PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.3385

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Accumulation of heavy metals (Cr, Cu, As, Cd, Pb, Zn, Fe, Ni, Co) in the water, soil and plants collected from Edayar Region, Ernakulam, Kerala, India

Chandni Asha Syamlal & D. Sayantan*

Department of Life Sciences, Christ University, Bengaluru - 560029, Karnataka, India

*Email: sayantan.d@christuniversity.in

OPEN ACCESS

ARTICLE HISTORY
Received: 13 February 2024
Accepted: 13 July 2024
Available online
Version 1.0 : 22 October 2024

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Syamlal CA, Sayantan D. Accumulation of heavy metals (Cr, Cu, As, Cd, Pb, Zn, Fe, Ni, Co) in the water, soil and plants collected from Edayar Region, Ernakulam, Kerala, India. Plant Science Today (Early Access). https://doi.org/10.14719/pst.3385

Abstract

The accumulation of heavy metals in the environment is a significant concern due to their potential toxicity and persistence. This study investigates the levels of heavy metal contamination in the water, soil and plants of the Edayar region in Ernakulam, Kerala, India. The region has experienced industrialization and urbanization, leading to concerns about heavy metal pollution. The study aims to assess the concentrations of chromium (Cr), copper (Cu), arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), nickel (Ni) and cobalt (Co) in water, soil, aquatic and terrestrial plants. Samples were collected from various locations within the Edayar region, and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was conducted to quantify heavy metal concentrations. The findings of this study will contribute to the assessment of heavy metal pollution in the Edayar region. Plants with a high diversity index were taken for analysis from both aquatic and terrestrial habitats. *Scoparia dulcis* L. seems to specialize in metal accumulation, possibly for protective purposes. *Synedrella nodiflora* Gaertn demonstrates adaptability to metal-rich environments through robust metal uptake and tolerance mechanisms. *Alternanthera philoxeroides* (Mart.) Griseb, on the other hand, appears to have developed mechanisms to manage heavy metal exposure. The results indicate significant levels of heavy metal contamination across all samples, with the highest concentrations detected in soil, followed by water and plants. Chromium and lead levels in soil exceeded the permissible limits set by international standards, posing potential risks to human health and the ecosystem. The accumulation patterns in plants varied, with higher bioaccumulation factors observed for zinc and copper, suggesting their preferential uptake. This study highlights the urgent need for remediation strategies and continuous monitoring to mitigate the impact of heavy metal pollution in the Edayar region. The results will help in understanding the environmental impact of human activities.

Keywords

industrialisation; toxicity; urbanization; ICP-MS

Introduction

The accumulation of heavy metals in the environment is a growing concern due to its detrimental impact on ecosystems and human health (1). Anthropogenic activities, such as industrial discharges, agricultural practices, and urbanization, release heavy metals like chromium (Cr), copper (Cu), arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), nickel (Ni) and cobalt

(Co) into the environment. The Edayar region, situated in Ernakulam, Kerala, India, has garnered attention as a potential hotspot for heavy metal accumulation in water, soil and plants. This region is characterized by various industrial activities, including manufacturing units, chemical plants and waste disposal sites, which may contribute to environmental contamination (2). Heavy metals, including chromium (Cr), copper (Cu), arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), nickel (Ni) and cobalt (Co), are naturally occurring elements that can also be released into the environment through human activities such as industrial processes, mining, agriculture and urbanization (3). These metals possess unique chemical properties that make them persistent and potentially toxic pollutants. The accumulation of heavy metals in the environment is a complex process influenced by various factors, including the intensity and nature of human activities, the geological characteristics of the area and the physicochemical properties of the ecosystem. The presence of heavy metals can disrupt aquatic and terrestrial ecosystems, resulting in the loss of biodiversity and impaired ecological functions (4).

The Edayar region, located in Ernakulam, Kerala, India, has become a focal point for studying heavy metal contamination in water, soil and plants. The area has experienced rapid industrialization and urbanization, which has led to the release of heavy metals into the environment. Industrial effluents, agricultural practices and urban runoff are common sources of heavy metal pollution in this region. Investigating the accumulation of heavy metals in water, soil and plants in the Edayar region is essential for assessing the environmental impact of human activities and guiding potential remediation efforts. By determining the levels of heavy metal contamination and understanding the associated physicochemical parameters, it becomes possible to evaluate the potential risks posed to human health and the overall ecological balance in the area (5).

To address the challenges caused by heavy metal accumulation, extensive research has been conducted worldwide to understand the distribution, sources, transport and fate of heavy metals in different environmental compartments. These studies have provided valuable insights into the pathways through which heavy metals enter the environment and have contributed to the development of effective strategies for pollution control and management. This study investigates the accumulation of heavy metals, including chromium, copper, arsenic, cadmium, lead, zinc, iron, nickel and cobalt, in the environment. The aim is to assess the levels and spatial distribution of these metals in water, soil and potentially affected biota. Additionally, the study aims to identify potential sources of heavy metal contamination and evaluate their impact on the surrounding ecosystem. The accumulation of heavy metals in the environment has become a significant concern due to their potential toxicity and persistence (6). Heavy metals, such as chromium (Cr), copper (Cu), arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), nickel (Ni) and cobalt (Co), are naturally occurring elements that can enter ecosystems through both natural processes and human activities (7). These metals pose a threat to ecosystems and human health as they can accumulate in the environment and subsequently enter the food chain. By examining the accumulation of heavy metals in the environment, this research aims to enhance our understanding of the ecological and health risks associated with these contaminants.

Materials and Methods

Study area

The study was conducted in all 4 seasons in the Edayar area of the Kadungalloor Grama Panchayat in Kerala, India. Kerala has a wide range of weather conditions. It spans the winter months of November through February, the springtime of March through May, the southwest monsoon of June through September and the northeast monsoon of October through November.

The Paravur Taluk in the Ernakulam district is where Kadungalloor Grama Panchayat is located. This panchayat has around 21 wards. The Kadungalloor area is where the Edayar industrial estates are situated. Ward number 18 in Edayar is located at 10°04'54"N, 76°19'18"E, respectively. There are 2054 people living in this area. Near Eloor, along the Periyar River, is the industrial belt zone. Hundreds of industries may be found in the Eloor-Edayar region. In this area, there are about 400 industries.

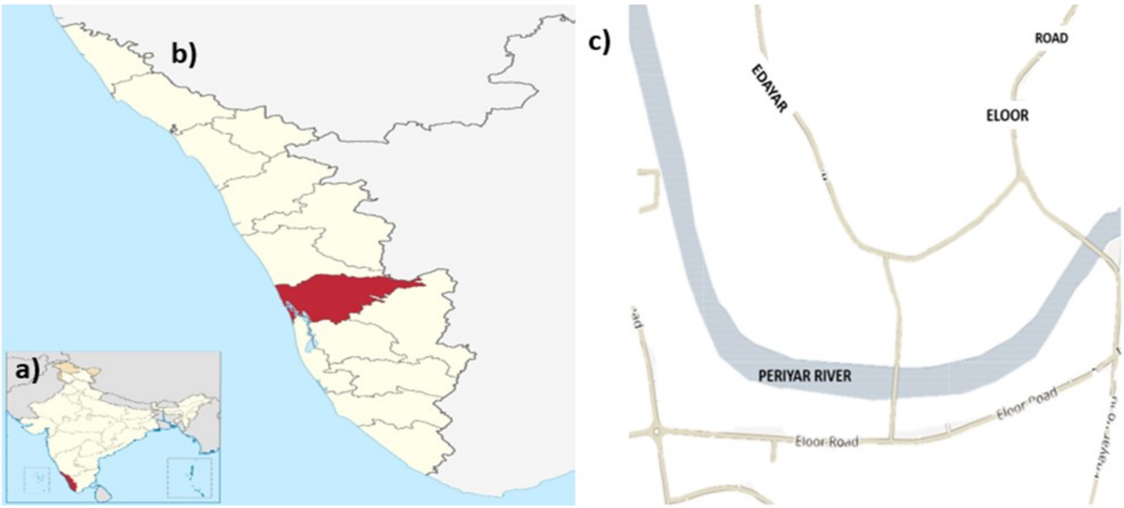

Fig. 1. (a) Map of India showing the location of Kerala, (b) Map of Kerala showing Ernakulam and (c) Study site in Ernakulam region, Edayar and Periyar river.

Collection of samples

Sample collection was done randomly from the area of Edayar as shown in Fig. 1c. Eight samples of groundwater, river water, aquatic soil and terrestrial soil were randomly collected from the Edayar region, represented in Fig. 1. Plant selection was done after performing diversity indices. Simpson and Shannon indexes were performed after the quadrat study of terrestrial and aquatic plants. Three varieties of plants that were dominant during each season were found after performing the diversity indices study. The terrestrial plants identified were *Scoparia dulcis* L., *Synedrella nodiflora* Gaertn, *Cleome rutidosperma* DC., *Cynodon dactylon* (L.) Pers. and *Sphagneticola trilobata* (L.) Pruski. The aquatic plants taken for the study were *Eicchornia crassipes* (Mart.) Solms, *Salvinia molesta* D.Mitch. and *Pistia stratiotes* L. *S. dulcis* is known for its medicinal properties, including anti-inflammatory, analgesic and anti-diabetic effects. It is also used in traditional medicine across various cultures (8). *S. nodiflora* is often studied for its allelopathic properties, which can influence the growth of surrounding plants. It is also known for its use in folk medicine (9). *C. rutidosperma* is often used in ethnobotanical studies due to its reported anti-inflammatory and antimicrobial properties (10). *C. dactylon* is a common weed, and extensive studies have been done on its ecological impact, allelopathic effects and use in traditional medicine (11). *S. trilobata*, known for its ornamental value and medicinal properties, was also studied for its invasive characteristics (12). *E. crassipes* is a highly invasive species known for its rapid growth and impact on aquatic ecosystems. It is also studied for its phytoremediation (13). *S. molesta* is a significant invasive aquatic plant that affects water quality and biodiversity. Its rapid growth and control measures make it a key subject of study (14). *P. stratiotes* is another invasive aquatic plant known for its impact on water bodies. It is also used in studies related to water purification and phytoremediation (15). Terrestrial plants were rooted out from the soil. They were carried in polythene bags.

Sample treatment

The microwave digestion technique was used to perform ICP-MS analysis on soil and plants. Plants were separated into shoots and roots and were oven-dried at 110°C. Soil samples were also oven-dried at 110°C. 2 g of each sample was acid-digested using nitric acid. Samples were kept on a hot plate. After removing from the hot plate, the sample was filtered in a 100 mL graduated cylinder up to 35 mL, so that 35 mL of each sample was prepared. Water samples were directly subjected to analysis (16). Three replicas for river water, groundwater, aquatic soil, terrestrial soil, aquatic plants and terrestrial plants were taken.

Sample analysis

Samples of plants, soil, and water were subjected to ICP-MS for analyzing metals like Cr, Cu, As, Cd, Pb, Zn, Fe, Ni and Co. The instrument setting and operational conditions were done in accordance with the manufacturers' specifications. The limit of detection was from 0 ppb to 1200 ppb. The method summary is briefed in Table 1.

