	Treelet	C, D, E, H
Citrus limon (L.) Osbeck	*Rutaceae*	Tree	D
Cornus alba L.	*Cornaceae*	Treelet	C
Cortaderia selloana (Schult. & Schult.f.) Asch. & Graebn.	*Poaceae*	Herbaceous	C, D, E
Cotoneaster franchetii Bois	*Rosaceae*	Bush	H
Cotoneaster horizontalis Decne.	*Rosaceae*	Bush	E, G, H
Cupressocyparis leylandii A.B.Jacks. & Dallim.) Garland & Gerry Moore	*Cupressaceae*	Tree	A, B, C, D, E, F, G, H
Cupressus arizonica (Greene) Bartel	*Cupressaceae*	Tree	A, E, G, H
Cupressus macrocarpa (Hartw.) Bartel	*Cupressaceae*	Tree	B, D, E, F, H
Cycas revoluta Thunb.	*Cycadaceae*	Treelet	A, B, C, D, H
Elaeagnus angustifolia L.	*Elaeagnaceae*	Tree	B, C
Euonymus japonicus Thunb.	*Celastraceae*	Bush	C, E, H
Euryops pectinatus (L.) Cass.	*Asteraceae*	Bush	B, D, E
Festuca arundinaceaVill.	*Poaceae*	Ground Cover	A, B, C, D, E, F, G, H
Festuca rubra L.	*Poaceae*	Ground Cover	A, B, C, D, E, F, G, H
Ficus carica L.	*Moraceae*	Tree	F
Fraxinus excelsior L.	*Oleaceae*	Tree	E
Forsythia × *intermedia* Zabel	*Oleaceae*	Bush	C
Gaura lindheimeri (Engelm. & A.Gray) W.L.Wagner & Hoch	*Onagraceae*	Bush	C
Hedera helix L.	*Araliaceae*	Climber	E, G
Jacobaea maritima (L.) Pelser & Meijden	*Asteraceae*	Bush	F
Juglans regia L.	*Juglandaceae*	Tree	D, E
Juniperus horizontalis Moench	*Cupressaceae*	Treelet	A, B, F
Juniperus sabina L.	*Cupressaceae*	Treelet	C, D, E, H
Koelreuteria paniculata Laxm.	*Sapindaceae*	Tree	C
Lavandula angustifolia L.	*Lamiaceae*	Bush	A, D, E
Ligustrum ovalifolium Hassk.	*Oleaceae*	Treelet	C, H
Ligustrum vulgare L.	*Oleaceae*	Treelet	B, E, H

