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Research Article

Screening Native Plant Species for Hyperaccumulation and Phytoremediation of Chromium in Mardan Industrial Estate, Pakistan

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ABSTRACT

Industrial estates are key drivers of economic development but often contribute to environmental degradation through heavy metal contamination. This study evaluates industrial composition in the Mardan Industrial Estate and assesses chromium (Cr) accumulation in soils and associated plant species to understand contamination status and phytoremediation potential. Results showed that the estate comprises 181 registered industrial units, of which 121 are operational. The marble industry exhibited the highest production output (55-65 tons/day), followed by iron and steel, and chipboard/Formica industries, indicating their dominant contribution to industrial activity. Cr, particularly hexavalent Cr, was identified as a highly toxic contaminant exceeding permissible limits (0.5 mg/kg). Soil Cr concentrations ranged from 8.89 to 402.9 mg/kg, while plant roots and shoots accumulated 30.73-800.2 mg/kg and 0.784-765.8 mg/kg, respectively, indicating significant bioaccumulation and transfer into plant tissues. Based on bio-concentration, translocation, and accumulation indices, 29 species were classified as phytoextractors, 16 as phytostabilizers, and 5 as excluders. Strong accumulators included *Sisymbrium officinale*, *Melilotus indicus*, and *Melia azedarach*. Multivariate analyses (PCA and correlation heatmaps) explained up to 93.96% of variance, revealing distinct clustering patterns associated with Cr uptake, root-shoot translocation, and soil contamination gradients. The findings demonstrate severe chromium contamination in industrial soils of Mardan, with substantial uptake in diverse plant species. Several species show strong phytoremediation potential, highlighting their usefulness in environmental cleanup strategies, while also indicating potential risks of Cr entry into the food chain.

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Introduction

Soil contamination by heavy metals is a serious environmental problem with profound implications for food safety, human health, and crop productivity. In agricultural lands, these contaminants pose risks to the nutritional quality of food, crop production, and overall agronomic sustainability. A holistic strategy is required to address this problem, including proper waste disposal, adoption of green farming practices, and continuous monitoring to safeguard food resources while protecting ecosystems and public welfare (Vasilachi et al., 2023).

As vegetables constitute a vital component of the human diet, their contamination with heavy metals (HMs) cannot be overlooked. Vegetables are rich sources of antioxidants, minerals, vitamins, and dietary fiber; however, the presence of elevated concentrations of heavy metals leads to adverse health effects by disrupting normal biological functions. The accumulation of heavy metals in soil plays a critical role in determining their uptake by plants. It is well established that higher concentrations of heavy metals in soil enhance their absorption by plants. However, the solubility and bioavailability of heavy metal ions are influenced by several factors; including soil physical and chemical properties, pH, and clay content (Fazil et al., 2023).

Chromium (Cr) is a naturally occurring heavy metal and ranks as the seventeenth most abundant element in the Earth's crust. At elevated concentrations, it becomes a significant environmental pollutant, although trace amounts are essential for some organisms. Chromium is released into ecosystems, including air, water, and soil, through both anthropogenic activities and natural processes, leading to widespread environmental contamination. This toxic element can enter the food chain and adversely affect all living organisms directly or indirectly through the contamination of agricultural soils and drinking water (Khatua and Dey, 2023).

Various industries, including electroplating, paint manufacturing, steel production, dyeing, wood preservation, leather tanning, metal processing, timber, and pulp and paper industries, contribute significantly to chromium emissions. Additional sources include tobacco smoke and leachates from improperly managed sanitary landfills. Chromium can also enter water resources through natural leaching processes. It is further utilized in cooling tower water treatment, nuclear research, magnetic tape production, photographic chemicals,

photocopier toners, and drilling muds. Anti-corrosion treatments and water purification processes also contribute to elevated chromium levels in water. Moreover, combustion of coal, tobacco smoking, and effluents from chromium-based automotive catalytic converters ultimately lead to its accumulation in soil (Sajad et al., 2020).

Elevated levels of chromium significantly affect numerous morphological and biochemical traits in plants, including reduced seed germination, decreased biomass, impaired photosynthetic activity, root damage, and overall inhibition of plant growth and development, ultimately leading to plant death. Interactions between chromium and essential nutrients can disrupt nutrient uptake in plants, particularly ions such as Mg^{2+} and Ca^{2+} , due to competitive interactions in the soil matrix. Furthermore, agricultural lands with high chromium contamination exhibit reduced crop productivity (Zulfiqar et al., 2023).

Chromium is a highly reactive metal and readily reacts with atmospheric oxygen. It exists in several oxidation states ranging from 0 to +6, with trivalent chromium [Cr(III)] and hexavalent chromium [Cr(VI)] being the most stable forms in nature. Cr(VI) is considerably more toxic than Cr(III) due to its higher solubility, mobility, and bioavailability in aqueous environments (Bhalerao and Sharma, 2015). Trivalent chromium (Cr(III)) is relatively less toxic and less mobile compared to hexavalent chromium (Cr(VI)), which is highly toxic, soluble, and environmentally mobile, posing severe ecological and human health risks. Both Cr(III) and Cr(VI) are taken up by plants through sulfate transporters. Moreover, the presence of organic acids in plant roots enhances chromium solubilization, thereby facilitating its uptake by plants (Srivastava et al., 2021).

Various strategies have been employed for chromium removal from contaminated environments; however, there is a growing need for sustainable, eco-friendly, and cost-effective technologies for chromium remediation from soil and wastewater as alternatives to conventional physicochemical methods. Phytoremediation is an economical and environmentally friendly plant-based approach for the removal of toxic chromium from contaminated soil and water. A comprehensive understanding of chromium behavior in the soil-water-plant system and its accumulation in plants is essential to enhance the efficiency of chromium remediation (Mohanty and Patra, 2023). This approach utilizes hyperaccumulator plant species that exhibit high

tolerance to heavy metals. In this method, green plants are employed for the removal, degradation, and detoxification of toxic metals (Bhat et al., 2022).

Thus, the present study aims to achieve the following objectives: (i) to assess chromium levels and explore effective approaches to mitigate its environmental impact; (ii) to quantify chromium concentrations in water and soil, as well as its transport and accumulation in plants; (iii) to evaluate the uptake potential of Cr in selected plants by calculating the bioconcentration factor (BCF); and (iv) to investigate the translocation of accumulated Cr from roots to shoots by determining the translocation factor (TF).

Materials and Methods

Research site location

The study area was located in district Mardan, Pakistan, between 34°05'N–34°32'N latitude and 71°48'E–72°25'E longitude, covering approximately 1,630 km². The district is bordered by Buner and Malakand Protected Areas in the north, Nowshera in the south, Swabi in the east, and Charsadda in the west. The Mardan Industrial Estate, established in the late 1970s, is a major industrial hub in the region (Khan et al., 2018; Ibrahim et al., 2019; Rashid et al., 2021, Hanif et al., 2025).