Table 1. Method summary for the ICP-MS analysis.

Isotope	Mode	Dwell Time (s)	No. of Channels	Spacing	Resolution
52Cr	STD	0.01	1	0.1	Normal
53Cr	STD	0.01	1	0.1	Normal
56Fe	STD	0.01	1	0.1	Normal
57Fe	STD	0.01	1	0.1	Normal
58Ni	STD	0.01	1	0.1	Normal
59Co	STD	0.01	1	0.1	Normal
60Ni	STD	0.01	1	0.1	Normal
63Cu	STD	0.01	1	0.1	Normal
63Zn	STD	0.01	1	0.1	Normal
65Cu	STD	0.01	1	0.1	Normal
66Zn	STD	0.01	1	0.1	Normal
75As	STD	0.01	1	0.1	Normal
111Cd	STD	0.01	1	0.1	Normal
114Cd	STD	0.01	1	0.1	Normal
206Pb	STD	0.01	1	0.1	Normal
208Pb	STD	0.01	1	0.1	Normal

No. of sweeps	Time per sweep (s)	Time per main run(s)
10	0.16	1.6

Results and Discussion

River water samples

The concentrations of heavy metals in the river water samples collected from the Edayar region of Kerala, India, revealed important insights into the presence and variability of these contaminants across different seasons (Table 2). Chromium (Cr) concentrations exhibited significant variation, with the highest levels recorded during the winter season (16470.33±1.4 ppb) and comparatively lower concentrations during the southwest monsoon (11648.87±1.8 ppb), northeast monsoon (11255.48±1.2 ppb) and summer (13126.76±1.2 ppb) seasons. Iron (Fe) concentrations displayed substantial differences across seasons, with the winter season exhibiting the highest concentration (5429452.9±1.5 ppb). The southwest monsoon (5737020.16±0.8 ppb), northeast monsoon (5454525.7±1.3 ppb) and summer (5277834.24±0.92 ppb) seasons also exhibited elevated iron levels. Nickel (Ni) concentrations demonstrated noticeable variation, with the winter season displaying the highest levels (47896.57±1.1 ppb), while the summer season recorded the lowest concentration (42657.36±1.4 ppb). The southwest monsoon (41469.61±1.25 ppb) and northeast monsoon (45627.51±0.9 ppb) seasons showed relatively lower nickel concentrations.

Cobalt (Co) concentrations exhibited minor variations across seasons, with comparable levels during the southwest monsoon (3308.28±0.8 ppb) and summer (3685.76±1.5 ppb) seasons. The winter season had the lowest concentration (3155.61±1.2 ppb) and the northeast monsoon season also showed relatively low cobalt levels (3253.58±1.26 ppb). Copper (Cu) concentrations vary among seasons, with the highest levels observed during the winter (5386.39±1.3 ppb) and summer (4408.14±1.57

Table 2. Heavy metal concentration (parts per billion, ppb) in river water samples of Edayar, Kerala India.

Sl No	Heavy Metals	Southwest Monsoon	Northeast Monsoon	Winter Season	Summer Season
1	Cr (ppb)	11648.87±1.8	11255.48±1.2	16470.33±1.4	13126.76±1.2
2	Fe (ppb)	5737020.16±0.8	5454525.7±1.3	5429452.9 ±1.5	5277834.24±0.92
3	Ni (ppb)	41469.61±1.25	45627.51±0.9	47896.57±1.1	42657.36±1.4
4	Co (ppb)	3308.28±0.8	3253.58±1.26	3155.61±1.2	3685.76±1.5
5	Cu (ppb)	4296.28±1.2	4205.66±1.31	5386.39±1.3	4408.14±1.57
6	As (ppb)	216.85±0.5	225.31±0.8	245.64±0.4	273.54±0.4
7	Cd (ppb)	1045.73±1.2	1247.99±0.83	1341.43±1.5	1544.64±0.8
8	Pb (ppb)	1510.92±1.2	144.24±0.91	1682.84±1.5	1270.78±1.25
9	Zn (ppb)	6371.33±0.71	6150.76±0.9	6123.14±1.32	6207.93±0.9

ppb) seasons. The northeast monsoon season showed a comparatively lower concentration (4205.66±1.31 ppb). Arsenic (As) concentrations were relatively low across all seasons, with the summer season exhibiting the highest concentration (273.54±0.4 ppb). The northeast monsoon (225.31±0.8 ppb) and winter monsoon (245.64±0.4 ppb) seasons also showed detectable levels, while the southwest monsoon season recorded the lowest concentration (216.85±0.5 ppb).

Cadmium (Cd) concentrations vary significantly, with the summer season displaying the highest concentration (1544.64±0.8 ppb), followed by the winter season (1341.43±1.5 ppb). The southwest monsoon and northeast monsoon exhibited much lower concentrations (1045.73±1.2 ppb and 1247.99±0.83 ppb, respectively). Lead (Pb) concentrations vary substantially across seasons, with the winter season recording the highest levels (1682.84±1.5 ppb). The southwest monsoon (1510.92±1.2 ppb) and summer (1270.78±1.25 ppb) seasons exhibited comparably lower concentrations, while the northeast monsoon season showed a moderate concentration (144.24±0.9 ppb). Zinc (Zn) concentrations showed variation among seasons, with the southwest monsoon season exhibiting the highest concentration (6371.33±0.71ppb). The northeast monsoon (6150.76±0.9 ppb) and winter (6123.14±1.32 ppb) and summer seasons (6207.93±0.9) also showed notable levels.

Chromium (Cr) concentrations

The recorded variations in chromium concentrations across seasons suggest that the Edayar region experiences significant fluctuations in Cr contamination. The highest levels during winter might be attributed to factors such as increased industrial activities and reduced dilution due to lower water flow. Conversely, the lower levels during the monsoon seasons could be attributed to enhanced rainfall and higher water flow, leading to greater dilution and potential flushing of contaminants (17). These results were consistent with studies that highlight the influence of climatic conditions on heavy metal transport and distribution.

Iron (Fe) concentrations

Elevated iron concentrations throughout the seasons indicated that this metal is likely derived from both natural geological processes and anthropogenic sources. Iron can be mobilized and transported by water. Groundwater flowing through iron-rich soils and rocks can dissolve iron and carry it to surface waters. Similarly, seasonal changes in water flow, such as increased runoff during rainy seasons, can lead to higher iron concentrations in rivers, lakes and streams. Industries such as mining, steel manufacturing, iron-containing fertilizers and pesticides and metalworking release iron into the environment. These activities can lead to elevated iron levels in nearby water bodies and soils through direct discharge or atmospheric deposition. Municipal and industrial wastewater can contain significant amounts of iron. Inadequate treatment of wastewater before discharge into natural water bodies can elevate iron concentrations. The consistent presence of high iron levels suggests the potential influence of industrial discharges or agricultural runoff containing iron-rich sediments. The variations in iron concentrations across seasons could also be influenced by precipitation patterns, which affect runoff and sediment transport (18, 19).

Nickel (Ni) concentrations

The variations in nickel concentrations across seasons may be linked to the interplay of pollutant sources and hydrological conditions. The elevated nickel levels during winter might be attributed to the combined effects of industrial emissions and reduced dilution. Conversely, the lower levels during summer could be due to increased dilution from higher water flow. The influence of anthropogenic activities on nickel concentrations is in line with studies that highlight the significance of human activities on heavy metal pollution (20). Edayar is a region with more than 400 industries. Industries involved in electroplating, metal finishing, and manufacturing of nickel-based products can release nickel into the environment through wastewater and emissions. The production and processing of stainless steel and other nickel-containing alloys can be a significant source of nickel pollution.

Cobalt (Co) concentrations

The relatively minor variations in cobalt concentrations across seasons could be indicative of stable sources contributing to cobalt pollution in the region. The consistent levels might be linked to common sources such as industrial discharges, vehicle emissions and natural weathering of cobalt-rich geological formations. The influence of local sources is consistent with research emphasizing the contribution of point sources to heavy metal contamination (21).

Copper (Cu) concentrations

The higher copper concentrations during winter and summer seasons could be associated with increased human activities during these periods. Anthropogenic sources like industrial processes and domestic runoff may contribute to these elevated levels (22). The lower concentrations during the monsoon seasons might be due to enhanced dilution and reduced runoff from these sources. Similar observations have been made in studies highlighting the impact of human activities on heavy metal concentrations in water bodies.

Arsenic (As) concentrations

The detectable levels of arsenic across all seasons suggest the presence of this toxic element in the region. The relatively higher concentrations during the summer season could be linked to the influence of temperature and precipitation on arsenic release from geological formations. The fluctuations across seasons could also be attributed to changes in water chemistry and redox conditions (23).

Cadmium (Cd) concentrations

The substantial variations in cadmium concentrations across seasons highlight the dynamic nature of this heavy metal's contamination. The higher concentrations during summer and winter could be due to increased human activities, potentially releasing cadmium from industrial processes and waste disposal (24).

Lead (Pb) concentrations

The significant variations in lead concentrations across seasons indicate the complex interplay of anthropogenic and natural sources. The elevated levels during winter might be linked to increased industrial activities and atmospheric deposition (25). The lower concentrations during monsoon seasons might be due to enhanced dilution and reduced atmospheric inputs. Similar observations have been reported in studies highlighting the impact of atmospheric deposition on heavy metal levels.

Zinc (Zn) concentrations

The variations in zinc concentrations across seasons could be attributed to the influence of multiple sources, including industrial discharges and urban runoff. The highest concentration during the southwest monsoon season might be due to enhanced runoff from impervious surfaces, carrying zinc-rich sediments into the river. The relatively consistent levels across other seasons could be linked to the consistent release of zinc from various sources (26).

Groundwater samples

According to the data in Table 3, the highest concentrations of chromium were observed during the southwest monsoon (5127.61±0.83ppb) and northeast monsoon (4914.49±1.3 ppb), indicating a potential source of contamination during these periods. The winter season (4280.67±0.94 ppb) and summer season (4188.24±1.76 ppb) showed lower concentrations. The northeast monsoon exhibited the highest concentration of iron (865724.09±0.87 ppb), followed by the winter season (848220.97±0.67 ppb). The southeast monsoon (829535.44±1.6 ppb) and summer season (808962.27±0.58 ppb) also displayed elevated iron levels. The northeast monsoon has the highest nickel concentration (8824.84±1.44 ppb), while the southeast monsoon (8339.31±1.37 ppb) and summer season (7918.67±0.33 ppb) showed relatively notable concentrations. The winter

Table 3. Heavy metal concentration (parts per billion, ppb) in groundwater samples of Edayar, Kerala India.