Table 2. Continued

Liquidambar orientalis Mill.	*Altingiaceae*	Tree	C, E
Lolium perenne L.	*Poaceae*	Ground Cover	A, B, C, D, E, F, G, H
Lonicera japonica Thunb.	*Caprifoliaceae*	Climber	E
Magnolia grandiflora L.	*Magnoliaceae*	Tree	D, E
Malus floribunda Siebold ex Van Houtte	*Rosaceae*	Treelet	D
Melia azedarach L.	*Meliaceae*	Tree	C, E
Mirabilis jalapa L.	*Nyctaginaceae*	Herbaceous	D, G
Morus alba L.	*Moraceae*	Tree	E, G
Morus nigra L. var. pendula	*Moraceae*	Treelet	A, C, D, E
Nandina domestica Thunb.	*Berberidaceae*	Bush	C, E
Nerium oleander L.	*Apocynaceae*	Treelet	D, E, F, G
Olea europaea L.	*Oleaceae*	Tree	A, B, C, E, G
Parthenocissus quinquefolia (L.) Planch.	*Vitaceae*	Climber	B
Pennisetum alopecuroides (L.) Spreng.	*Poaceae*	Herbaceous	C, D
Phoenix canariensis H.Wildpret	*Arecaceae*	Tree	A, C, D, E, H
Photinia x *fraseri* Dress	*Rosaceae*	Bush	C, E
Phyllostachys aurea (André) Rivière & C.Rivière	*Poaceae*	Bush	C
Pinus brutia Ten.	*Pinaceae*	Tree	E, F, G, H
Pinus pinea L.	*Pinaceae*	Tree	E, F, G, H
Pistacia lentiscus L.	*Anacardiaceae*	Treelet	G
Pittosporum tobira (Thunb.) W.T.Aiton	*Pittosporaceae*	Bush	B, C, G, H
Platanus orientalis L.	*Platanaceae*	Tree	A, B, C, D, E, F, G, H
Platycladus orientalis (L.) Franco	*Cupressaceae*	Treelet	A, C, D, E, F, G, H
Poa pratensis L.	*Poaceae*	Ground Cover	A, B, C, D, E, F, G, H
Populus alba L.	*Salicaceae*	Tree	D, E
Pyracantha coccinea M.Roem.	*Rosaceae*	Bush	H
Quercus cerris L.	*Fagaceae*	Tree	G
Robinia pseudoacacia L.	*Fabaceae*	Tree	B, D, F, G
Rosa semperflorens W.M.Curtis	*Rosaceae*	Bush	E, F
Rosmarinus officinalis L.	*Lamiaceae*	Bush	A, B
Ruscus aculeatus L.	*Asparagaceae*	Bush	B, D
Salix babylonica L.	*Salicaceae*	Tree	C, E
Santolina chamaecyparissus L.	*Asteraceae*	Herbaceous	C
Schinus molle L.	*Anacardiaceae*	Tree	F, G
Styphnolobium japonicum (L.) Schott	*Fabaceae*	Tree	E
Tagetes erecta L.	*Asteraceae*	Herbaceous	E, F, G
Viburnum opulus L.	*Viburnaceae*	Bush	A, E, F, G, H
Viburnum tinus L.	*Viburnaceae*	Bush	A, E, F, G, H
Vitex agnus-castus L.	*Lamiaceae*	Treelet	G
Washingtonia filifera (Rafarin) H.Wendl. ex de Bary	*Arecaceae*	Tree	A, B, C, D, H
Washingtonia robusta (H.Wendl.) Parish	*Arecaceae*	Tree	A, B, C, D, H
Yucca filamentosa L.	*Asparagaceae*	Treelet	A, B, C, D, H

Table 3. Plant species with bioaccumulator and phytoremediation properties identified in the study areas, the heavy metals they accumulate, and the organs where they accumulate heavy metals

Plant Species	Organs That Accumulate Heavy Metals	Heavy Metals Accumulated	Reference
Acacia dealbata	Roots	Cu	[14]
Acer platanoides	Leaves	Ba ve Fe	[15]
Ailanthus altissima	Leaves	Pb ve Cd	[16]
Atriplex halimus	Roots and Leaves	Cd, Sr, Zn ve Cu	[17]
Berberis thunbergii	Leaves and Branches	Cu, Ni, Pb, Cd, Ca ve Mn	[18]
Bougainvillea spectabilis	Leaves, Stems and Roots	Cd	[19]
Buxus sempervirens	Leaves and Branches	Cu, Ni, Pb, Cd, Ca ve Mn	[18]
Casuarina equisetifolia	Roots	Pb, Fe ve Zn	[20]
Elaeagnus angustifolia	Leaves	Ni, Fe, Mn, Cu ve Zn	[21]
Euonymus japonicus	Leaves and Branches	Cu, Ni, Pb, Cd, Ca ve Mn	[22]
Juniperus sabina	Leaves and Branches	Cu, Ni, Pb, Cd, Ca ve Mn	[23]
Ligustrum ovalifolium	Leaves	Zn, Cr, Cd, Co, Ni, Pb ve Cu	[22]
Ligustrum vulgare	Leaves and Branches	Cu, Ni, Pb, Cd, Ca ve Mn	[24]
Melia azedarach	Leaves, Roots and Stem Bark	Pb, Zn ve Cu	[16]
Nerium oleander	Leaves	Pb, Cd ve Ni	[25]
Olea europaea	Leaves and Fruits	Cd ve Pb	[25]
Photinia x fraserii	Roots	Zn	[26]
Pittosporum tobira	Leaves	Cu, Ni, Pb ve Zn	[27]
Platanus orientalis	Leaves	Pb ve Cd	[23]
Pyracantha coccinea	Seeds, Branches, and Leaves	Pb ve Cd	[25]
Robinia pseudoacacia	Stem Bark	Pb, Zn ve Cd	[28]
Rosmarinus officinalis	Leaves	Ni, Pb ve Cd	[29]
Salix babylonica	Leaves	Cd, Ni ve Pb	[30]
Tagetes erecta	Leaves	Zn, Cu, Pb ve Cd	[31]
Viburnum tinus	Roots	Zn	[27]

Based on the data presented in Table 2 and Table 3, the number and proportional distribution of plant species reported to have bioaccumulator and phytoremediation potential in recreational areas within the total plant species diversity per area are shown in Table 4.