Sample collection, identification, and assessment

Plant, soil, and effluent samples were collected from multiple industrial units, including steel, marble, beverage, match, pipe, aluminum, pharmaceutical, and ghee industries within the Mardan Industrial Estate, Khyber Pakhtunkhwa (KPK), Pakistan. Sampling was performed in triplicate at each site with spatial replication across the industrial estate. Temporal sampling was conducted once during the dry season (2021) to minimize seasonal variability.

Soil samples were collected from the rhizosphere (root-bound area) of each plant and stored in clean polythene bags. Background chromium (Cr) concentrations in soil were also determined. Plant species were identified according to the Flora of Pakistan (Ralph, 1939; Ali, 1978; Nüsser, 1998; Dickoré and Nüsser, 2000). Plant samples were air-dried in shade for one week and subsequently oven-dried at 105°C for 24 h. Dried samples were ground using a mortar and pestle. The powdered material was digested with concentrated nitric acid (HNO₃), diluted appropriately, and analyzed for Cr concentration. Data were categorized using both primary (field and laboratory analysis) and secondary sources obtained from relevant government

departments overseeing industrial estates (Sajad et al., 2020; Fazil et al., 2023).

Collection of effluent samples

Wastewater samples were collected from discharge outlets of selected industrial units within the estate using pre-cleaned 0.5 L polyethylene bottles. Bottles were washed with metal-free detergent, rinsed with 10% HNO₃, and subsequently washed with double-deionized water to prevent contamination. A total of 30 effluent samples were collected.

In situ measurements of pH and electrical conductivity (EC) were recorded at the time of sampling. Samples were transported to the laboratory and preserved by adding 1 mL of concentrated HNO₃ to inhibit microbial activity. Samples were stored at room temperature until analysis. Chromium concentration was determined using atomic absorption spectrophotometry (Fazil et al., 2023).

Determination of soil pH and electrical conductivity (EC)

Soil samples were collected using a soil auger from a depth of up to 30 cm. Samples were air-dried, homogenized, and passed through a 2 mm sieve to remove stones and coarse root fragments. Soil pH was determined using a calibrated pH meter (Khan et al., 2017). For EC analysis, soil was saturated with distilled water, filtered, and electrical conductivity was measured using an EC meter (Iqbal, 2018).

Determination of Cr concentration in soil

Soil Cr concentration was determined following the method of Shriadah (1999). A 5 g soil sample was placed in a 100 mL beaker, and 3 mL of 30% H₂O₂ was added. The mixture was left to stand for 1 h until the reaction subsided. Subsequently, 75 mL of 0.5 M HCl was added, and the mixture was heated on a hot plate for 2 h. The digest was filtered through Whatman filter paper, and the filtrate was analyzed for Cr content using atomic absorption spectrophotometry (AAS). All analyses were performed in triplicate, and results are expressed as mean values (mg/kg).

Determination of Cr accumulation in plant samples

Plant samples were thoroughly washed with tap water followed by distilled water to remove adhered soil particles. Samples were then oven-dried at 105°C for 24 h. Digestion was carried out following Awofolu (2005). A 0.5 g subsample was placed in a 100 mL beaker, and 5 mL of 65% HNO₃ and 2 mL of HClO₄ were added. The mixture was heated on a hot plate until a clear digest was obtained. After cooling, the digest was filtered and transferred to a 50 mL volumetric flask and diluted to

volume with distilled water.

Quality assurance and quality control (QA/QC)

Quality assurance and quality control procedures were strictly followed throughout the analytical process. Certified reference materials (CRMs) were used for calibration of the atomic absorption spectrophotometer. Reagent blanks were included after every 10 samples to monitor contamination. All analyses were conducted in triplicate, and precision was ensured by maintaining a relative standard deviation (RSD) of less than 5%.

Plant species were classified as Cr hyperaccumulators based on established criteria, including a bio-concentration factor (BCF) > 1 and shoot Cr concentrations exceeding 1,000 mg/kg dry weight. In highly contaminated sites, species exhibiting a translocation factor (TF) > 1 along with elevated tissue Cr concentrations relative to rhizosphere soil were also considered potential hyperaccumulators.

Bio-concentration and translocation factors

The bio-concentration factor (BCF) indicates the ability of plants to accumulate heavy metals from soil into their tissues and was calculated as:

$$BCF = \frac{C_p}{C_s}$$

Where C_p is the metal concentration in plant tissues and C_s is the metal concentration in soil (Aziz et al., 2023).

The translocation factor (TF) represents the ability of plants to translocate metals from roots to shoots and was calculated as:

$$TF = \frac{C_{shoots}}{C_{roots}}$$

Where C_{shoots} and C_{roots} represent metal concentrations in shoots and roots, respectively (Wu et al., 2024). These indices were used to evaluate the phytoextraction potential of the studied plant species for chromium.

Statistical analysis

Multivariate statistical analysis was performed using OriginPro 2024b (Academic version). Pearson correlation analysis was conducted to assess relationships among soil pH, electrical conductivity (EC), and plant bio-concentration factor (BCF). Principal Component Analysis (PCA) was applied to identify underlying patterns in the dataset and to better understand the relationships among variables. PCA is a widely used multivariate statistical technique that reduces a large set of correlated variables into a smaller number of principal components, which collectively explain most of the total variance (Jolliffe, 2002; Khan et al., 2025).

Results

Major industrial groups and production capacities in Mardan industrial estate

Table 1 summarizes the industrial composition, operational status, and average daily production capacities of industries located in the Mardan Industrial Estate. A total of 181 industrial units are registered within the estate, of which 121 are currently operational.

The pharmaceutical sector represents the largest industrial group, comprising 30 registered units, with 19 currently in operation and an average production capacity of 3-4 tons per day. The marble industry consists of 29 units, of which 25 are operational, and has the highest production volume, with an estimated output of 55-65 tons of processed marble per day. The furniture manufacturing sector includes 25 units, with 15 currently operational; however, production varies considerably depending on product specifications, market demand, and customized orders.

The food processing industry comprises 23 units, of which 13 are functional, producing approximately 5-6 tons of products per day. The match industry includes 17 registered units, with 15 operational, each producing approximately 10-12 tons per day. The beverage and juice sector consists of eight units, five of which are currently operational, with an average daily production of approximately 13 tons.

The chipboard and Formica manufacturing sector comprises seven units, six of which are operational, producing approximately 25-30 tons per day. The iron and steel industry includes seven registered units, with six currently operating and generating an average output of about 50 tons per day. Similarly, the aluminum industry consists of five registered units, of which two are operational, with an estimated production capacity of 10-12 tons per day.

Overall, the marble, iron and steel, and chipboard/Formica industries contribute the largest share of daily industrial output within the Mardan Industrial Estate, reflecting their substantial production capacities and operational activity.

Standard limits and toxicological effects of Cr

Cr, particularly in its hexavalent form (Cr^{6+}), is recognized as a hazardous environmental pollutant due to its strong carcinogenic potential and severe adverse health impacts. The U.S. Environmental Protection Agency (EPA) classifies hexavalent chromium as a probable human carcinogen. Acute exposure, especially via ingestion, may lead to

gastrointestinal irritation and food poisoning, whereas inhalation exposure has been associated with respiratory disorders and, in severe cases, mortality due to pulmonary complications (Langat, 2018; Yu et al., 2021; EPA, 2022).