Sl No	Heavy Metals	Southwest Monsoon	Northeast Monsoon	Winter Season	Summer Season
1	Cr (ppb)	5127.61±0.83	4914.49±1.3	4280.67±0.94	4188.24±1.76
2	Fe (ppb)	829535.44±1.6	865724.09±0.87	848220.97±0.67	808962.27±0.58
3	Ni (ppb)	8339.31±1.37	8824.84±1.44	7521.13±0.83	7918.67±0.33
4	Co (ppb)	1443.34±1.22	1247.03±0.75	1303.02±0.34	1737.46±1.66
5	Cu (ppb)	1974.13±0.8	1577.44±0.63	1820.92±1.53	1231.89±1.23
6	As (ppb)	54.83±1.26	49.31±0.95	42.16±0.77	56.20±0.82
7	Cd (ppb)	94.42±0.68	83.23±0.94	87.421±1.5	84.12±0.87
8	Pb (ppb)	492.42±1.27	480.72±1.64	360.95±0.94	324.19±0.86
9	Zn (ppb)	2152.36±1.17	2613.05±1.84	2830.34±1.25	2642.87±1.05

season (7521.13±0.83 ppb) falls in between. Minor variations in cobalt concentrations were observed among the seasons. The summer season (1737.46±1.66 ppb) showed slightly higher concentrations, followed by the southwest monsoon (1443.34±1.22), while the northeast monsoon (1247.03±0.75 ppb) and winter season 1303.02±0.34 ppb) have lower levels. The southwest monsoon displayed the highest copper concentration (1974.13±0.8 ppb), followed by the winter Season (1820.92±1.53 ppb). The northeast monsoon (1577.44±0.63 ppb) and summer season (1231.89±1.23 ppb) exhibited comparatively lower concentrations. Arsenic concentrations were relatively low across all seasons. The summer season has the highest concentration (56.20±0.82 ppb), followed by the southwest monsoon (54.83±1.26 ppb) and northeast monsoon (49.31±0.95 ppb). The winter season (42.16±0.77 ppb) showed the lowest concentration. The southwest monsoon displayed the highest cadmium concentration (94.42±0.68 ppb), followed by the winter season (87.421±1.5 ppb). The northeast monsoon (83.23±0.94 ppb) exhibited the lowest concentration, while the summer season (84.12±0.87 ppb) falls in between. The southwest showed the highest lead concentration (492.42±1.27 ppb), followed by the northeast monsoon (480.72±1.64 ppb). The winter season (360.95±0.94 ppb) and summer season (324.19±0.86 ppb) exhibited relatively lower concentrations. The winter season displayed the highest zinc concentration (2830.34±1.25 ppb), followed by the summer season (2642.87±1.05 ppb) and northeast monsoon (2613.05±1.84 ppb) and southwest monsoon (2152.36±1.1 ppb) exhibited relatively lower concentrations.

The elevated concentration of chromium during the southwest and northeast monsoons suggests that increased rainfall and subsequent leaching could mobilize chromium from industrial sources and soil, resulting in higher concentrations during the monsoon seasons (27). The higher iron concentration during the northeast monsoon and winter seasons enhances water flow during these periods and increases the contact between groundwater and iron-bearing minerals. The elevated nickel concentrations during the northeast monsoon explain that nickel sources, including anthropogenic activities and natural mineral dissolution, contribute to its temporal variations in groundwater (28). The minor variations in cobalt concentrations across seasons were relatively stable, which suggests that while cobalt is less sensitive to seasonal fluctuations, anthropogenic influences can still play a role in its presence. The findings of higher copper concentrations during the southwest monsoon identify industrial discharges and urban runoff as potential sources of copper contamination. The low concentrations of arsenic across all seasons highlight the relatively low levels of arsenic in the region, attributing them to the geology and hydrogeochemical conditions of the aquifers (29). The observations of higher cadmium concentrations during the southwest monsoon were influenced by increased surface runoff during the monsoon. The high concentrations of zinc during the winter season resonates with the research paper's findings that zinc levels are influenced by factors such as mineral dissolution and groundwater flow (30).

Aquatic soil samples

The highest concentration of chromium was observed during the northeast monsoon (35153.93±0.94 ppb), while the lowest concentration was recorded during the winter season (29237.32±0.6 ppb) (Table 4). The southwest monsoon (34889.29±1.06 ppb) and summer season (30192.47±0.8 ppb) exhibited intermediate levels of chromium. Iron concentrations showed variability across seasons, with the highest levels during the southeast monsoon (54105.02±1.2 ppb) and summer season (53130.53±0.6 ppb). The northeast monsoon (51703.69±1 ppb) and winter season (50177.37±0.65 ppb) displayed relatively lower concentrations of iron. Nickel concentrations vary among seasons, with the highest levels observed during the summer season (985.87±0.8 ppb). The northeast monsoon (950.19±1.3 ppb) and southwest monsoon (924.07±0.7 ppb) exhibited intermediate concentrations, while the winter season (841.04±1.3 ppb) showed a lower level of nickel. Cobalt concentrations exhibited minor variations across seasons,

Table 4. Heavy metal concentration (parts per billion, ppb) in aquatic soil samples of Edayar, Kerala India.

Sl No	Heavy Metals	Southwest Monsoon	Northeast Monsoon	Winter Season	Summer Season
1	Cr (ppb)	34889.29±1.06	35153.93±0.94	29237.32±0.6	30192.47±0.8
2	Fe (ppb)	54105.02±1.2	51703.69±1	50177.37±0.65	53130.53±0.6
3	Ni (ppb)	924.07±0.7	950.19±1.3	841.04±1.3	985.87±0.8
4	Co (ppb)	103.28±0.5	135.44±1	101.75±1	115.67±0.9
5	Cu (ppb)	2133.57±1.2	2172.73±0.8	2676.42±0.5	2213.07±1.5
6	As (ppb)	5.24±0.4	5.77±0.5	8.18±0.5	6.62±0.5
7	Cd (ppb)	7.62±0.5	6.42±0.8	6.06±0.8	7.54±0.5
8	Pb (ppb)	85.04±1.2	80.93±1.2	84.68±1.4	82.39±1.5
9	Zn (ppb)	37504.55±0.8	39289.16±1.2	39083.77±2	36635.56±2.5

with slightly higher levels during the southwest monsoon (103.281 ppb) and winter season (101.756 ppb). The northeast monsoon (135.444 ppb) and summer season (115.672 ppb) showed lower concentrations of cobalt. Copper concentrations vary, with the highest levels observed during the northeast monsoon (135.44±1 ppb) and summer season (115.67±0.9 ppb). The southwest monsoon (103.28±0.5 ppb) and winter season (101.75±1 ppb) showed relatively lower concentrations of copper. Arsenic concentrations were relatively low across all seasons, with the winter season exhibiting the highest concentration (8.18±0.5 ppb). The summer season (6.62±0.5 ppb), northeast monsoon (5.774 ±0.5 ppb), and southwest monsoon (5.24±0.4 ppb) showed lower levels of arsenic. Cadmium concentrations vary, with the southwest monsoon (7.62±0.5 ppb) showing the highest concentration. The winter season (6.06±0.8 ppb) and northeast Monsoon (6.42±0.8 ppb) exhibited lower levels, while the summer season (7.54±0.5 ppb) falls in between. Lead concentrations also vary among seasons, with the highest levels observed during the southwest monsoon (85.04±1.2 ppb) and the winter season (84.68±1.4 ppb). The northeast monsoon (80.93±1.2 ppb) and summer season (82.39±1.5 ppb) showed lower concentrations of lead. Zinc concentrations exhibited significant variation across seasons, with the highest concentration observed during the northeast monsoon (39289.16±1.2 ppb) followed by the winter season (39083.77±2 ppb). The southwest monsoon (37504.55±0.8 ppb) also showed a notable level of zinc, followed by the summer season (36635.56±2.5 ppb).

The data indicates that the highest concentration of chromium was observed during the northeast monsoon, with the lowest during the summer season. This trend could be associated with increased leaching and runoff during the monsoon, leading to the mobilization of chromium from soil and other sources. (31). Industries such as leather tanning, electroplating, steel manufacturing and textile production use chromium compounds extensively. Effluents from these industries can contain high levels of chromium, which can be washed into water bodies during the monsoon. Urban areas contribute to chromium pollution through runoff from roads, buildings and industrial sites. Chromium from vehicle emissions, construction materials, and other urban sources can be mobilized during heavy rains. Variability in iron concentrations across seasons was observed, with elevated levels during the southeast monsoon and summer season emphasizing the influence of seasonal changes on iron mobilization from soil and its subsequent impact on water quality. Increased precipitation during these seasons could enhance iron leaching (32). The highest nickel concentrations were observed during the summer season, indicating a potential source of contamination. This could be due to factors like increased human activities during this time. Higher rates of waste generation during the summer, including industrial, municipal and agricultural waste, can lead to more significant leaching of nickel from landfills and waste storage areas. The use of nickel-containing agricultural inputs in nearby farmlands can lead to increased nickel runoff during summer irrigation practices. Higher temperatures during the summer can lead to increased evaporation of water bodies, concentrating nickel and other dissolved metals in the remaining water. Minor variations in cobalt concentrations were observed among the seasons that discuss cobalt's presence in soil due to both natural geological sources and anthropogenic activities. Copper concentrations display variation, with elevated levels during the northeast monsoon and summer season, which highlights the significance of land use practices, agriculture and industrial activities (33). Arsenic concentrations were relatively low across all seasons, with the highest during the winter season. This could be due to factors like soil characteristics and geochemical interactions that influence arsenic mobility, the presence of arsenic in soil and its potential implications for groundwater quality. Cadmium concentrations vary, with the southwest monsoon showing the highest concentration, emphasizing the need for effective management strategies (34). Lead concentrations vary among seasons, with the highest levels during the southwest monsoon and winter seasons, which discusses the role of urbanization and industrial activities in contributing to lead contamination in soil (32). Zinc concentrations exhibited significant variation across seasons, with the highest during the northeast monsoon, highlighting the potential sources of zinc contamination in soil, including industrial activities and urban runoff (35).

Terrestrial soil samples

Chromium concentrations showed variation across seasons as shown in Table 5, with the highest levels recorded during the southwest monsoon (17769.16±1.2 ppb) and summer season (17205.28±1.5 ppb). The northeast monsoon (15025.46±0.8 ppb) and winter season (14450.48±1.5 ppb) exhibited lower concentrations of chromium. Iron concentrations display significant differences among seasons. The highest concentration was observed during the summer season (3825633.2±1.2 ppb), followed by the northeast monsoon (3248803.08±0.8 ppb). The southwest monsoon (3196436.88±1 ppb) and winter season (3130443.91±1.5 ppb) also showed elevated iron levels. Nickel concentrations showed variation, with the highest levels observed during the summer season (27644.73±1 ppb) and winter season (27055.7±0.8 ppb). The southwest monsoon (21248.52±0.5 ppb) and northeast monsoon (22569.53±1 ppb) exhibited relatively lower concentrations. Cobalt concentrations exhibited minor variations across seasons. The winter season (2694.36±0.5 ppb) showed a higher concentration, followed by southwest monsoon (2593.36±0.5), summer season (2547.21±0.7) and northeast monsoon (2180.76±0.5). Copper concentrations vary among seasons, with the highest levels observed during the northeast monsoon (2834.73±1.5 ppb) followed by the southwest monsoon (2753.42±0.5 ppb), summer season (2685.54±0.5 ppb) and winter season (2464.04±0.5 ppb). Arsenic concentrations were relatively low across all seasons, with the summer season (153.83±0.85 ppb) exhibiting the highest concentration, followed by northeast monsoon (137.2±0.5), winter season (122.7±1) and

Table 5. Heavy metal concentration (parts per billion, ppb) in terrestrial soil samples of Edayar, Kerala India.