Table 4. Distribution of plant species reported in the literature to have bioaccumulation and phytoremediation potential in recreation areas, based on area and total identified plant species

Area	Total Number of Plant Species in the Area	Number of Bioaccumulator or Phytoremediation Effective Plant Species in the Area	Ratio (%)
A	28	7	25.00
B	28	11	39.29
C	42	14	33.33
D	31	5	16.13
E	51	17	33.33
F	26	9	34.62
G	30	10	33.33
H	31	10	32.26

The number of plant species reported in the literature to have bioaccumulation and phytoremediation potential in the study areas, as well as the surface area covered by these species, is also quite important. The proportion of such species alone may not fully reflect their actual ecological representation within the area. Even if the proportion of potential bioaccumulator and phytoremediation species is high, the environmental relevance may remain quantitatively limited if their population size is small. Conversely, ecological functionality can be enhanced when a larger number of individuals of these species are present, even if species' richness is lower. Therefore, assessments based on species number, when considered together with individual counts and area size, provide a more comprehensive view of the

potential ecological contribution of these species. The surface measurements of the study areas, the total plant population, and the population of species reported to have bioaccumulation and phytoremediation potential in each area, along with their representation ratio, are specified in Table 5.

Table 5. Number of plant species reported in the literature to have bioaccumulation and phytoremediation potential

Research Area	Surface Area (m²)	Total Number of Plants in the Area (Units)	Bioaccumulator and Phytoremediation Species Found in the Area	Number of Plants (Units)	Population Representation Ratio (%)
Area A	13905	1656	*Acacia dealbata*	14	21.68
			Atriplex halimus	65	
			Buxus sempervirens	150	
			Olea europaea	7	
			Platanus orientalis	33	
			Rosmarinus officinalis	70	
			Viburnum tinus	20	
Area B	9165	492	*Acacia dealbata*	7	77.03
			Atriplex halimus	12	
			Bougainvillea spectabilis	6	
			Buxus sempervirens	120	
			Elaeagnus angustifolia	2	
			Ligustrum vulgare	12	
			Olea europaea	20	
			Pittosporum tobira	154	
			Platanus orientalis	20	
			Robinia pseudoacacia	6	
			Rosmarinus officinalis	20	
Area C	65213	4466	*Acer platanoides*	192	45.50
			Atriplex halimus	28	
			Berberis thunbergii	160	
			Buxus sempervirens	280	
			Elaeagnus angustifolia	19	
			Euonymus japonicus	300	
			Juniperus sabina	25	
			Ligustrum ovalifolium	6	
			Melia azedarach	21	
			Olea europaea	67	
			Photinia x fraserii	400	
			Pittosporum tobira	500	
			Platanus orientalis	20	
			Salix babylonica	14	
Area D	53775	273	*Atriplex halimus*	5	30.77
			Juniperus sabina	24	
			Nerium oleander	16	
			Platanus orientalis	3	
			Robinia pseudoacacia	36	
Area E	71715	3248	*Acer platanoides*	14	48.95
			Ailanthus altissima	20	
			Berberis thunbergii	170	
			Bougainvillea spectabilis	2	
			Buxus sempervirens	72	
			Casuarina equisetifolia	12	
			Euonymus japonicus	250	
			Juniperus sabina	20	
			Ligustrum vulgare	14	
			Melia azedarach	6	
			Nerium oleander	151	
			Olea europaea	80	
			Photinia x fraserii	400	
			Platanus orientalis	20	
			Salix babylonica	2	
			Tagetes erecta	300	