It is important to note that the EPA-referenced regulatory threshold of 0.5 mg/kg in this study pertains specifically to Cr^{6+} , the most toxic and mobile chromium species. Although total chromium concentrations in soil are often higher, the levels reported in this study indicate potential environmental risk because a fraction of the total chromium may exist in bioavailable forms capable of plant uptake and entry into the food chain.

Due to these toxicological concerns, regulatory limits for chromium in environmental matrices have been established. The EPA has suggested a maximum allowable concentration of 0.5 mg/kg for chromium in soil, while the U.S. Food and Drug Administration (FDA) has set a permissible limit of 0.05 mg/L for chromium in drinking (bottled) water. These regulatory thresholds are essential for assessing contamination in industrial and agricultural environments and underscore the need for regular monitoring to mitigate health risks associated with chromium exposure (Table 2).

Chromium accumulation in soil and various plant species collected from industrial zones of Mardan

Considerable species-specific and spatial variability was observed in Cr concentrations in soils and plant tissues (roots and shoots) collected from 52 sites across the Hattar Industrial Estate (HIE), Mardan (Table 3). Table 3 presents the calculated bio-concentration factor ($\text{BCF} = \text{shoot Cr} / \text{soil Cr}$), translocation factor ($\text{TF} = \text{shoot Cr} / \text{root Cr}$), and bioaccumulation coefficient ($\text{BAC} = \text{root Cr} / \text{soil Cr}$) for 50 plant species, organized into three phytoremediation categories: hyperaccumulators/phytoextractors ($\text{BCF} > 1$ and $\text{TF} > 1$; $n = 29$ species), phytostabilizers ($\text{BCF} > 1$ and $\text{TF} \leq 1$; $n = 16$ species), and excluders ($\text{BCF} \leq 1$; $n = 5$ species). This classification helps to clearly distinguish phytoextracting species from those that restrict metal translocation, thereby facilitating targeted phytoremediation strategies.

Across all samples, soil Cr concentrations ranged from 8.89 to 402.9 mg/kg, substantially exceeding the maximum permissible limit of 0.5 mg/kg (EPA, 2022). Similarly, Cr concentrations in roots ranged from 30.73 to 800.2 mg/kg, while shoots contained 0.784 to 765.8 mg/kg, indicating pronounced bioaccumulation and, in several species, efficient translocation from roots to aerial parts.

Table 1. Major industrial groups in the Mardan industrial estate.

Sr. No.	Industry	Number	Functional	Production/ Industry/ day (tons)
1	Pharmaceutical	30	19	3-4
3	Marble	29	25	55-65
4	Furniture	25	15	Varies
5	Food	23	13	5-6
6	Match	17	15	10-12
7	Beverages/ Juices	8	5	13
8	Chipboard/Formica	7	6	25-30
9	Iron and Steel	7	6	50
10	Aluminum	5	2	10 -12

Table 2. Toxicological effects and permissible standards of Cr in environmental and food matrices.

Effects	Standards
• Carcinogen reported by Environmental Protection Agency • High doses results food poisoning and bronchitis • Cause, pulmonary disease, often fatal when expose to high concentrations	• Environmental Protection Agency: maximum concentration 0.5 mg/kg. • Food and Drugs Admin: Maximum limit of cadmium in bottled water: 0.05 mg/L

Table 3. Concentrations of Cr (mg/kg) in soil, roots, and shoots; bio-concentration factor (BCF), translocation factor (TF), and bioaccumulation coefficient (BAC) in 50 native plant species collected from the Mardan Industrial Estate, grouped by phytoremediation category.

Sr. No.	Category	Family	Species	C.P.	Name of Site	Soil (mg/kg)	Roots (mg/kg)	Shoots (mg/kg)	BCF	TF	BAC
Hyperaccumulator (BCF > 1, TF > 1)											
1	Hyperaccumulator	Asteraceae	<i>Parthenium hysterophorus</i> L.	2	HIE-ST-3 Iftikhar Eng. Works	20.28	292.2	310.8	15.33	1.06	14.41
2	Hyperaccumulator	Asteraceae	<i>Conyza canadensis</i> (L.) Cronquist.	4	HIE-ST-6 Sana Aluminum Indust.	36.35	39.36	399.9	11.0	10.16	1.08
3	Hyperaccumulator	Asteraceae	<i>Xanthium strumarium</i> L.	5	HIE-ST-4 FF Steel	40.5	417.2	456.1	11.26	1.09	10.3
4	Hyperaccumulator	Asteraceae	<i>Chrysanthemum indicum</i> L.	6	HIE-ST-10 Arco Industries	28.62	427.7	614.5	21.47	1.44	14.94
5	Hyperaccumulator	Asteraceae	<i>Artemisia vulgaris</i> L.	22	HIE-ST-5 Sohail Vegetable Ghee Mills	23.14	323.6	427.8	18.49	1.32	13.98
6	Hyperaccumulator	Amaranthaceae	<i>Amaranthus retroflexus</i> L.	8	HIE-ST-10 Asim Match Ind. Pvt Ltd	21.49	310.3	325.2	15.13	1.05	14.44
7	Hyperaccumulator	Amaranthaceae	<i>Chenopodium album</i> L.	9	HIE-ST-5 Stanley Pharma	24.71	301.3	521.5	21.1	1.73	12.19
8	Hyperaccumulator	Amaranthaceae	<i>Chenopodium murale</i> L.	11	HIE-ST-12 Tri Star Adhesive Pro.	354.1	553.8	724.8	2.05	1.31	1.56
9	Hyperaccumulator	Brassicaceae	<i>Thlaspi arvense</i> L.	12	HIE-ST-5 Roryan Pharmaceutical Ind.	246.1	31.3	524.1	2.13	16.74	0.13
10	Hyperaccumulator	Brassicaceae	<i>Lipidium didimum</i> L.	13	HIE-ST-6 Silve Stone United Rubber Ind.	228.7	370.1	421.5	1.84	1.14	1.62
11	Hyperaccumulator	Caryophyllaceae	<i>Stellaria media</i> (L.) Vill.	16	HIE-ST-9 Deluce Food Ind. Pvt Ltd.	287.8	44.5	645.2	2.24	14.5	0.15
12	Hyperaccumulator	Caryophyllaceae	<i>Cerastium dichotomum</i> L.	18	HIE-ST-10 Neutra Biotics	33.1	496.6	584.6	17.66	1.18	15.0
13	Hyperaccumulator	Euphorbiaceae	<i>Chrozophora tinctoria</i> (L.)	20	HIE-ST-5 Bilour Industries	17.68	271.5	325.4	18.4	1.2	15.36
14	Hyperaccumulator	Fabaceae	<i>Trifolium pratense</i> L.	21	HIE-ST-2 Durani Paints	13.06	124.1	495.2	37.92	3.99	9.5