Sl No	Heavy Metals	Southwest Monsoon	Northeast Monsoon	Winter Season	Summer Season
1	Cr (ppb)	17769.16±1.2	15025.46±0.8	14450.48±1.5	17205.28±1.5
2	Fe (ppb)	3196436.88±1	3248803.08±0.8	3130443.91±1.5	3825633.2±1.2
3	Ni (ppb)	21248.52±0.5	22569.53±1	27055.7±0.8	27644.73±1
4	Co (ppb)	2593.36±0.5	2180.76±0.5	2694.36±0.5	2547.21±0.7
5	Cu (ppb)	2753.42±0.5	2834.73±1.5	2464.04±0.5	2685.54±0.5
6	As (ppb)	112.42±1.5	137.2±0.5	122.7±1	153.83±0.85
7	Cd (ppb)	234.76±0.75	287.34±0.8	281.09±0.5	282.02±0.84
8	Pb (ppb)	853.89±0.6	807.68±1.2	881.82±1.5	810.72±1
9	Zn (ppb)	9923.68±0.5	9812.82±0.5	9360.27±0.7	9261.91±0.85

southwest monsoon (112.42±1.5). Cadmium concentrations vary, with the northeast monsoon (287.34±0.8 ppb) exhibiting the highest concentration, followed by the summer season (282.02±0.84 ppb), winter season (281.09±0.5 ppb) and southeast monsoon (234.76±0.75 ppb). Lead concentrations vary among seasons, with the winter season (881.82±1.5 ppb) exhibiting the highest levels, followed by the southwest monsoon (853.89±0.6 ppb), summer season (810.72±1 ppb) and northeast monsoon. Zinc concentrations showed variation among seasons, with the southwest monsoon (9923.68 ppb) exhibiting the highest concentration. The northeast monsoon (9812.824 ppb) and winter season (6360.27 ppb) also showed notable levels, while the summer season (261.91 ppb) recorded a relatively lower concentration.

The observed variations in chromium concentrations across seasons can be attributed to factors such as precipitation and temperature changes (24). During the southwest monsoon and summer seasons, higher precipitation and warmer temperatures can enhance the leaching and mobilization of chromium from soil and sediment, leading to increased concentrations. This aligns with studies that have shown elevated heavy metal concentrations during wetter and warmer periods. The significant differences in iron concentrations among seasons suggest seasonal variations in the sources of iron and its transport mechanisms. Seasonal weathering processes, runoff and anthropogenic activities can influence iron levels (36). The higher concentrations during the summer season might be associated with increased soil erosion and agricultural activities (37). This is in line with research indicating that iron concentrations can be influenced by both natural and human-induced processes. The seasonal variability in nickel concentrations can be attributed to sources such as industrial emissions, vehicular traffic and atmospheric deposition. The higher levels during the summer and winter seasons might be linked to increased human activities and atmospheric transport. Nickel's behaviour often reflects its association with anthropogenic sources, as evidenced by previous studies (38). The minor variations in cobalt concentrations across seasons suggest a relatively stable behaviour. Cobalt's mobility and distribution are influenced by factors such as soil characteristics and redox conditions. The higher concentration during the winter season might be attributed to factors like increased energy consumption, which could contribute to anthropogenic cobalt emissions (39). The seasonal variations in copper concentrations can be attributed to both natural sources and human activities. Anthropogenic sources like industrial processes and stormwater runoff can contribute to copper concentrations in urban environments, as highlighted in previous studies. The observed low concentrations of arsenic across all seasons suggest relatively stable behaviour. Arsenic's mobility is influenced by factors like pH, redox conditions and sorption processes. The highest concentration during the summer season might be related to changes in environmental conditions affecting arsenic speciation and transport (40). The highest cadmium concentrations during the northeast monsoon might be influenced by atmospheric deposition and regional sources. Cadmium's behaviour is often linked to industrial activities and atmospheric transport. The variation in concentrations across seasons underscores the role of atmospheric pathways in cadmium distribution. Lead concentrations showed distinct seasonal variations, with the highest levels during the winter season. This can be attributed to factors like increased energy consumption, which can release lead-containing particles from various sources (41). The significant variations in zinc concentrations across seasons suggest a strong influence on human activities. Higher concentrations during the southwest monsoon align with increased runoff and leaching from zinc-containing materials. Zinc's presence in industrial emissions and urban runoff contributes to its seasonally variable distribution.

Terrestrial plants in southwest monsoon

As shown in Table 6, *Scoparia dulcis* exhibited high concentrations of chromium (31,498±0.5 ppb), iron (348322.91±0.8 ppb) and nickel (3186.63±0.6 ppb) in its shoot. Other heavy metals such as nickel, copper, arsenic, cadmium, lead and zinc were also present but at lower levels. The root showed relatively higher concentrations of

Table 6. Heavy metal concentration (parts per billion, ppb) in the shoot and root of terrestrial plants during southwest monsoon of Edayar, Kerala India.

Season	Plant Species	Plant Part	Cr (ppb)	Fe (ppb)	Ni (ppb)	Co (ppb)	Cu (ppb)	As (ppb)	Cd (ppb)	Pb (ppb)	Zn (ppb)
Southwest Monsoon	*Scoparia dulcis* L.	Shoot	31498.22±0.5	348322.912±0.8	3186.63±0.6	2238.41±1	2198.44±1	11.2±1	1881.44±0.5	173.85±0.5	21388.8±1.5
		Root	34295.21±1.5	305691.48±0.4	2885.94±0.8	2288.98±0.6	2605.68±0.5	11.1±0.5	2083.91±0.67	147.68±0.4	28767.42±1.6
	Synedrella nodiflora Gaertn	Shoot	43960.37±1.3	91388.29±0.5	1876.18±1.7	2149.63±1	2605.68±1.2	11.10±1.3	2183.91±0.5	147.68±1.4	27767.42±0.5
		Root	54271.48±0.5	147368.55±1.4	1476.3±0.86	1851.02±1	1948.31±0.93	5.04±0.2	2665.7±0.47	121.74±0.58	29372..09±0.52
	Alternanthera philoxeroides (Mart.) Griseb	Shoot	7756.48±1	124435.21±0.7	1133.6±0.5	2776.31±0.21	1997.36±0.43	11.27±1	1663.28±0.65	155.72±1.5	182097.86±1.3
		Root	9254.21±0.45	199832.31±0.2	1853.93±1.4	2976.03±1.2	1165.16±0.6	9.12±1.4	1991.38±0.6	182.25±0.3	122259.62±0.75

heavy metals compared to the shoot, including chromium (34295.21±1.5 ppb), iron (305691.48±0.4 ppb) and copper (2605.68±0.5 ppb). Other heavy metals were also detected but at varying levels. *Synedrella nodiflora* exhibited elevated concentrations of chromium (43960.37±1.3 ppb) and copper (2605.68±1.2 ppb) in its shoot. Other heavy metals such as iron, nickel, cobalt, arsenic, cadmium, lead and zinc were present but at relatively lower levels. The root contains higher concentrations of chromium (54271.48±0.5 ppb) and iron (47368.55±1.4 ppb). Other heavy metals were also detected but at varying levels. *Alternanthera philoxeroides* showed relatively lower concentrations of heavy metals in its shoot compared to the other two plant species. It contained chromium (7756.48±1 ppb), iron (124435.21±0.7 ppb), and copper (1997.36±0.43 ppb). Other heavy metals were also present but at lower levels. The root exhibited similar heavy metal concentrations as the shoot, including chromium (9254.21 ±0.45 ppb), iron (199832.31 ±0.2 ppb) and copper (2976.03±1.2 ppb). Other heavy metals were also detected but at varying levels.

The provided dataset presents a comprehensive analysis of heavy metal concentrations in the shoot and root tissues of 3 terrestrial plant species during the southwest monsoon season in Edayar, Kerala, India. The results indicated that the accumulation patterns and tolerance strategies toward various heavy metals between these plants have been observed.

S. dulcis is characterized by its significant accumulation of heavy metals in both shoot and root tissues. Notably, the shoot of this species displays high concentrations of chromium, iron and nickel. The presence of such elevated levels of chromium and iron suggests that *S. dulcis* has evolved efficient mechanisms for the uptake and storage of heavy metals. This could involve specialized transporters and chelating compounds that aid in the absorption and retention of these metals (42). The observation of higher metal concentrations in the root compared to the shoot implies a possible preference for sequestering heavy metals in the root system, thereby safeguarding the aerial parts of the plant from potential toxicity (43). *S. nodiflora* presents a distinct pattern of heavy metal accumulation. Its shoot demonstrates considerable amounts of chromium and copper. Particularly, the higher concentrations of chromium in both shoot and root tissues suggest the species' adaptation to environments rich in heavy metals. This could involve genetic adaptations that facilitate enhanced metal uptake and tolerance. The relatively lower levels of other heavy metals like iron and nickel could imply either a selective metal uptake strategy or a finely tuned mechanism to maintain equilibrium among different metal ions (44). *A. philoxeroides*, in contrast, exhibited relatively lower heavy metal concentrations, especially in the shoot, when compared to the other species. Although chromium, iron, and copper were present in both shoot and root tissues, their levels are notably subdued. This hints at potential mechanisms within *A. philoxeroides* that regulate heavy metal uptake or effectively detoxify these metals (45). The consistency in metal concentrations between shoot and root further suggests a uniform distribution of heavy metals within the plant. The presence of varying levels of arsenic, cadmium, lead and zinc among these species contributes significantly to the broader discussion on metal accumulation and plant tolerance. These heavy metals are often associated with environmental contamination and pose substantial risks to plant health. The inter-species differences in their accumulation could be attributed to varying strategies related to metal uptake, transport and detoxification.

Terrestrial plants in northeast monsoon

The results suggested that the terrestrial plants studied during the northeast monsoon season (Table 7) accumulate various heavy metals in their shoot and root tissues. Chromium, iron and copper were consistently present across the plant species analysed, with varying concentrations. Other heavy metals also exhibited detectable levels depending on the plant and plant part. The presence of these heavy metals in plants raises concerns about potential environmental contamination

Table 7. Heavy metal concentration (parts per billion, ppb) in the shoot and root of terrestrial plants during northeast monsoon of Edayar, Kerala India.