Table 5. Continued

			Viburnum tinus	57	
Area F	33229	369	*Ailanthus altissima*	12	56.37
			Berberis thunbergii	36	
			Buxus sempervirens	72	
			Casuarina equisetifolia	6	
			Nerium oleander	6	
			Platanus orientalis	14	
			Robinia pseudoacacia	20	
			Tagetes erecta	30	
			Viburnum tinus	12	
Area G	2100	141	*Acer platanoides*	1	60.28
			Ailanthus altissima	7	
			Casuarina equisetifolia	1	
			Nerium oleander	3	
			Olea europaea	1	
			Pittosporum tobira	25	
			Platanus orientalis	2	
			Robinia pseudoacacia	5	
			Tagetes erecta	30	
			Viburnum tinus	10	
Area H	8000	320	*Acer platanoides*	16	71.87
			Berberis thunbergii	30	
			Euonymus japonicus	70	
			Juniperus sabina	6	
			Ligustrum ovalifolium	4	
			Ligustrum vulgare	2	
			Pittosporum tobira	30	
			Platanus orientalis	2	
			Pyracantha coccinea	50	
			Viburnum tinus	20	

The data presented in Table 5 indicates that evaluating the representation of plant species reported in the literature to have bioaccumulation and phytoremediation potential based solely on species diversity ratios may be insufficient. For example, in Area H, although the proportion of such species is 32.26%, their individuals constitute 71.87% of the area's total plant population. Similarly, in Area G, the species diversity ratio is 33.33%, while their population representation reaches 60.28%. This situation shows that, even when the diversity ratio is moderate rather than very low, these species can dominate the plant composition of the area due to their high population representation. Therefore, considering both species number and individual representation provides a more comprehensive view of their potential ecological contribution. In contrast, in some areas, the difference between species diversity ratio and population representation is more limited. For example, in Area A, the diversity ratio of bioaccumulator and phytoremediation effective species is 25%, while population representation is 21.68%. In Area C, these values are 33.33% and 45.50%, respectively; in Area D, 16.13% and 30.77%; in Area E, 33.33% and 48.95%; and in Area F, 34.62% and 56.37%. The data in Table 5 shows differences between species diversity ratios and population-based representation of plant species reported in the literature to have bioaccumulation and phytoremediation potential. For example, in Area H, the proportion of such species is 32.26%, while their individuals constitute 71.87% of the total plant population. Similarly, in Area G, the species diversity ratio is 33.33%, whereas their population representation reaches 60.28%. These results indicate that population-based representation values may differ substantially from species-based ratios.

To enable a more accurate interpretation of the findings presented in Table 4 and Table 5 and to understand the distribution of effective plants for phytoremediation within the study areas, the locations of recreational areas relative to heavy industrial centers in the region must also be taken into account. In this context, the spatial locations of the study areas relative to the PETKİM/SOCAR Refinery, Aliağa Port, and Aliağa Organized Industrial Zones were considered an important evaluation criterion. These industrial facilities are areas where intensive industrial activities are carried out in the region and are considered potential sources of environmental pollutant dispersion. Therefore, the location of recreational areas relative to these industrial zones contributes to a more ecologically meaningful interpretation of the use of plants with bioaccumulator and phytoremediation potential. The location of the study areas relative to heavy industrial zones is shown in Figure 2.