15	Hyperaccumulator	Lamiaceae	<i>Thymus vulgaris</i> L.	29	HIE-ST-1 Vect Eng. Services	8.89	98.5	153.4	17.26	1.56	11.08
16	Hyperaccumulator	Meliaceae	<i>Melia azedarach</i> L.	31	HIE-ST-10 Hamdard Laboratories	33.44	524.9	765.8	22.9	1.46	15.7
17	Hyperaccumulator	Nyctaginaceae	<i>Mirabilis jalapa</i> L.	34	HIE-ST-16L Marble City	23.1	287.0	290.0	12.55	1.01	12.42
18	Hyperaccumulator	Nyctaginaceae	<i>Boerhavia procumbens</i> Banks ex Roxb.	35	HIE-ST-1 Maso Print Packages	28.68	92.0	105.8	3.69	1.15	3.21
19	Hyperaccumulator	Poaceae	<i>Digitaria sanguinalis</i> (L.) Scop.	36	HIE-ST-12L Medicare Center	49.41	412.9	419.4	8.49	1.02	8.36
20	Hyperaccumulator	Poaceae	<i>Sorghum halepense</i> (L.) Pers.	38	HIE-ST-13L Z-Jans Pharma	39.75	582.9	754.8	18.99	1.29	14.66
21	Hyperaccumulator	Poaceae	<i>Cynodon dactylon</i> (L.) Pers.	39	HIE-ST-13L Olympia Foam	32.2	255.4	345.2	10.72	1.35	7.93
22	Hyperaccumulator	Polygonaceae	<i>Polygonum plebeium</i> R.Br.	40	HIE-ST-14L Pak Prin Copo.	37.37	407.5	414.7	11.1	1.02	10.9
23	Hyperaccumulator	Primulaceae	<i>Anagallis arvensis</i> L.	43	HIE-ST-10 ARY Steel Mills	38.21	393.6	411.7	10.77	1.05	10.3
24	Hyperaccumulator	Rubiaceae	<i>Galium aparine</i> L.	45	HIE-ST-7 Bryon Pharma	39.22	412.9	415.6	10.6	1.01	10.53
25	Hyperaccumulator	Solanaceae	<i>Datura metel</i> L.	46	HIE-ST-10 ZRK Group	20.6	306.8	308.9	15.0	1.01	14.89
26	Hyperaccumulator	Solanaceae	<i>Withania somnifera</i> (L.) Dunal	47	HIE-ST-4 Moon Marble and Granite	33.75	362.0	367.0	10.87	1.01	10.73
27	Hyperaccumulator	Scrophulariaceae	<i>Verbascum thapsus</i> L.	48	HIE-ST-5 Butterfly Enterprise	34.71	54.5	61.4	1.77	1.13	1.57
28	Hyperaccumulator	Zygophyllaceae	<i>Tribulus terrestris</i> L.	50	HIE-ST-6 Wood Woolen Mills	212.7	328.5	332.9	1.57	1.01	1.54
29	Hyperaccumulator	Mimosaceae	<i>Prosopis juliflora</i> (Swartz) DC.	52	HIE-ST-4 Moon Marble and Granite	41.02	302.1	491.1	11.97	1.63	7.36

Phytostabilizer (BCF > 1, TF ≤ 1)											
1	Phytostabilizer	Asteraceae	<i>Cnicus benedictus</i> L.	1	HIE-ST-2 Imperial Furniture	21.4	282.6	283.7	13.26	1.0	13.21
2	Phytostabilizer	Asteraceae	<i>Verbesina enceliodes</i> (Cav.)	3	HIE-Beside Main Road-Prime Poly Tax	20.67	30.73	30.094	1.46	0.98	1.49
3	Phytostabilizer	Asteraceae	<i>Conyza sumatrensis</i> (S.F.Blake)	7	HIE-ST-10 Asim Match Ind. Pvt Ltd	33.52	484.4	235.2	7.02	0.49	14.45
4	Phytostabilizer	Amaranthaceae	<i>Amaranthus viridis</i> L.	10	HIE-ST-7 Rehman Industries	29.88	396.9	215.4	7.21	0.54	13.28
5	Phytostabilizer	Convolvulaceae	<i>Convolvulus arvensis</i> L.	19	HIE-Beside Road-Khan Polymers Pvt Ltd.	26.67	350.9	126.7	4.75	0.36	13.16
6	Phytostabilizer	Fabaceae	<i>Lathyrus aphaca</i> L.	24	HIE-ST-9 Pepsico Industries	30.16	420.9	408.4	13.54	0.97	13.96
7	Phytostabilizer	Fabaceae	<i>Dalbergia sissoo</i> Roxb.	25	HIE-Beside Road-Shangai PVC Pipe	30.16	451.7	421.4	13.97	0.93	14.98
8	Phytostabilizer	Lamiaceae	<i>Teucrium fruticans</i> L.	28	HIE-ST-17L Haq Aluminium	22.84	361.1	246.9	10.81	0.68	15.81
9	Phytostabilizer	Lamiaceae	<i>Salvia egyptiaca</i> L.	30	HIE-ST-3 Hussain Steel Mills	11.88	139.7	68.7	5.78	0.49	11.76
10	Phytostabilizer	Malvaceae	<i>Bombax ceiba</i> L.	32	HIE-ST-15L Mehran Marble Ind.	51.85	703.2	628.5	12.12	0.89	13.56
11	Phytostabilizer	Moraceae	<i>Morus alba</i> L.	33	HIE-ST-16L Sher Match Ind.	42.87	765.2	257.4	6.0	0.34	17.85
12	Phytostabilizer	Poaceae	<i>Avena sativa</i> L.	37	HIE-ST-8 Fort Frontier Ceramics	30.85	108.21	107.0	3.47	0.99	3.51
13	Phytostabilizer	Polygonaceae	<i>Persicaria hydropiper</i> (L.) Spach.	41	HIE-Beside Road-Pharma Plast	32.41	393.7	351.2	10.84	0.89	12.15
14	Phytostabilizer	Polygonaceae	<i>Rumex dentatus</i> L.	42	HIE-ST-7 Super Polyfit PVC Pipes	37.59	412.5	411.6	10.95	1.0	10.97
15	Phytostabilizer	Ranunculaceae	<i>Ranunculus muricatus</i> L.	44	HIE-ST-14L Royal PVC Pipe	38.56	411.6	403.3	10.46	0.98	10.67

16	Phytostabilizer	Verbenaceae	<i>Verbena officinalis</i> L.	49	HIE-ST-11 Aries Pharma	44.03	403.3	395.2	8.98	0.98	9.16
Excluder (BCF ≤ 1)											
1	Excluder	Brassicaceae	<i>Sisymbrium officinale</i> (L.) Scop.	14	HIE-Beside Road-Saydon Pharma	402.9	604.9	387.4	0.96	0.64	1.5
2	Excluder	Caryophyllaceae	<i>Silene conoidea</i> L.	15	HIE-ST-8 Rolex PVC Pipes	287.8	421.5	124.1	0.43	0.29	1.46
3	Excluder	Caryophyllaceae	<i>Arenaria serpyllifolia</i> Bourg.	17	HIE-ST-9 Coca Cola Ind. Pvt Ltd.	362.8	457.8	238.5	0.66	0.52	1.26
4	Excluder	Fabaceae	<i>Medicago polymorpha</i> (L.)	23	HIE-Beside Road-Prime PVC Pipe	25.42	326.2	0.784	0.03	0.0	12.83
5	Excluder	Fabaceae	<i>Melilotus indicus</i> L. All.	26	HIE-ST-6 Lahore Steel Mills	44.71	800.2	8.487	0.19	0.01	17.9