Season	Plant Name	Plant Part	Cr (ppb)	Fe (ppb)	Ni (ppb)	Co (ppb)	Cu (ppb)	As (ppb)	Cd (ppb)	Pb (ppb)	Zn (ppb)
Northeast Monsoon	*Scoparia dulcis* L.	Shoot	1020.95±0.5	438812.73±1.4	1442.4±0.85	224.03±1.26	275.84±0.61	25.09±1.5	343.52±0.53	74.17±0.5	3645.79±1.5
		Root	1107.26±1	442104.63±1.56	1481.8±2.5	325.46±1.29	301.75±0.5	35.79±1.05	373.71±0.5	115.1±1.95	3678.98±0.58
	Synedrella nodiflora Gaertn	Shoot	1387.28±2.5	338795.48±1.45	1388.39±0.5	325.7±1.34	340.2±1.43	35.46±1.5	392.17±1	92.87±1.7	3306.36±0.76
		Root	1163.96±0.42	331118.008±0.5	1311.65±2.1	324.03±1.41	275.84±1.5	34.09±0.49	413.52±0.57	114.17±0.25	4645.79±0.83
	Alternanthera philexeroides (Mart.) Griseb	Shoot	1455.47±2.3	340835.88±1	1409.39±0.5	352.02±	245.89±1.80	26.54±1	342.65±0.74	87.65±0.5	3303.58±1.8
		Root	1238.74±0.83	237382.65±0.53	1929.69±0.5	393.45±1.2	276.51±2.4	34.93±0.57	422.15±1.3	108.26±1.8	4454.88±0.66

and the need for further assessment of their impacts on ecosystem health and human well-being.

S. dulcis exhibited moderate concentrations of chromium (1020.95±0.5 ppb), iron (438812.73±1.4 ppb) and copper (275.84±0.61 ppb) in the shoot. Other heavy metals such as nickel, cobalt, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root showed similar concentrations of heavy metals compared to the shoot, including chromium (1107.26±1 ppb), iron (42104.63±1.56 ppb) and copper (301.75±1.29 ppb). Other heavy metals were also detected but at varying levels. *S. nodiflora* plant species exhibited higher concentrations of heavy metals in the shoot, including chromium (1387.28±2.5 ppb), iron (338795.48±1.45 ppb) and copper (3306.36±0.76 ppb). Other heavy metals such as nickel, cobalt, arsenic, cadmium, lead and copper were also present but at relatively lower levels. The root exhibited relatively lower concentrations of heavy metals compared to the shoot, including chromium (1163.96±0.42 ppb), iron (331118.008±0.5 ppb) and zinc (4645.79±0.83 ppb). Other heavy metals were also detected but at varying levels. *A. philexeroides* plant showed moderate concentrations of heavy metals in the shoot, including chromium (1455.47±2.3 ppb), iron (340835.88±1 ppb) and zinc (3303.58±1.8 ppb). Other heavy metals such as nickel, cobalt, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root exhibited higher concentrations of heavy metals compared to the shoot, including chromium (1238.74±0.83 ppb), iron (237382.65±0.53 ppb) and zinc (4454.88±0.66 ppb). Other heavy metals were also detected but at varying levels.

In the case of *S. dulcis*, the shoot and root tissues exhibited moderate concentrations of chromium, iron, and copper. The observed presence of these heavy metals, combined with the lower levels of other metals, suggests a propensity for *S. dulcis* to accumulate these elements from its surroundings (46). Although the absolute concentrations may not raise immediate alarm, the potential for prolonged exposure and accumulation of these metals necessitates a thorough investigation into the plant's role within the local ecosystem's metal dynamics and the potential ramifications for ecosystem health (47). Similarly, *A. philoxeroides* exhibited moderate concentrations of heavy metals, notably chromium, iron and zinc, in both shoot and root tissues. The consistency in heavy metal concentrations between the two plant parts might suggest a uniform distribution strategy within the plant (48). The fact that *A. philoxeroides* appears to accumulate these heavy metals without reaching alarming levels could imply the effectiveness of detoxification mechanisms or an inherent ability to regulate metal uptake. The distinct accumulation patterns among these species indicate variations in metal uptake, translocation and tolerance mechanisms. This underscores the critical importance of comprehending the intricate interactions between plants and metals, especially in the context of potential environmental contamination and its potential repercussions.

Terrestrial plants in winter

Based on the provided data on heavy metal concentrations (parts per billion, ppb) in the shoot and root of terrestrial plants during the winter season in Edayar, Kerala, India, represented in Table 8, the following analysis can be made:

S. dulcis plant exhibited moderate concentrations of chromium (3006.90±0.5 ppb), iron (696353.63±1.2 ppb) and nickel (4515.66±1.7 ppb) in the shoot. Other heavy metals such as copper, cobalt, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root showed higher concentrations of heavy metals compared to the shoot, including chromium (2118.91±0.85 ppb), iron (803766.99±1.5 ppb) and nickel (7181.05±1.32 ppb). Other heavy metals were also detected but at varying levels. *S. nodiflora* plant species exhibited high concentrations of heavy metals in the shoot, including chromium (10332.2±1.3 ppb), iron (3612143.12±0.52 ppb) and copper (3525.21±1.25 ppb). Other heavy metals such as nickel, cobalt, arsenic, cadmium, lead and zinc were also present but at varying levels. The root exhibited even higher concentrations of heavy metals compared to the

Table 8. Heavy metal concentration (parts per billion, ppb) in the shoot and root of terrestrial plants during winter season of Edayar, Kerala India.

Season	Plant Species	Plant Part	Cr (ppb)	Fe (ppb)	Ni (ppb)	Co (ppb)	Cu (ppb)	As (ppb)	Cd (ppb)	Pb (ppb)	Zn (ppb)
Winter Season	*Scoparia dulcis* L.	Shoot	3006.9±0.5	696353.63±1.2	4515.66±1.7	215.49±0.6	889.97±0.5	129.8±1.3	223.73±0.58	236.68±0.42	4352.67±1.7
		Root	2118.91±0.85	803766.99±1.5	7181.05±1.32	291.52±1.72	774.76±2.1	150.3±1.83	332.85±0.47	423.82±0.72	5249.14±1.1
	Synedrella nodiflora Gaertn	Shoot	10332.2±1.3	3612143.12±0.52	31648.48±0.7	1773.83±1.4	3525.21±1.25	185.96±0.74	203.41±0.28	1917.23±1.4	7873.51±.1.73
		Root	16597.6±0.58	5485676.4±1.41	49052.56±0.72	2158.28±0.5	5114.47±0.59	245.94±1.43	228.36±1.57	2121.25±1.18	9556.55±0.83
	Alternanthera philoxeroides (Mart.) Griseb	Shoot	16829.14±0.63	1445062.9±0.46	19421.48±1.5	326.79±1.06	2291.49±1.28	146.08±1.5	163.33±0.58	325.7±0.51	10895.66±0.73
		Root	20199.28±1.4	2311077.41±1.73	20277.20±0.62	414.95±0.59	2393.7±0.26	126.28±0.51	177.83±0.5	955.56±1.3	11520.56±1.07

shoot, including chromium (16597.6±0.58 ppb), iron (5485676.4±1.41 ppb) and copper (5114.47±0.59 ppb). Other heavy metals were also detected but at varying levels. *A. philoxeroides* plant showed relatively lower concentrations of heavy metals in the shoot, including chromium (16829.14±0.63 ppb), iron (1445062.9±0.46 ppb), and zinc (10895.66±0.73 ppb). Other heavy metals such as nickel, cobalt, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root exhibited higher concentrations of heavy metals compared to the shoot, including chromium (20199.28±1.4 ppb), iron (2311077.41±1.73 ppb) and zinc (11520.56±1.07 ppb). Other heavy metals were also detected but at varying levels.

The analysis revealed the presence of various heavy metals, including chromium, iron, nickel, copper, cobalt, arsenic, cadmium, lead and zinc, with their concentrations measured in parts per billion (ppb). These findings hold significant implications for understanding the potential risks of environmental contamination and its potential consequences for both ecosystems and human health.

S. dulcis displayed moderate concentrations of chromium, iron and nickel in its shoot, with higher levels found in its root tissues. This accumulation pattern implies the plant's ability to absorb and store these metals from its environment (49). Such an adaptive mechanism could involve the utilization of metal transporters and chelating compounds, facilitating the efficient absorption and management of heavy metals. The elevated concentrations detected in the root tissues might indicate a preference for metal storage, which could serve to shield the above-ground parts of the plant from potential metal toxicity (49). *S. nodiflora* demonstrated elevated concentrations of heavy metals in its shoot, specifically chromium, iron and copper. These high levels might suggest an evolutionary response to a metal-rich environment, potentially linked to genetic traits enhancing the plant's metal uptake and accumulation capabilities (50). The higher concentrations observed in the root tissues in comparison to the shoot may suggest effective mechanisms for metal translocation, aiding in transporting absorbed metals to the root system (51). However, the presence of various heavy metals in detectable quantities raises the necessity for a more comprehensive exploration of their potential ecological implications. *A. philoxeroides*, in contrast, presents relatively lower heavy metal concentrations in its shoot, including chromium, iron and zinc. This could point toward mechanisms that regulate metal uptake or efficient detoxification processes within the plant (52). The uniformity in heavy metal concentrations between the shoot and root suggests a consistent strategy for metal distribution, which might indicate a well-balanced mechanism for metal regulation (52).

Terrestrial plants in summer

Based on the provided data on heavy metal concentrations (parts per billion, ppb) in the shoot and root of terrestrial plants during the summer season in Edayar, Kerala, India, the following analysis can be made (Table 9):

S dulcis plant exhibited relatively higher concentrations of nickel (43223.28±1.07 ppb), iron (460191.19±1.4 ppb) and copper (4774.76±0.29 ppb) in the shoot. Other heavy metals such as chromium, cobalt, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root showed higher concentrations of heavy metals compared to the shoot, including chromium (14966.73±0.47 ppb), iron (5578948.14±1.23 ppb) and nickel (50883.36±0.82 ppb). Other heavy metals were also detected but at varying levels. *Sphagneticola trilobata* exhibited relatively low concentrations of heavy metals in the shoot, including chromium (513.48±1.58 ppb), iron (21302.11±0.79 ppb) and cobalt (319.45±1.3 ppb). Other heavy metals such as nickel, copper, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root showed moderate concentrations of heavy metals, including chromium (774.53±0.46 ppb), iron (291676.21±0.5 ppb) and copper (948.71±1.92 ppb). Other heavy metals were also detected but at varying levels. *A. philexeroides*

Table 9. Heavy metal concentration (parts per billion, ppb) in the shoot and root of terrestrial plants during summer season of Edayar, Kerala India.