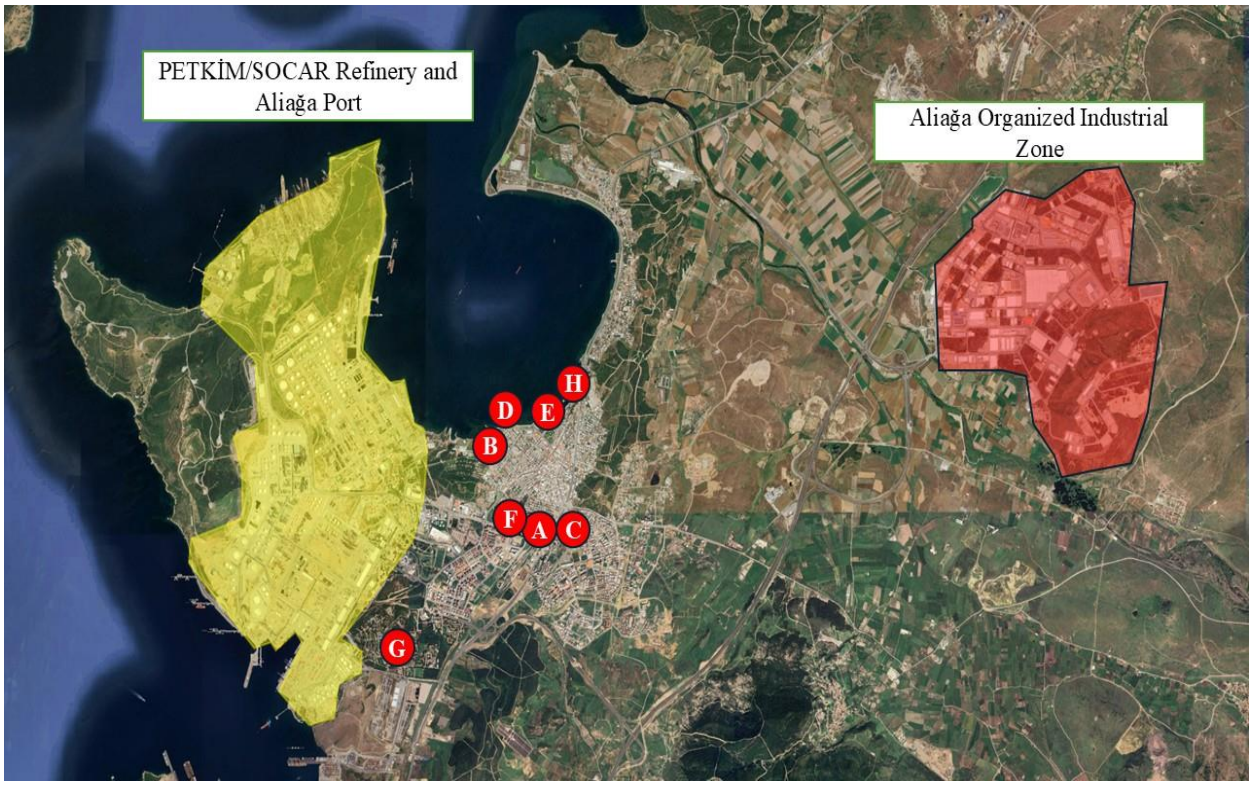


Figure 2. Locations of study areas relative to heavy industrial zones [12]

Figure 2 shows the spatial relationship between the study areas and the main heavy industry hubs in Aliağa, namely the PETKİM/SOCAR Refinery, Aliağa Port, and Aliağa Organized Industrial Zone. Most of the study areas are located within the urban settlement fabric close to the refinery and port area. Table 5 indicates that in some areas located relatively closer to industrial activities, the population representation rates of plant species reported in the literature to have bioaccumulation and phytoremediation potential exceed 50%, and in certain cases approach 80%. In contrast, species diversity ratios remain lower in some areas, indicating that a limited number of species are represented by a relatively high number of individuals.

The distribution of effective plants for biocumulation and phytoremediation according to their life forms has also been evaluated. Within this scope, the distribution of all plant species identified in the study areas according to their life form was compared with the life form distribution of species with bioaccumulator and phytoremediation potential. This comparison aims to reveal the general plant composition in the study areas and the life forms in which species with environmental remediation potential are concentrated (Table 6).

Table 6. Comparison of the distribution of all plant species identified in recreation areas, as well as bioaccumulator and phytoremediation effective plant species, according to their life form

Life Form	All Plant Species (%)	Plant Species with Bioaccumulator/Phytoremediation Effects (%)
Tree	40.70	40
Treelet	16.28	16
Bush	27.91	36
Climber	5.81	4
Herbaceous	4.65	4
Ground Cover	4.65	0

When examining the comparative distribution presented in Table 6, a clear structural parallelism is observed between the overall life form composition in recreational areas and the life form distribution of species effective for biocumulation or phytoremediation. While the tree form represents 40.70% of the total species composition, this rate is determined as 40% among species effective for bioaccumulation or phytoremediation. Similarly, while the bush form accounts for 27.91% of the total species, this rate reaches 36% among species with potential environmental improvement capacity. In the Treelet form, the ratios are seen to be quite close to each other (16.28%). In contrast, it was found that herbaceous and climbing-creeping species are represented at a limited level in both groups, while no ground cover species identified in the study areas were listed among the species reported in the literature to have bioaccumulation or phytoremediation potential. These findings reveal that the existing plant composition in the study

areas offers potential ecological improvement capacity, particularly through woody species, but that environmental functionality remains relatively limited in understory vegetation. The dominance of the tree form in the life form distribution of particularly bioaccumulative and species reported in the literature to have bioaccumulation and phytoremediation potential can be attributed to these plants having large leaf surfaces, being long-lived, and having the capacity to accumulate heavy metals from air and soil sources in both their leaves and woody tissues. Considering these characteristics, the high representation of tree-form plants in recreational areas in cities with intensive industrial activities and high environmental pollution pressure, such as Aliağa, can be considered a positive situation in terms of environmental improvement potential.