The highest soil Cr concentration (402.9 mg/kg) was recorded in *Sisymbrium officinale* (Brassicaceae) at the HIE-Beside Road-Saydan Pharma site, whereas *Tribulus terrestris* (Zygophyllaceae) at HIE-ST-6 Wood Woolen Mills showed 212.7 mg/kg. The maximum root Cr concentration (800.2 mg/kg) was observed in *Melilotus indicus* (Fabaceae) at HIE-ST-6 Lahore Steel Mills, while the highest shoot concentration (765.8 mg/kg) was recorded in *Melia azedarach* (Meliaceae) at HIE-ST-10 Hamdard Laboratories.

Species exhibiting both $BCF > 1$ and $TF > 1$ were considered phytoextractors (hyperaccumulators), whereas those with $BCF > 1$ and $TF \leq 1$ were classified as phytostabilizers. Additional species identified as strong Cr accumulators, including

Chenopodium murale, *Chrysanthemum indicum*, *Xanthium strumarium*, *Lepidium didymum*, *Sisymbrium officinale*, and *Arenaria serpyllifolia*, showed substantial Cr accumulation in both roots and shoots, further supporting their potential role in phytoremediation.

An interesting pattern was observed in species growing in moderately contaminated soils, such as *Verbesina encelioides* and *Stellaria media*, which exhibited differential Cr translocation between roots and shoots, suggesting selective uptake and/or tolerance mechanisms. Collectively, these findings highlight the bioindicator potential of the recorded plant species for chromium contamination in industrially impacted environments. The elevated Cr levels, far exceeding permissible limits, underscore the

urgent need for soil remediation and the application of phytoremediation-based management strategies. Moreover, such contamination poses a significant risk of entry into the food chain, thereby threatening ecosystem stability and public health.

Figure 1 presents the PCA results based on Table 2. As shown in Figure 1, PC1 accounted for 46.17% of the total variance, while PC2 accounted for 29.19%, giving a cumulative variance of 75.36% for the first two components (PC1 + PC2).

Overall, four distinct clusters were identified within the four-quadrant biplot. The biplot revealed clear clustering patterns among species and soil and plant variables (roots and shoots), providing valuable insights into the accumulation behavior of Cr across different plant parts.

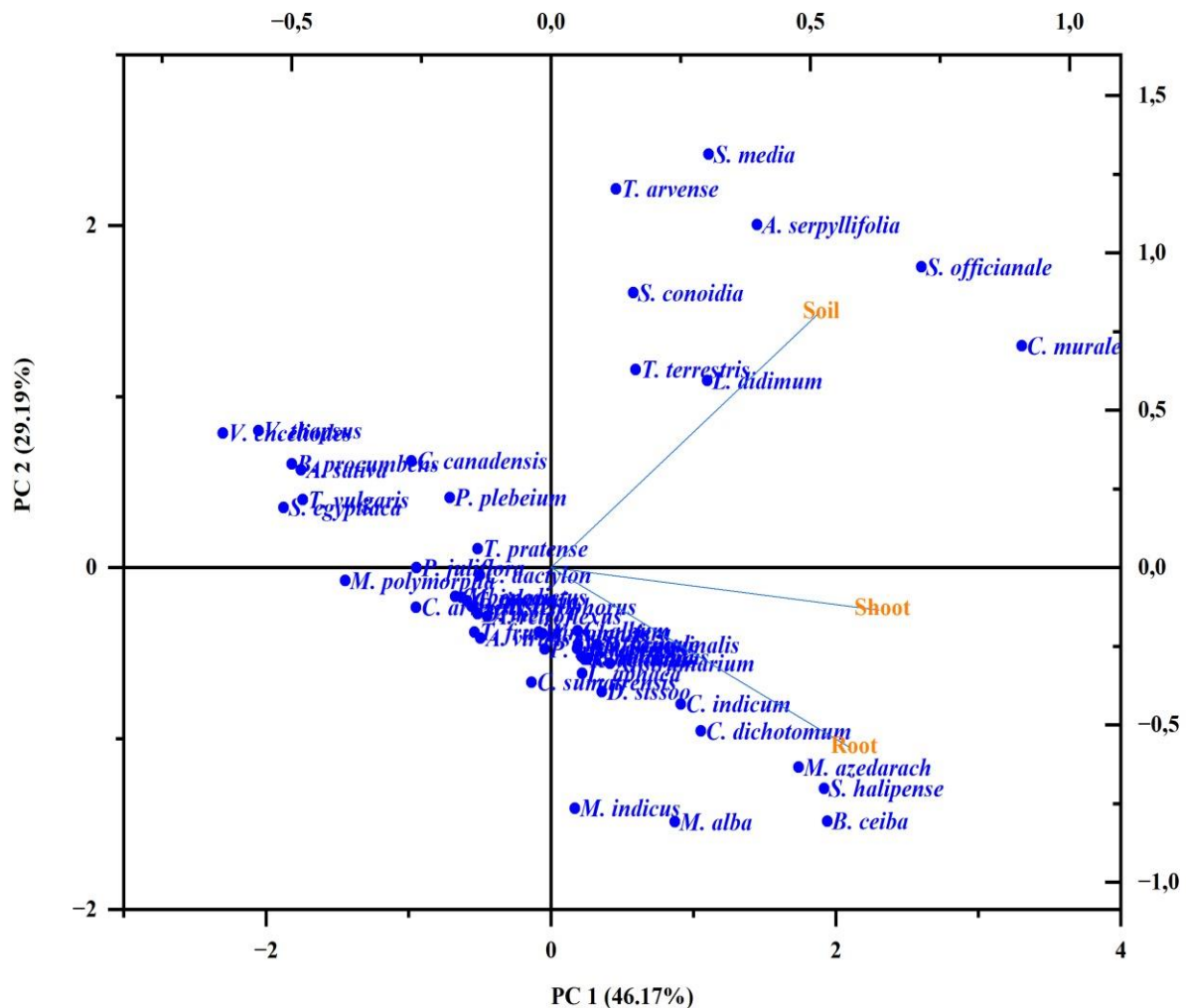


Figure 1. Biplot PCA analysis created using shoot, root, and soil data for the species.

Cluster 1 consisted of species located in the upper-left quadrant, which were separated from other groups and showed no strong association with any of the measured variables. This indicates a limited contribution to the explained variance and suggests a low level of chromium bioaccumulation. Consequently, these species may pose a comparatively lower risk in terms of Cr accumulation in human nutrition.