Seasons	Plant Species	Plant Part	Cr (ppb)	Fe (ppb)	Ni (ppb)	Co (ppb)	Cu (ppb)	As (ppb)	Cd (ppb)	Pb (ppb)	Zn (ppb)
Summer Season	*Scoparia dulcis* L.	Shoot	11700.46±0.5	460191.19±1.4	43223.28±1.07	2142.98±0.63	4774.76±0.29	250.31±0.58	132.85±0.72	1423.82±1.05	1849.14±0.86
		Root	14966.73±0.47	5578948.14±1.23	50883.36±0.82	2251.95±0.72	5529.96±0.59	265.44±0.83	147.57±1.69	2183.1±0.78	2012.55±1.89
	Sphagneticolatrilobata (L.) Pruski	Shoot	513.48±1.58	21302.11±0.79	2200.087±0.29	319.45±1.3	725.39±1.48	210.39±1.29	315.2±0.62	110.27±1.29	715.03±0.94
		Root	774.53±0.46	291676.21±0.5	2491.86±1.43	390.43±0.5	948.71±1.92	257.03±0.58	470.61±0.75	172.91±1.7	843.86±0.37
	Alternanthera philexeroides (Mart.) Griseb	Shoot	303.81±0.59	389693.81±0.74	2816.78±0.73	547.35±0.82	325.39±1.47	111.39±1.49	215.2±0.94	110.27±0.5	715.03±1.96
		Root	468.18±0.83	411837.42±0.5	3418.8±0.83	783.49±0.49	411.78±0.73	115.11±0.5	470.61±1.14	172.91±0.74	843.86±2.6

exhibited relatively low concentrations of heavy metals in the shoot, including chromium (303.81±0.59 ppb), iron (389693.81±0.74 ppb) and copper (325.39±1.47 ppb). Other heavy metals such as nickel, cobalt, arsenic, cadmium, lead and zinc were also present but at relatively lower levels. The root showed moderate concentrations of heavy metals, including chromium (468.18±0.83 ppb), iron (411837.42±0.5 ppb) and copper (783.49±0.49 ppb). Other heavy metals were also detected but at varying levels. Chromium, iron and copper were consistently present across the plant species analyzed, with varying concentrations. A consistent trend was apparent across the studied plant species. *S. dulcis*, for example, showcased relatively high concentrations of nickel, iron and copper in its shoot, with even higher levels detected in its root tissues. This accumulation pattern suggests the plant's proficiency in absorbing and storing these metals from its surroundings (53). The mechanism behind this capability may involve the utilization of metal transporters and chelating compounds, enabling the plant to efficiently uptake and manage heavy metals. The elevated concentrations in the root tissues could imply a preference for metal storage, possibly to shield the above-ground parts of the plant from potential metal toxicity (53).

On the other hand, *S. trilobata* displayed comparatively low concentrations of heavy metals in its shoot, particularly for chromium, iron and cobalt. The root, in contrast, exhibited moderate concentrations of these metals. This distribution might suggest a regulated mechanism for metal uptake and translocation within the plant. Such a pattern could indicate the presence of metal transporters that effectively regulate metal movement and accumulation (54).

A. philoxeroides similarly presented low concentrations of heavy metals in its shoot, including chromium, iron and copper, with moderate levels observed in the root. This could indicate the presence of mechanisms that control metal uptake and accumulation, or perhaps a more efficient detoxification system. The uniformity in heavy metal concentrations between shoot and root suggests a well-balanced strategy for metal distribution within the plant (55).

Aquatic plants in all seasons

A comprehensive analysis of the data revealed distinct trends and potential implications for the aquatic ecosystem's health and human welfare. The heavy metal concentrations showed variations across different seasons and among different plant species (Table 10). This suggests the influence of factors such as water quality, nutrient availability and climatic conditions on metal accumulation (56). For instance, the seasonal variation in *Eichhornia crassipes*, especially in shoot concentrations, could be attributed to changes in water chemistry and growth dynamics in response to the varying environmental conditions. Each aquatic plant species exhibited distinct patterns of heavy metal accumulation. *Pistia stratiote*s tends to accumulate higher levels of heavy metals in both shoot and root tissues during the southwest monsoon and winter seasons. *E. crassipes*, on the other hand, displayed relatively lower concentrations, while *Salvinia molesta*. falls in between the two. These differences could be due to species-specific traits, growth strategies and adaptations to the local environment (57). Comparing metal concentrations between the shoot and root parts of the same plant species revealed interesting trends. For example, *P. stratiotes* and *E. crassipes* exhibited higher metal concentrations in their root tissues compared to the shoot, suggesting the potential role of roots in metal uptake and accumulation. This distinction in accumulation patterns could be indicative of root-mediated mechanisms for metal tolerance and detoxification (58). The elevated concentrations of heavy metals in aquatic plants during all seasons, particularly in the root tissues, raise concerns about the potential ecological and human health implications. Heavy metals, even at low concentrations, can accumulate over time, leading to bioaccumulation in aquatic organisms and potential entry into the food chain. This bioaccumulation can have cascading effects on aquatic ecosystems and ultimately impact human health through consumption of contaminated aquatic organisms.

Table 10. Heavy metal concentration (parts per billion, ppb) in the shoot and root of aquatic plants during all the seasons of Edayar, Kerala India.

Seasons	Plant Species	Plant Part	Cr (ppb)	Fe (ppb)	Ni (ppb)	Co (ppb)	Cu (ppb)	As (ppb)	Cd (ppb)	Pb (ppb)	Zn (ppb)
Southwest Monsoon	*Pistia stratiotes* L.	Shoot	54939.52± 0.5	158174.72± 1.5	9446.69 3±0.6	1095.56 ±0.5	1911.31 ±0.62	15.21± 1.2	1276.52 ±1.52	864.37± 0.83	2259.6 2±0.47
		Root	55694.21± 0.35	260630.09± 0.74	9604.21 1±1.52	1930.63 ±0.5	2344.94 ±1.38	16.06± 0.68	1830.04 ±0.35	1112.04 ±0.5	2699.4 ±1.5
	Eicchornia crassipes (Mart.) Solms	Shoot	9685.49± 1.05	60979.16± 2.8	2587.44 ±0.38	635.5±0. 61	510.2± 0.74	9.37± 0.1.5	323.38± 0.53	26.71± 0.62	832.85 ±1.46
		Root	12636.54± 0.83	62577.38± 1.54	2608.35 ±0.25	735.84± 1.78	274.91± 0.72	10.68± 0.27	414.09± 0.62	28.46±0. 29	992.79 ±0.75
	Salvinia molesta D.Mitch.	Shoot	4201.2± 1.5	455196.5± 0.62	4472.78 ±0.27	1039.11 ±0.5	142.42± 0.5	36.33± 0.5	442.59± 1.48	9.01±0.8 2	307.42 ±0.3
		Root	4367.61± 0.83	546969.87± 0.39	4499.54 ±0.37	1834.65 ±1	211.97± 1	48.85± 0.5	492.42± 0.5	20.17±1	677.2± 0.5
North east monsoon	*Eicchornia crassipes* (Mart.) Solms	Shoot	244.32±1	720790.72± 0.36	5828.91 ±0.9	1103.78 ±0.2	479.66± 1	70.40± 0.38	3.31±0. 30	20.74±0. 64	940.7± 1
		Root	382.97±1	857493.43± 1.5	6233.52 ±1.5	2310.28 ±0.58	731.32± 0.37	94.54± 0.73	8.87±0. 5	31.15±1. 3	1131.7 5±
Winter Season	*Eicchornia crassipes* (Mart.) Solms	Shoot	215.002±1	243536.15± 1.67	1970.81 ±2.5	72.63±2. 86	254.97± 1.69	19.19± 0.5	3.6± 0.27	17.21± 2.1	9284.2 ±0.5
		Root	387.51± 0.46	336923.6± 0.35	2344.35 ±1.3	99.82± 1.5	383.6±1	27.2±1	5.64± 0.93	19.65±1	13187. 16±1.6 2
	Pistia stratiotes L.	Shoot	20673.47± 1	3640518.84 ±1.42	32200.1 ±1	790.53± 0.47	3537.79 ±0.69	188.81 ±1.63	169.46± 1	1609.19 ±1	9303.5 1±1
		Root	29090.67± 0.85	2280351.91 ±0.5	42578.7 8±1	988.91± 1	4606.85 ±1.94	216.10 ±1.73	273.05± 1	2125.84 ±1.62	10014. 2±1
Summer Season	*Eicchornia crassipes* (Mart.) Solms	Shoot	2123.66± 1.53	26560.94± 0.5	196.32± 0.73	12.54± 0.5	584.32± 1.4	4.32± 0.3	3.2± 0.01	65.17± 1.57	3689.0 9±1.64
		Root	2818.42± 0.47	49802.43± 0.27	256.4± 0.62	32.03± 0.5	741.4±0. 38	2.02±0 .1	4.02± 0.3	82.32±0. 5	4688.3 ±2.48
	Salvinia molesta D.Mitch.	Shoot	119.42± 0.4	58532.14± 2.4	104.2± 1.83	25.04± 0.5	215.32± 1	1.81±0 .2	3.87± 0.2	63.2±0.2	1182.2 8±1.2
		Root	220.79±1	72892.54±	284.03±	38.31± 0.15	308.27± 0.41	3.54±0 .48	6.51± 0.5	82.05± 0.5	1806.4 1±1.4
	Pistia stratiotes L.	Shoot	121.42± 0.4	25432.21± 1.64	189.86± 0.6	83.1± 0.5	80.4±1.7 6	0.37± 0.2	3.21± 0.5	62.52± 0.25	1402.3 ±1
		Root	122.42± 0.63	14538.32± 2.04	80.52± 0.53	97.52± 0.81	111.83± 0.46	2.41± 0.2	5.32± 0.2	78.81± 0.92	1688.9 3±1.83

Plants and their heavy metal concentration

Seasonal analysis of the heavy metal concentration of terrestrial and aquatic plants was carried out. Plants were selected according to their dominance. Diversity indices were carried out using PAST 4.03 software to identify the dominant species in a particular season.

During southwest monsoon *S. dulcis*, *S. nodiflora* and *A. philoxeroides* were found dominant at Edayar. The concentration of each heavy metal was found using ICP-MS analysis. In *S. dulcis*, iron, chromium and nickel concentrations were found at maximum and arsenic, cadmium and lead were at the minimum in their shoots. In the roots of the plant, the heavy metal concentration was more than that of the shoots. Iron, nickel, chromium and copper concentrations were higher in the roots, with arsenic and cadmium being the lowest. In *S. nodiflora*, heavy metals such as chromium, iron, cobalt and copper were found maximum in the shoots and arsenic, cadmium being the lowest. In the roots of the plant, except for chromium, cadmium and zinc, the concentration of heavy metals was less than that of shoots. In *A. philoxeroides*, the heavy metal concentration in roots was higher than that of the shoot except for nickel. Chromium, iron, nickeland zinc concentrations were higher in both shoot and root. Chromium, cobalt, copper and lead concentrations were higher in the shoots and roots of *S. nodiflora*. Iron and nickel concentrations were higher in *S. dulcis*. Zinc concentrations were found more in the roots and shoots of *A. philoxeroides*.

During the northeast monsoon, *S. dulcis*, *S. nodiflora* and *A. philoxeroides* were found dominant. In *S. dulcis*, chromium, iron and zinc were found in higher concentrations and lead, arsenic and cadmium in lower concentrations. Heavy metals were present more in the roots than in the shoots. In *S. nodiflora*, iron and zinc were found in more amounts, with arsenic, cadmium and lead being the lowest. Cadmium and lead were more in the roots than in the shoot. Other heavy metals such as chromium, iron, nickel, cobalt, copper, arsenic and zinc were found more in the shoots than in the roots. In *A. philoxeroides* chromium and iron were found more in amount. Iron and chromium were found more in the shoots of the plant and other heavy metals such as nickel, cobalt, copper, arsenic, cadmium and lead were found more in the roots than in the shoot.