The distribution of plant organs in which heavy metal accumulation occurs in bioaccumulator, and species reported in the literature to have bioaccumulation and phytoremediation potential is presented in Figure 3. Based on the reported heavy metal accumulation organs for bioaccumulator and phytoremediation-effective plants, the distribution among organs was examined based on frequency (number). The main reason for this is that many plant species can accumulate heavy metals in more than one organ. According to the findings, heavy metal accumulation is most commonly found in leaf tissue (20). Leaves are followed by root (7) and stem (6) tissues. Accumulation in bark (2), stem (1), fruit (1), and seed (1) tissues have been reported for a more limited number of species. The results reveal that bioaccumulator and phytoremediation-effective plants can accumulate heavy metals in multiple organs, but according to the literature, the most frequently reported organ of accumulation is leaves. This may be related to the large surface area of leaves, their direct exposure to atmospheric pollutants, and their particle retention capacity [32].

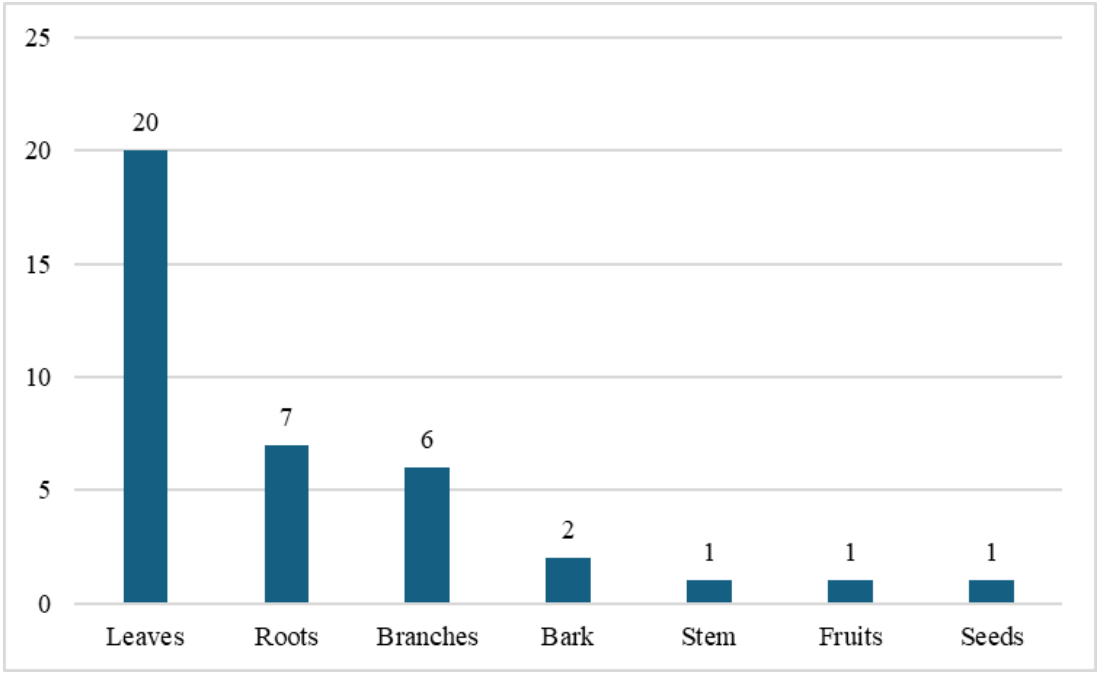


Figure 3. Distribution of heavy metal accumulation by organ (number) in plant species reported in the literature to have bioaccumulation and phytoremediation potential

It has been observed that the plant compositions in the recreational areas of Aliağa city center exhibit varying levels of ecological representation. The findings reveal that a high total number of plant species alone does not reflect the representation level of species reported in the literature to have bioaccumulation and phytoremediation potential. Table 5 shows that in some areas, the population representation rates of these species exceed 50%, and in certain cases approach 80%, while species diversity ratios remain lower.