In Cluster 2, species were positioned in the upper-right quadrant and were strongly associated with soil related variables. This association suggests that these species either accumulate or tolerate chromium and may therefore serve as indicators of soil contamination. However, their accumulation potential also highlights a possible risk for entry of heavy metals into the food chain, warranting cautious utilization.

Cluster 3 included species located in the lower-left quadrant, which were also weakly associated with the

measured variables and thus contributed minimally to the explained variance, similar to Cluster 1.

Cluster 4 comprised species in the lower-right quadrant, which were associated with root and shoot variables. This cluster reflects variation in chromium uptake and translocation within plant tissues. Given that excessive chromium intake in humans (approximately 1-5 g of chromium salts) can cause acute toxicity, including gastrointestinal disorders, hemorrhaging, seizures, and potentially fatal cardiovascular shock (Çağlarırnak and Hepçimen, 2010), the bioaccumulation patterns observed in this cluster indicate that careful monitoring is necessary to prevent health risks associated with Cr exposure through consumption.

As shown in Figure 2, a triangular heat map based on a correlation matrix among species is presented. In this heat map, green indicates negative correlations

between variables and species, whereas red indicates positive correlations. Consistent with the PCA results, the data revealed varying degrees of correlation among clusters, ranging from strong negative to strong positive relationships. Species grouped within the

same cluster also exhibited different levels of positive association, including weak, moderate, and strong correlations. Overall, these results support and complement the PCA findings, providing a more robust interpretation of the relationships within the dataset.

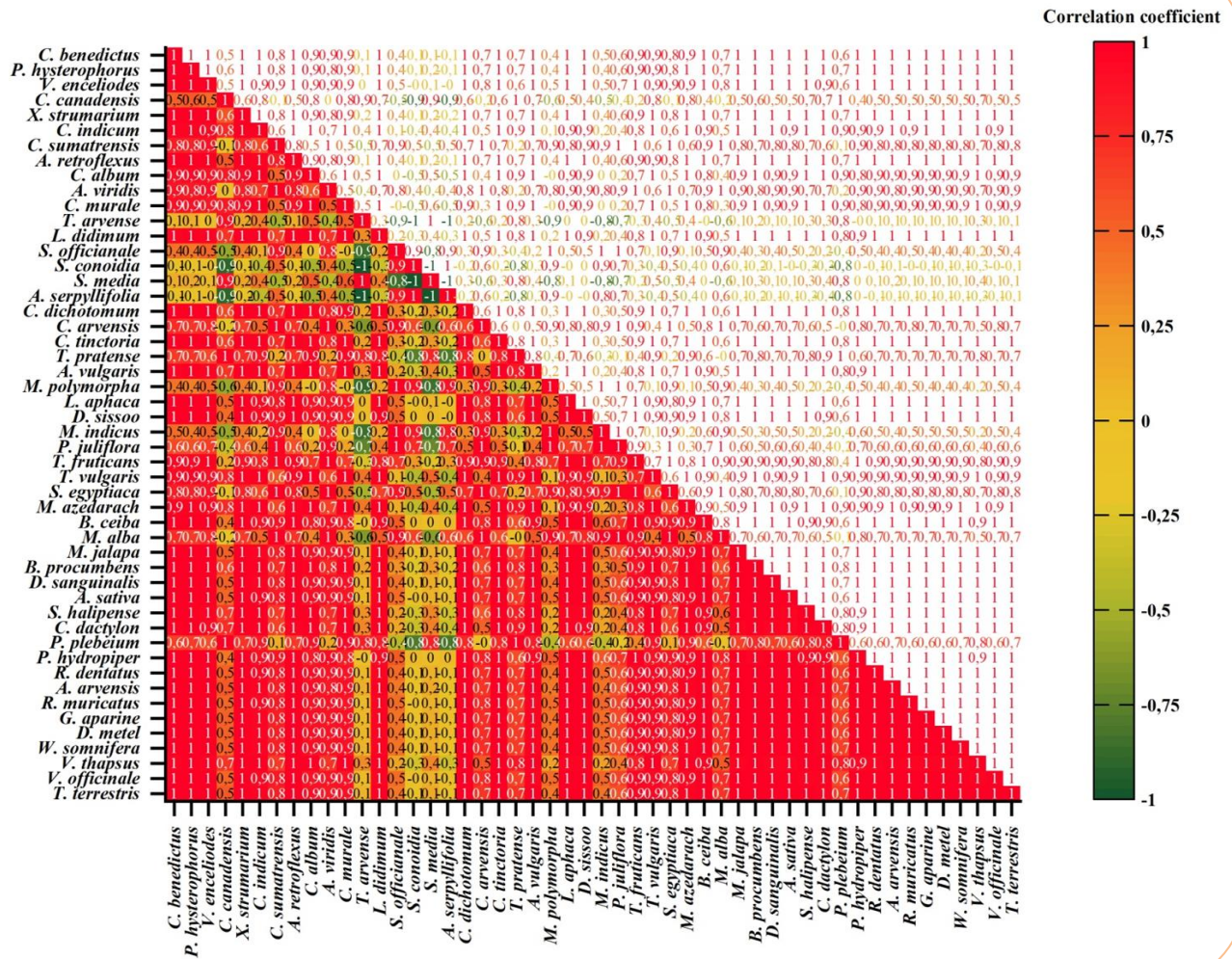


Figure 2. Triangular heat map containing the correlation matrix created using the soil, shoot, and root values for the species.

As shown in Figure 3, PC1 accounted for 57.54% of the total variance, while PC2 explained 36.42%, with a cumulative variance of 93.96% (PC1 + PC2).

Based on the PCA biplot, four distinct clusters were identified across the four quadrants. Cluster 1 comprised species positioned in the upper-left quadrant, clearly separated from the other groups and positively associated with the TF variable. Cluster 2 included species located in the upper-right quadrant, which were strongly associated with BAC variants.

Cluster 3 consisted of species positioned in the lower-left quadrant; these were isolated from other groups and showed no strong association with any of the

measured variables, thereby contributing minimally to the explained variance, similar to Cluster 1. Cluster 4 was located in the lower-right quadrant, where species were associated with the BCF variable.

Figure 4 presents a triangular heatmap displaying the correlation matrix among species. The results indicated correlations ranging from negative to positive across different species pairs. Overall, positive correlations were more frequently observed, indicating generally coherent relationships among the species. This visualization further clarifies and supports the multivariate relationships observed in the dataset.