During the winter season, *S. dulcis*, *S. nodiflora*, *A. philoxeroides* were found dominant. In *S. dulcis*, chromium, iron, nickel, copper and zinc were found in higher concentrations. Arsenic and cadmium were found in the lowest concentration. All the heavy metals except chromium, copper and zinc were found more in the shoot than in the roots. In *S. nodiflora*, chromium, iron, nickel and zinc were found in higher concentrations. Almost all the heavy metals were found in higher amounts in the shoots and roots of this plant. All the heavy metals were found more in the roots than in the shoot region of the plant.

During the summer season, *S. dulcis*, *S. trilobata* and *A. philoxeroides* were found dominant. In *S. dulcis*, chromium, iron, nickel, cobalt and copper were found in more concentrations. Almost all the heavy metals were found in more concentration in the plants during the summer season than any other season. Arsenic was found in higher concentrations during the summer season. In *S. trilobata*, chromium, iron, nickel and cadmium were found in higher concentrations, arsenic being the lowest. More heavy metals were found in the root part than in the shoot region. In *A. philoxeroides*, chromium, iron, nickel and cadmium were found in higher concentrations than all other heavy metals. All the heavy metals except copper were found more in the roots than in the shoot region.

Aquatic macrophytes like *P. stratiotes*, *E. crassipes* and *S. molesta* were reported from Edayar during all the seasons. In the southwest monsoon, *P. stratiotes* showed a high amount of chromium, iron, nickel and zinc. Arsenic was reported less in *P. stratiotes*. All the heavy metals except nickel and lead were found more in the shoot region than the root part. In *E. crassipes*, chromium, iron and nickel were found in higher concentrations. Arsenic and lead were found in low concentration. All the heavy metals except iron were found more in the shoot region than in the root. In *S. molesta*, chromium, iron and cobalt were found in more amounts. Lead and arsenic were the lowest. All the heavy metals except chromium, iron, and cobalt were found more in the root region than the shoot region.

During the northeast monsoon, *E. crassipes* were only reported. Iron, nickel, cobalt and zinc were reported to have higher concentrations. Arsenic and lead were the lowest. All the heavy metals except cobalt, copper and zinc were found more in the shoot than in the root region. During the winter season, *E. crassipes* and *P. stratiotes* were reported from the region. In *E. crassipes*, iron, nickel, and zinc were found in higher amounts than other heavy metals. Arsenic, cadmium and lead were found in lower concentrations.

Conclusion

In conclusion, the assessment of heavy metal accumulation in water, soil and plants in the Edayar region of Ernakulam, Kerala, identified significant levels of chromium (Cr), copper (Cu), arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), nickel (Ni) and cobalt (Co). Elevated levels of these metals pose environmental risks, including bioaccumulation in aquatic organisms and potential impacts on crop quality and human health. Terrestrial plants such as *Scoparia dulcis* and *Alternanthera philoxeroides*, along with the aquatic plant *Salvinia molesta*, were found to be effective accumulators of heavy metals. Addressing pollution sources like industrial discharges and inadequate waste management is crucial to prevent further contamination and protect environmental health. Further research is needed to investigate specific sources, pathways and health impacts of heavy metal contamination in this region.

Acknowledgements

The authors thank the Department of Life Sciences, CHRIST (Deemed to be University), Bangalore for providing the necessary facilities for the successful execution of this research work. The authors express their gratitude to Central Laboratory for Instrumentation and Facilitation (CLIF), University of Kerala. This research is funded by CSIR -UGC Junior Research Fellowship.

Authors' contributions

CAS and DS designed the study. DS carried out supervision. CAS conducted the fieldwork, collected the data, prepared the original draft and performed analysis, writing and editing. CAS and DS jointly interpreted the results and drafted the manuscript. CAS prepared the tables which visually represent the heavy metal content of both terrestrial and aquatic plants. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None.

References

1. Jaiswal A, Verma A, Jaiswal P. Detrimental effects of heavy metals in soil, plants and aquatic ecosystems and in humans. J Environ Pathol Toxicol Oncol [Internet]. 2018;37(3):183-97. Available from: http://dx.doi.org/10.1615/JEnvironPatholToxicolOncol.2018025348
2. Salas PM, Sujatha CH, Ratheesh Kumar CS, Cheriyan E. Heavy metal distribution and contamination status in the sedimentary environment of Cochin estuary. Mar Pollut Bull [Internet]. 2017;119(2):191-03. Available from: http://dx.doi.org/10.1016/j.marpolbul.2017.04.018
3. Edelstein M, Ben-Hur M. Heavy metals and metalloids: Sources, risks and strategies to reduce their accumulation in horticultural crops. Sci Hortic [Internet]. 2018;234:431-44. Available from: https://www.sciencedirect.com/science/article/pii/S0304423817307628
4. Cristiano W, Giacoma C, Carere M, Mancini L. Chemical pollution as a driver of biodiversity loss and potential deterioration of ecosystem services in Eastern Africa: A critical review. S Afr J Sci [Internet]. 2021 [cited 2023 Jul 24];117(9/10):1-7. Available from: http://www.scielo.org.za/scielo.php?pid=S0038-23532021000500011&script=sci_arttext
5. Hasan M, Rahman M, Ahmed A al, Islam MA, Rahman M. Heavy metal pollution and ecological risk assessment in the surface water from a marine protected area, Swatch of No Ground, north-western part of the Bay of Bengal. Regional Studies in Marine Science [Internet]. 2022;52. Available from: https://www.sciencedirect.com/science/article/pii/S2352485522000615
6. Ali H, Khan E, Ilahi I. Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity and bioaccumulation. J Chem Chem Eng [Internet]. 2019 [cited 2023 Jul 24];2019. Available from: https://www.hindawi.com/journals/jchem/2019/6730305/abs/
7. Nagajyoti PC, Lee KD, Sreekanth TVM. Heavy metals, occurrence and toxicity for plants: a review. Environ Chem Lett [Internet]. 2010 Sep 1;8(3):199-216. Available from: https://doi.org/10.1007/s10311-010-0297-8
8. Pamunuwa G, Karunaratne DN, Waisundara VY. Antidiabetic properties, bioactive constituents and other therapeutic effects of *Scoparia dulcis*. Evid Based Complement Alternat Med [Internet]. 2016;2016. Available from: http://dx.doi.org/10.1155/2016/8243215
9. Varpe BD. Allelopathic effect of *Synedrella nodiflora* (L.) Gaertn on seed germination and seedling growth in wheat (*Triticum aestivum* L.). International Journal of Research and Analytical [Internet]. 2019; Available from: http://ijrar.com/upload_issue/ijrar_issue_20543792.pdf
10. del Carmen Juárez-Vázquez M, Jiménez-Arellanes MA. Phytochemical investigation, anti-inflammatory and antinociceptive activities from some species of Cleomaceae family: A systematic review. Adv Med Plans [Internet]. 2019;7:107-28. Available from: https://netjournals.org/pdf/AMPR/2019/4/19-039.pdf
11. Gebashe F, Aremu AO, Finnie JF, Van Staden J. Grasses in South African traditional medicine: A review of their biological activities and phytochemical content. S Afr J Bot [Internet]. 2019;122:301-29. Available from: https://www.sciencedirect.com/science/article/pii/S0254629918314595
12. Qi SS, Dai ZC, Zhai DL, Chen SC, Si CC, Huang P, et al. Curvilinear effects of invasive plants on plant diversity: plant community invaded by *Sphagneticola trilobata*. PLoS One [Internet]. 2014;9(11):e113964. Available from: http://dx.doi.org/10.1371/journal.pone.0113964
13. Khan HN, Faisal M. Phytoremediation of industrial wastewater by hydrophytes. In: Ansari AA, Gill SS, Gill R, R. Lanza G, Newman L, editors. Phytoremediation: Management of Environmental Contaminants, Volume 6 [Internet]. Cham: Springer International Publishing; 2018. 179-200. Available from: https://doi.org/10.1007/978-3-319-99651-6_8
14. Lal A. *Salvinia molesta*: an assessment of the effects and methods of eradication. 2016; Available from: https://repository.usfca.edu/capstone/572/
15. Bartram J, Ballance R. Water quality monitoring: A practical guide to the design and implementation of freshwater quality studies and monitoring programmes [Internet]. CRC Press. 2020;400 Available from: https://play.google.com/store/books/details?id=uzgDEAAAQBAJ
16. Mokoena DP, Mngadi SV, Sihlahla M, Dimpe MK, Nomngongo PN. Development of a rapid and simple digestion method of freshwater sediments for as, Cd, Cr, cu, Pb, Fe and Zn determination by inductively coupled plasma-optical emission spectroscopy (ICP-OES): An evaluation of dilute nitric acid. Soil Sediment Contam [Internet]. 2019;28(3):323-33. Available from: https://www.tandfonline.com/doi/abs/10.1080/15320383.2019.1575334?casa_token=OjYu8mE59_sAAAAA:nhpVC8eVcwqwXHG1IVSVg_6rYPwPRkkFWU7jK5x35egXwMBfWbFBbrEdfhjbYNeub9Wqh1r55EGL-wc
17. Fahad S, Hasanuzzaman M, Alam M, Ullah H, Saeed M, Khan IA, et al. Environment, climate, plant and vegetation growth [Internet]. Springer Nature. 2020;686 Available from: https://play.google.com/store/books/details?id=N0QBEAAAQBAJ
18. Patel P, Raju NJ, Reddy BCSR, Suresh U, Sankar DB, Reddy TVK. Heavy metal contamination in river water and sediments of the Swarnamukhi river Basin, India: risk assessment and environmental implications. Environ Geochem Health [Internet]. 2018;40(2):609-23. Available from: http://dx.doi.org/10.1007/s10653-017-0006-7
19. Kaur N, Brraich OS. Detrimental influence of industrial effluents, especially heavy metals, on limnological parameters of water and nutritional profile in addition to enzymatic activities of fish, *Sperata seenghala* (Sykes, 1839) from diverse Ramsar sites, India (Punjab). Environ Monit Assess [Internet]. 2023;195(8):1012. Available from: http://dx.doi.org/10.1007/s10661-023-11600-3
20. Gupta A. Heavy metal and metalloid contamination of surface and underground water: Environmental, policy and ethical issues [Internet]. CRC Press. 2020;262 p. Available from: https://play.google.com/store/books/details?id=bhYHEAAAQBAJ
21. Singer M. Ecosystem crises interactions: Human health and the changing environment [Internet]. John Wiley and Sons. 2021;400. Available from: https://books.google.com/books/about/Ecosystem_Crises_Interactions.html?hl=&id=4xQjEAAAQBAJ
22. Sharma SK. Heavy metals in water: Presence, removal and safety [Internet]. Royal Society of Chemistry. 2014;382. Available from: https://books.google.com/books/about/Heavy_Metals_In_Water.html?hl=&id=BF_YBAAAQBAJ
23. Tiwari AK, Kumar A, Singh AK, Singh TN, Suozzi E, Matta G, et al. Water scarcity, contamination and management [Internet]. Elsevier. 2022;606. Available from: https://play.google.com/store/books/details?id=YN5sEAAAQBAJ
24. Kumar V, Sharma A, Cerda A. Heavy metals in the environment: Impact, assessment and remediation [Internet]. Elsevier.