Previous studies conducted in Aliağa and its surroundings have reported that heavy metals such as Ni, Pb, Cr, and Cd are found at levels close to or approaching limit values in soils, especially in areas with intensive industrial and transportation activities, while heavy metal accumulation in plants mostly occurs in leaf tissue [33]. This finding is consistent with the frequent reporting of heavy metal accumulation in leaf tissue in our study, suggesting that leaves play an important role as biomonitoring tools and early indicators of environmental pressures in urban areas. However, the accumulations observed in roots, branches, and other woody tissues indicate that phytoremediation processes involve multidimensional soil–plant interactions. In this context, consciously choosing species with high bioaccumulator and phytoremediation potential in the botanical design of recreational green spaces, rather than focusing solely on aesthetic and usage criteria, may be an important strategy for supporting environmental quality in industrially pressured urban areas.

4. Conclusions and discussion

It has been determined that the plant species found in urban recreation areas in Aliağa district do not show a homogeneous distribution within the study areas in terms of their bioaccumulator and phytoremediation potential. The findings indicate that a high total number of species alone does not reflect environmental improvement capacity; this capacity is largely related to the representation ratio and functional characteristics of species reported in the literature to have bioaccumulation and phytoremediation potential within the area. Furthermore, heavy metal accumulation in such plants has been reported to occur in multiple organs, with leaf tissue being the most frequently documented accumulation site.

Previous research in Aliağa and its surroundings has shown that heavy metals such as Ni, Pb, Cr, and Cd are present in soils at levels close to or approaching limit values, particularly in areas with intensive industrial and transportation activities [33]. Our findings, which highlight the frequent reporting of accumulation in leaf tissue, are consistent with these studies and support the role of leaves as biomonitoring tools. However, the observed accumulations in roots, branches, and woody tissues indicate that phytoremediation processes involve multidimensional soil–plant interactions rather than being limited to superficial mechanisms.

The heterogeneous distribution of species with bioaccumulation and phytoremediation potential among the study areas may be explained by several factors:

- Industrial pressure: Proximity to refinery, port, and industrial zones likely influences planting choices and ecological responses.
- Transportation activities: High-traffic corridors contribute to localized heavy metal deposition, affecting species' composition.
- Ecological functionality: Recreational areas may prioritize certain species for buffering and stabilization functions, leading to uneven representation.

To improve readability, Aliağa-specific and general recommendations are consolidated below:

- Species selection: Priority should be given to species with documented bioaccumulator and phytoremediation potential, alongside aesthetic and usage criteria.
- Tree preservation: Existing tree and treelet species should be preserved, and new plantings should emphasize species with literature-reported bioaccumulator properties.
- Monitoring: Periodic monitoring of species accumulating heavy metals in leaf tissue should be conducted to track temporal changes in environmental pressures.
- Soil stabilization: Increasing the use of species capable of accumulating in roots and woody tissues can contribute to heavy metal stabilization in soils.
- Integrated planning: Plant design decisions should be addressed holistically, considering environmental risk maps and pollution potential.

This study serves as a preliminary assessment based on literature data rather than direct experimental analysis. The absence of controlled sampling and laboratory measurements limits the ability to quantify heavy metal concentrations in plant tissues. Future research should include experimental studies to directly determine accumulation levels in different plant organs, thereby enabling a more concrete evaluation of phytoremediation capacity. In this respect, the current study provides a preliminary framework and guide for subsequent experimental and monitoring-based research.

Artificial Intelligence Statement
(X) This article did not use artificial intelligence.
( ) This article does use artificial intelligence.

Conflicts of interest: No Conflict of Interest

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Data Availability Statement
( ) Option A (Public Repository): "The research data supporting this study are publicly available in [Name of Repository: e.g., Zenodo, Figshare, Dryad] with the permanent DOI link [URL/DOI]."
(**X**) Option B (Upon Request): "The raw data supporting the findings of this study are available from the corresponding author [Author Initials] upon reasonable request and within ethical boundaries."

( ) Option C (Third-Party Data): "The data used in this study were obtained from [Name of Institution/Source] and are subject to third-party restrictions regarding redistribution."
( ) Option D (No Data): "No new data were created or analysed in this study. Data sharing is not applicable to this article."

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