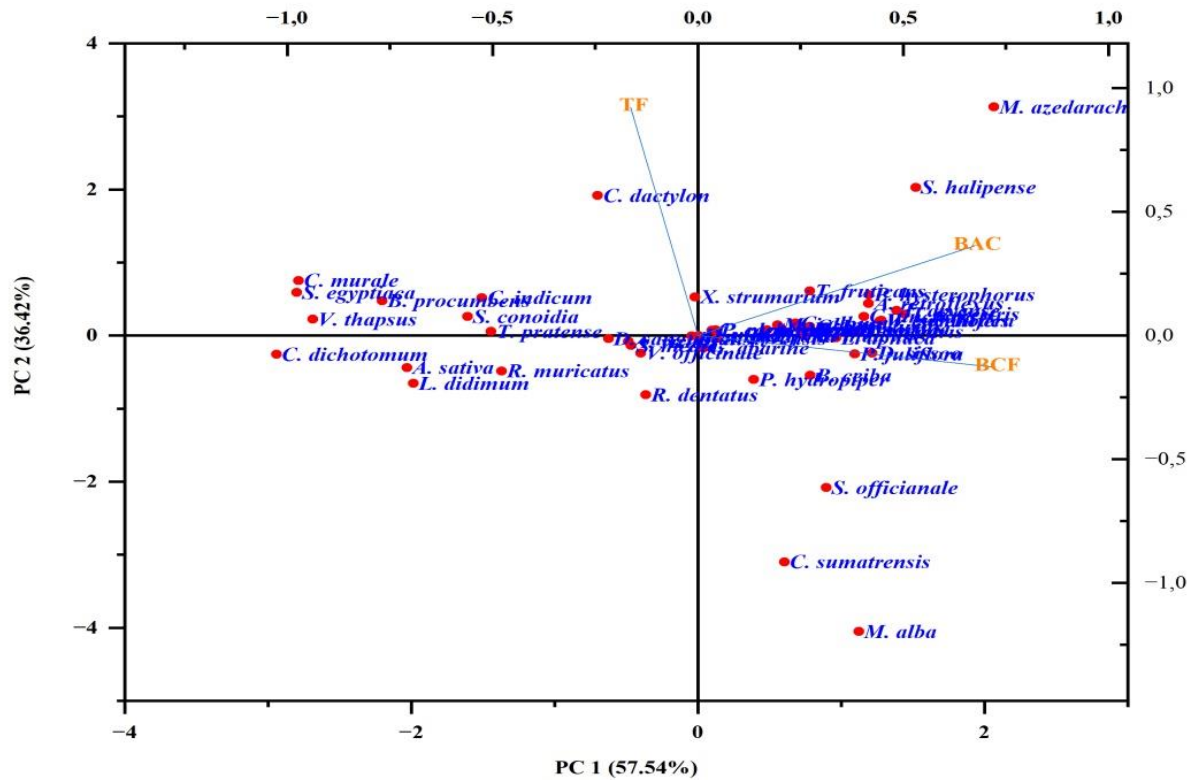


Figure 3. Biplot PCA analysis created using BCF, TF, and BAC data for the species.

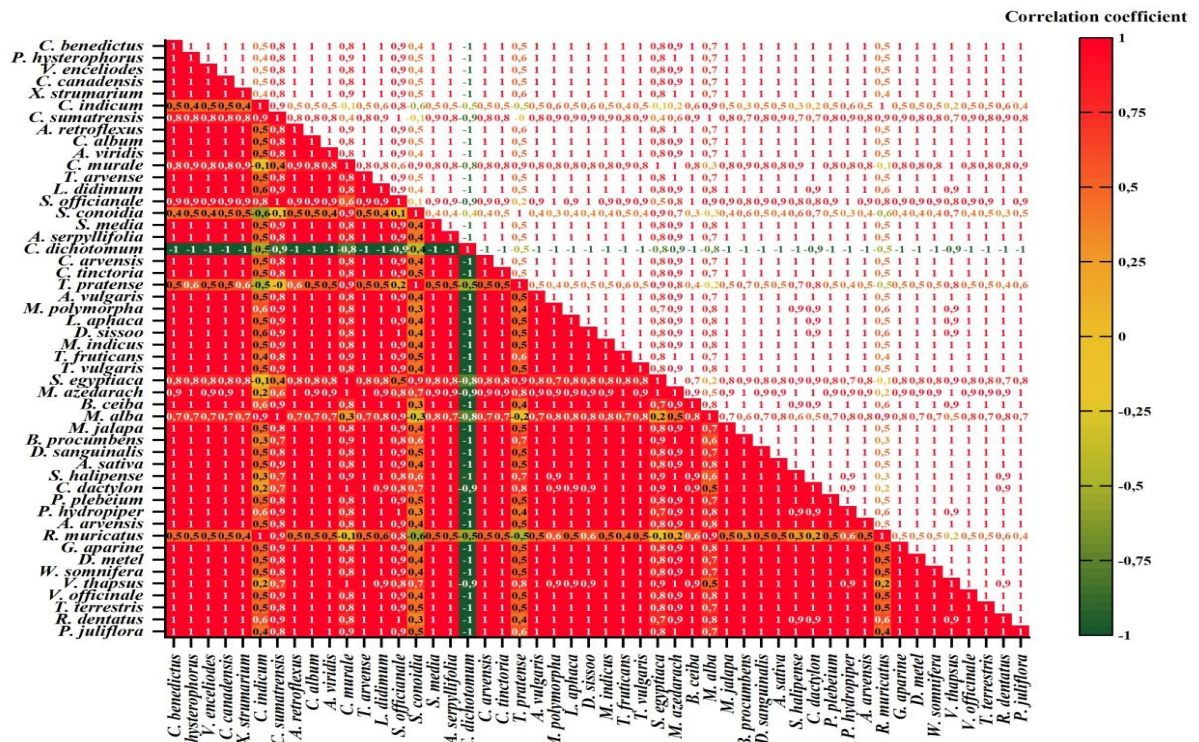


Figure 4. Triangular heat map containing the correlation matrix created using the BCF, TF, and BAC values for the species.

Discussion

Industrial operations are a major source of environmental pollution due to the generation of various waste streams, including liquid effluents, solid waste, and gaseous emissions. The literature indicates that Pakistan faces a serious industrial waste management challenge, with Khyber Pakhtunkhwa province particularly characterized by inadequate effluent treatment and limited solid waste management infrastructure. Previous studies have demonstrated that the discharge of untreated industrial effluents can cause severe contamination of receiving water bodies. Strategic zoning policies and industrial symbiosis approaches can support sustainable industrial development while promoting improved waste management practices (Shah, 2014).

The pharmaceutical industry in the study area primarily engages in the repackaging of imported medicinal products, resulting in comparatively low pollution levels. Similarly, plastic manufacturing units produce finished goods from imported raw materials, with emissions largely restricted to indoor vapors and fumes, and minimal reported community-level environmental complaints. In contrast, marble processing operations are highly resource-intensive and represent persistent sources of environmental pollution. The furniture industry relies heavily on timber species such as *Populus* spp. (poplar), *Morus* spp. (mulberry), and *Dalbergia sissoo* (shisham), raising concerns regarding the sustainable utilization of forest resources. Other significantly polluting industries include match manufacturing, paper mills, chipboard production, ceramics, ghee processing, beverage production, tire manufacturing, and packaging units, all of which are characterized by intensive resource consumption and continuous pollutant emissions.

Operational data from the Mardan Industrial Estate indicate that 121 out of 181 registered industrial units are operational. Among these, marble and iron/steel processing units exhibit the highest daily production capacities, ranging from 55-65 tons and approximately 50 tons, respectively. Chipboard, beverage, and food processing industries follow in terms of production output. Such high levels of industrial activity imply substantial raw material requirements and consequently large volumes of waste generation, particularly from resource-intensive sectors such as match production, ghee processing, and chipboard manufacturing.