2020;244. Available from: https://play.google.com/store/books/details?id=5OgGEAAAQBAJ

25. Sharma RK, Agrawal M, Marshall FM. Atmospheric deposition of heavy metals (Cu, Zn, Cd and Pb) in Varanasi city, India. Environ Monit Assess [Internet]. 2008;142(1-3):269-78. Available from: http://dx.doi.org/10.1007/s10661-007-9924-7
26. Negm AM, Bouderbala A, Chenchouni H, Barceló D. Water resources in Algeria - Part I: Assessment of surface and groundwater resources [Internet]. Springer Nature. 2020;336. Available from: https://play.google.com/store/books/details?id=T-oEEAAAQBAJ
27. Matern K, Weigand H, Singh A, Mansfeldt T. Environmental status of groundwater affected by chromite ore processing residue (COPR) dumpsites during pre-monsoon and monsoon seasons. Environ Sci Pollut Res Int [Internet]. 2017;24(4):3582-92. Available from: http://dx.doi.org/10.1007/s11356-016-8110-2
28. Lata S. Irrigation water management for agricultural development in Uttar Pradesh, India [Internet]. Springer. 2019;372. Available from: https://play.google.com/store/books/details?id=DM6CDwAAQBAJ
29. Ramanathan AL, Johnston S, Mukherjee A, Nath B. Safe and sustainable use of arsenic-contaminated aquifers in the gangetic plain: A multidisciplinary approach [Internet]. Springer. 2015;302. Available from: https://books.google.com/books/about/Safe_and_Sustainable_Use_of_Arsenic_Cont.html?hl=&id=TCbMCQAAQBAJ
30. Re V, Manzione RL, Abiye TA, Mukherji A, MacDonald A. Groundwater for sustainable livelihoods and equitable growth [Internet]. CRC Press. 2022;468. Available from: https://play.google.com/store/books/details?id=mmZjEAAAQBAJ
31. Singh VP, Yadav S, Yadava RN. Environmental pollution: Select proceedings of ICWEES-2016 [Internet]. Springer. 2017;571. Available from: https://play.google.com/store/books/details?id=YeJEDwAAQBAJ
32. Yadav B, Mohanty MP, Pandey A, Singh VP, Singh RD. Sustainability of water resources: Impacts and management [Internet]. Springer Nature. 2022;415 p. Available from: https://play.google.com/store/books/details?id=-6yYEAAAQBAJ
33. Panneerselvam B, Pande CB, Muniraj K, Balasubramanian A, Ravichandran N. Climate change impact on groundwater resources: Human health risk assessment in arid and semi-arid regions [Internet]. Springer Nature. 2022;484. Available from: https://play.google.com/store/books/details?id=BTaFEAAAQBAJ
34. Shrestha S, Pandey VP, Thatikonda S, Shivakoti BR. Groundwater environment in Asian cities: Concepts, methods and case studies [Internet]. Butterworth-Heinemann. 2016;542. Available from: https://play.google.com/store/books/details?id=aV6dBgAAQBAJ
35. Dhanakumar S, Murthy KR, Solaraj G, Mohanraj R. Heavy-metal fractionation in surface sediments of the Cauvery river Estuarine region, Southeastern coast of India. Arch Environ Contam Toxicol [Internet]. 2013;65(1):14-23. Available from: http://dx.doi.org/10.1007/s00244-013-9886-4
36. Sutton RK. Green roof ecosystems [Internet]. Springer. 2015;447. Available from: https://play.google.com/store/books/details?id=zlHMCQAAQBAJ
37. Jones JB, Stanley E. Stream ecosystems in a changing environment [Internet]. Elsevier. 2016;548. Available from: https://play.google.com/store/books/details?id=klACBAAAQBAJ
38. Tvarijonaviciute A, Martínez-Subiela S, López-Jornet P, Lamy E. Saliva in health and disease: The present and future of a unique sample for diagnosis [Internet]. Springer Nature. 2020;326 p. Available from: https://play.google.com/store/books/details?id=3EzcDwAAQBAJ
39. Shukla PC, Belgiorno G, Di Blasio G, Agarwal AK. Alcohol as an alternative fuel for internal combustion engines [Internet]. Springer Nature. 2021;266. Available from: https://play.google.com/store/books/details?id=7eAuEAAAQBAJ
40. Patel M, Kumari A, Parida AK. Arsenic tolerance mechanisms in plants and potential role of arsenic hyperaccumulating plants for phytoremediation of arsenic-contaminated soil. In: Hasanuzzaman M, editor. Plant Ecophysiology and Adaptation under Climate Change: Mechanisms and Perspectives II: Mechanisms of Adaptation and Stress Amelioration [Internet]. Singapore: Springer Singapore; 2020.. 137-62. Available from: https://doi.org/10.1007/978-981-15-2172-0_7
41. Charlesworth SM, Booth CA. Urban pollution: Science and management [Internet]. John Wiley and Sons. 2019;466. Available from: https://books.google.com/books/about/Urban_Pollution.html?hl=&id=BwpxDwAAQBAJ
42. Aileni M. Environment sustainability and role of biotechnology. In: Arora S, Kumar A, Ogita S, Yau YY, editors. Innovations in Environmental Biotechnology [Internet]. Singapore: Springer Nature Singapore; 2022. 21-64. Available from: https://doi.org/10.1007/978-981-16-4445-0_2
43. Shahid M, Dumat C, Khalid S, Schreck E, Xiong T, Niazi NK. Foliar heavy metal uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. J Hazard Mater [Internet]. 2017;325:36-58. Available from: http://dx.doi.org/10.1016/j.jhazmat.2016.11.063
44. Gavrilescu M. Removal of heavy metals from the environment by biosorption. Eng Life Sci [Internet]. 2004;4(3):219-32. Available from: https://onlinelibrary.wiley.com/doi/10.1002/elsc.200420026
45. Sharma P, Tripathi S, Chandra R. Highly efficient phytoremediation potential of metal and metalloids from the pulp paper industry waste employing *Eclipta alba* (L.) and *Alternanthera philoxeroide* (L.): Biosorption and pollution reduction. Bioresour Technol [Internet]. 2021;319:124147. Available from: http://dx.doi.org/10.1016/j.biortech.2020.124147
46. Fattorini S, Mantoni C, Di Biase L, Pace L. Mountain biodiversity and sustainable development. In: Leal Filho W, Azul AM, Brandli L, Lange Salvia A, Wall T, editors. Life on Land [Internet]. Cham: Springer International Publishing; 2021. 640-60. Available from: https://doi.org/10.1007/978-3-319-95981-8_144
47. Stankovic S, Stankovic AR. Bioindicators of toxic metals. In: Lichtfouse E, Schwarzbauer J, Robert D, editors. Green Materials for Energy, Products and Depollution [Internet]. Dordrecht: Springer Netherlands; 2013. 151-28. Available from: https://doi.org/10.1007/978-94-007-6836-9_5
48. Wang Y, Chen C, Xiong Y, Wang Y, Li Q. Combination effects of heavy metal and inter-specific competition on the invasiveness of *Alternanthera philoxeroides*. Environ Exp Bot [Internet]. 2021;189. Available from: https://www.sciencedirect.com/science/article/pii/S0098847221001623
49. Chandrasekhar C, Ray JG. Lead accumulation, growth responses and biochemical changes of three plant species exposed to soil amended with different concentrations of lead nitrate. Ecotoxicol Environ Saf [Internet]. 2019;171:26-36. Available from: http://dx.doi.org/10.1016/j.ecoenv.2018.12.058
50. Manara A, Fasani E, Furini A, DalCorso G. Evolution of the metal hyperaccumulation and hypertolerance traits. Plant Cell Environ [Internet]. 2020;43(12):2969-86. Available from: http://dx.doi.org/10.1111/pce.13821
51. Bortoloti GA, Baron D. Phytoremediation of toxic heavy metals by *Brassica* plants: A biochemical and physiological approach. Environmental Advances [Internet]. 2022;8. Available from:

https://www.sciencedirect.com/science/article/pii/S2666765722000400

52. Spormann S, Soares C, Teixeira J, Fidalgo F. Polyamines as key regulatory players in plants under metal stress-A way for an enhanced tolerance. Ann Appl Biol [Internet]. 2021;178(2):209-26. Available from: https://onlinelibrary.wiley.com/doi/10.1111/aab.12660

53. Mohan I, Goria K, Dhar S, Kothari R, Bhau BS, Pathania D. Phytoremediation of heavy metals from the biosphere perspective and solutions [Internet]. Pollutants and Water Management. Wiley. 2021; 95-127. Available from: https://onlinelibrary.wiley.com/doi/10.1002/9781119693635.ch5

54. Verbruggen N, Hermans C, Schat H. Molecular mechanisms of metal hyperaccumulation in plants. New Phytol [Internet]. 2009 Mar;181(4):759-76. Available from: http://dx.doi.org/10.1111/j.1469-8137.2008.02748.x

55. Bruni R, Sacchetti G. Factors affecting polyphenol biosynthesis in wild and field grown St. John's Wort (*Hypericum perforatum* L. Hypericaceae/Guttiferae). Molecules [Internet]. 2009 14(2):682-725. Available from: http://dx.doi.org/10.3390/molecules14020682

56. Khan A, Khan S, Khan MA, Qamar Z, Waqas M. The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients and associated health risk: a review. Environ Sci Pollut Res Int [Internet]. 2015;22(18):13772-99. Available from: http://dx.doi.org/10.1007/s11356-015-4881-0

57. Maseko Z. The effect of shade on the biological control of *Salvinia molesta* DS Mitchell [Salviniaceae] by the weevil, Cyrtobagous salviniae Calder and Sands … [Internet]. core.ac.uk; 2016 [cited 2023 Aug 18]. Available from: https://core.ac.uk/download/pdf/145039681.pdf

58. Rajabpoor S, Ghaderian SM, Schat H. Antimony tolerance and accumulation in a metallicolous and a non-metallicolous population of *Salvia spinosa* L. Plant Soil [Internet]. 2019;437(1-2):11-20. Available from: https://idp.springer.com/authorize/casa?redirect_uri=https://link.springer.com/article/10.1007/s11104-019-03961-x&casa_token=xUGWLaAYVFoAAAAA:SKzbxRfCQcxKLsySjw-RNDP2DOj8OKd-9f90H7YfkiQa4chPqktjUyJ3ZD2sstSxUn2NNpgLpnvpzMH7_-M