Environmental monitoring has revealed widespread

chromium contamination across the study area. Although regulatory standards specify maximum permissible limits of 0.5 mg/kg in soil and 0.05 mg/L in water, the recorded concentrations substantially exceed these thresholds. Soil chromium concentrations ranged from 8.89 to 402.9 mg/kg, while even higher levels were detected in plant tissues, reaching 800.2 mg/kg in roots and 765.8 mg/kg in shoots. These elevated concentrations represent a serious ecotoxicological and public health concern due to bioaccumulation in plants and potential entry into the food chain.

Among the plant species collected from highly industrialized sites, *Melia azedarach*, *Chenopodium murale*, *Melilotus indicus*, and *Xanthium strumarium* were identified as strong chromium accumulators. These species may serve as effective bioindicators of industrial pollution pressure. Of particular interest, *Sisymbrium officinale* and *Tribulus terrestris* were found exclusively in heavily contaminated soils, indicating their potential association with highly polluted industrial effluent zones. These findings highlight the need to integrate phytoremediation strategies with strengthened regulatory frameworks for industrial wastewater treatment and zoning enforcement.

The high chromium accumulation observed in species such as *M. azedarach* and *C. murale* suggests the presence of efficient translocation mechanisms, potentially involving organic acid exudation in the rhizosphere that enhances chromium bioavailability. This study provides a baseline for future investigations into detoxification pathways and physiological responses, including antioxidant enzyme activity, in chromium-tolerant and hyperaccumulating species under Cr stress. These biochemical responses are consistent with findings from similar studies. Sajad et al. (2020) reported comparable hyperaccumulation in *Cannabis sativa* and *Allium griffithianum* in Dir Lower, Pakistan. The elevated shoot chromium concentrations observed in *M. azedarach* (765.8 mg/kg) and *X. strumarium* (456.1 mg/kg) in the present study exceed values reported by Zulfiqar et al. (2023) for comparable arid-zone species, suggesting that intense industrial loading in the Mardan iron and steel belt may induce enhanced stress-response mechanisms.

The findings of this study have direct implications for plant protection, crop safety, and agricultural sustainability in the Mardan region. Chromium phytotoxicity at the levels reported can reduce seed germination, impair photosynthetic efficiency, inhibit root elongation, and disrupt nutrient homeostasis, ultimately leading to reduced crop yield and

compromised produce quality (Zulfiqar et al., 2023). Several species identified in this study, including *C. murale* and *A. retroflexus*, are consumed as leafy vegetables or used as fodder in Pakistan. Their elevated shoot chromium concentrations (724.8 mg/kg and 325.2 mg/kg, respectively) indicate a direct pathway for chromium entry into the human and livestock food chain, posing serious food safety risks beyond the industrial estate boundary. Furthermore, chromium accumulation in plant tissues may increase susceptibility to biotic stresses by disrupting enzyme systems involved in plant defense, thereby linking heavy metal contamination with reduced plant protection capacity against pathogens. This relationship is particularly critical in peri-industrial agricultural systems where crop health management is essential. These findings underscore the urgent need for regulatory interventions and phytomanagement strategies that address not only remediation efficiency but also the protection of crops, fodder species, and human health in chromium-contaminated environments. Pearson correlation analysis was conducted between soil chromium concentrations and phytoremediation indices across 50 plant species. Soil chromium concentration showed a significant negative correlation with the bio-concentration factor ($r = -0.517$), indicating that increased soil chromium levels reduce relative translocation efficiency from soil to shoots, likely due to root-level immobilization under high contamination stress. A stronger negative correlation was observed between soil chromium and the bioaccumulation coefficient ($r = -0.676$), suggesting reduced uptake efficiency at elevated contamination levels, consistent with saturation kinetics in root absorption systems. In contrast, the correlation between soil chromium and translocation factor was weakly positive ($r = 0.299$), indicating that translocation capacity is largely species-dependent rather than governed by soil concentration alone. Although soil pH and EC were measured during sampling, they are not presented as a separate dataset in this study; therefore, their influence on BCF and related indices should be considered in future multivariate analyses. These correlation patterns, derived from calculated BCF, TF, and BAC values (Table 3), provide a quantitative framework for selecting suitable plant species for phytoremediation in the Mardan Industrial Estate.

Conclusion

This study evaluated chromium accumulation in fifty plant species belonging to twenty-one families collected from industrial sites. Chromium concentrations were

determined in soil, roots, and shoots. To assess phytoremediation potential, the bio-concentration factor, translocation factor, and bioaccumulation coefficient were calculated. Species with $BCF > 1$ and $TF > 1$ were classified as phytoextractors, while those with $BCF > 1$ and $TF < 1$ were categorized as phytostabilizers. Soil chromium concentrations ranged from 8.89 to 402.9 mg/kg, showing considerable spatial variation across industrial zones. Several plant species exhibited strong potential for chromium phytoremediation based on the defined indices. Effective phytoextractors ($BCF > 1$ and $TF > 1$), suitable for contaminant removal through harvest, included *Mirabilis jalapa*, *Thymus vulgaris*, *Morus alba*, *Melia azedarach*, *Anagallis arvensis*, *Bombax ceiba*, and *Chenopodium murale*. These species demonstrated efficient translocation of chromium from roots to shoots, making them suitable for phytoextraction-based remediation. For phytostabilization ($BCF > 1$ and $TF < 1$), the most effective species were *Chrysanthemum indicum*, *Convolvulus arvensis*, *Ranunculus muricatus*, *Thlaspi arvense*, and *Tribulus terrestris*. These species exhibited strong root accumulation with limited translocation to aerial parts, making them suitable for immobilizing chromium within the rhizosphere and reducing its environmental mobility.

Overall, the correlation analyses provide a scientific basis for understanding plant-metal interactions and offer practical guidance for selecting plant species for phytoremediation and environmental management in chromium-contaminated industrial areas.

Authors' Contribution

MF and RN conceptualized the study and designed the overall research framework. MF and MNK conducted the field investigations and was primarily responsible for executing the experimental work. RN and MNK contributed to data curation, while RN and MNK performed the formal analysis of the dataset. HA, HG developed the methodology and provided critical technical input throughout the study. UY, AK managed project administration and ensured coordination among all research activities. K and HG were responsible for resources acquisition and support, while AK and K contributed to software development and data processing tools. HG, KK, and MNK participated in validation of results to ensure accuracy and reliability of findings. UA, RN prepared the visualization outputs and graphical representations. MF and HG prepared the initial draft of the manuscript, including interpretation and structuring of results. AK

contributed to critical review, editing, and refinement of the manuscript to improve scientific clarity and coherence. All authors reviewed the manuscript, provided intellectual feedback, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 3: Good Health and Well-being

SDG 6: Clean Water and Sanitation

SDG 15: Life on Land

Policy Addressed

The study aligns with Pakistan Environmental Protection Act (1997), National Environmental Quality Standards (NEQS), and international frameworks such as the Basel Convention.

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