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A Green Approach to Landfill Remediation: The Efficacy of Indigenous *Zygophyllum coccineum* L. and *Leptadenia pyrotechnica* L. in Phytoremediating a Heavy Oil Flay Ash-contaminated Landfill in Rabigh, Saudi Arabia

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Abstract. **This study investigated the impact of the heavy oil fly ash landfill at Rabigh governorate, Saudi Arabia, on the growth and heavy metal accumulation in the indigenous plants *Zygophyllum coccineum* L. and *Leptadenia pyrotechnica* L. Samples of these two plant species together with the soil were collected from inside the landfill and at distances of 250, 500, and 1000 m away from the landfill in the north, east, west, and south locations. Data of the fresh and dry weights of the plant samples (aerial parts and roots) were collected and elemental analyses of the plant samples were conducted. The results showed that vegetation within the landfill exhibited the lowest overall fresh and dry biomass values of aerial and root parts. However, growth progressively improved with the increasing distance, with maximum growth reached at 1000 m from the landfill. Metal concentrations were highest in the samples collected from inside the landfill, and they diminished with increasing distance away from it. Plants located in the south exhibited the greatest metal deposition. Roots consistently surpassed aerial parts in terms of metal accumulation, both proximally and distally. Sulfur, aluminum, and iron were the predominant elements accumulated in *Z. coccineum* and *L. pyrotechnica* plants across all sites and distances from the landfill. The sequence of heavy metal concentrations from highest to lowest in the roots and shoots was as follows: sulfur > aluminum > iron > zinc > manganese > nickel > chromium > vanadium > copper > cobalt. The plants exhibited elevated chromium levels that surpassed the European Union (2002) requirements; however, they remained below Indian regulations. Zinc concentrations, however, exceeded both the European Union and World Health Organization (WHO)/Food and Agriculture Organization (FAO) guidelines. All other heavy metals were within the permissible levels established by the WHO/FAO, European Union, and Indian regulations. The translocation factor for heavy metals from roots to shoots was less than one for all 10 metals, signifying metal build-up in roots relative to the shoots. It could be concluded that there is a significant relationship between the plant growth rate and magnitude of metal accumulation. Plants with the lowest growth rate exhibited the highest heavy metals accumulation, as seen at the southern location, whereas plants with the highest growth rate (those at the northern location) had the least metal accumulation. This phenomenon highlights the potential of these plants for phytoremediation and phytostabilization to extract deleterious heavy metals from contaminated landfill soils.**

Saudi Arabia is a country that consumes large quantities of heavy oil in water desalination operations and power plants, with over 40 million metric tons of oil consumed every year, resulting in the production of large quantities of heavy oil fly ash (HOFA) (Al-Malack et al. 2013). Increasing industrialization and urbanization have posed a serious threat to the environment (Amen et al. 2020). In Saudi Arabia, power stations and water desalination plants generate large amounts of HOFA, which is acidic and contains highly toxic elements, by using heavy oil as fuel (Al-Solaimani et al. 2024; Bakkar et al. 2023). Because HOFA is typically disposed of in landfills, it may pose significant risks to the surrounding environment and have adverse effects on plants as well as ground and surface waters (Al-Malack et al. 2016).

Because HOFA contains significant amounts of heavy metals, which are mostly disposed of in landfills, it is considered hazardous waste (Bakkar et al. 2023). Rainwater percolates through HOFA deposited in the landfill, leading to the decomposition of the moist waste, which results in the formation of liquid effluent known as landfill leachate (Costa et al. 2019). Consequently, the growth of resident plants is reduced by these leachates (Attalage et al. 2023). This statement has been confirmed by several previous studies, including one by the current authors in which it was evident that planting common sage plants and lemongrass plants in HOFA soil significantly decreased the growth and biomass of both plant species and common sage accumulated more elements than lemongrass (Al-Solaimani et al. 2024). Reduction in the growth of landfill-growing plants in Korea has been reported by Wong (1995), and reductions in alder, willow, and poplar trees planted in four landfill sites in Merseyside that showed inhibition and reduction in growth have been reported by Dobson and Moffat (1999). In their recent publication, Al-Solaimani et al. (2022) confirmed that all heavy metals (excluding cadmium) were concentrated in the fine roots of mangrove plants.

Several methods are used to clean environments polluted by these contaminants. One of these methods is phytoremediation, whereby plants are used to remediate landfill-polluted soils from toxic heavy metals. Phytoremediation has become an effective and affordable technological solution for extracting or removing metal pollutants from polluted soils. Phytoremediation involves the use of plant species as extractors and translocators of heavy metals, as well as other toxic substances, from contaminated soil. Several plant species possess genetic capabilities to remove, degrade, metabolize, or immobilize a wide range of contaminants through natural biochemical processes, including adsorption, transport and translocation, hyperaccumulation, transformation, and mineralization. These processes remediate pollutant materials, thus making the soil more favorable for plant growth (Islam et al. 2007; Meagher 2000). Some plants withstand high concentrations of heavy metals, absorb these toxic metals, and help clean polluted sites (Mudgal et al. 2010). Highly accumulating plants are known as plants that can withstand and accumulate large concentrations of minerals in their vegetative parts (Kamnev and Van der Lelie 2000; Macnair 2003). Ideal plants for these processes must exhibit rapid growth rates, dense and deep roots, substantial biomass production, and ease of harvesting (Alkorta et al. 2004). Several treatments can alleviate the adverse effects of metal toxicity on plant growth, such as amending contaminated soil with EDTA or treating plants with jasmonic acid (Ibrahim et al. 2022). Thus, plants' abilities to extract heavy metals from soil can be enhanced.

Many plant species have succeeded in absorbing heavy metals from polluted soils (Atkinson et al. 2010). Nevertheless, the search for more efficient phytoremediator species continues, with a focus on evaluating native plants. In the current study, two plant species naturally growing in the study site were targeted. *Zygophyllum coccineum* is commonly found in limestone "wadis" and plains of the Eastern desert in Saudi Arabia and demonstrates high salinity tolerance (Al-Salihi and Al-Rammahi 2014). Morphologically, *Z. coccineum* is a small shrub, perennial herb, or desert succulent undershrub that can reach up to 75 cm in height and is characterized by erect multistemmed green branches (Reed 1997). It is not used for grazing or as a fuel source (Al-Salihi and Al-Rammahi 2014). *Z. coccineum* is rich in saponins, with the major secondary metabolites being a class of quinovic acid compounds that belong to the ursane-type triterpene saponins (Ahmad et al. 2012). The other species is *Leptadenia pyrotechnica*, which belongs to the Asclepiadaceae family (Ram et al. 2008). Being highly drought-resistant, this herb thrives in areas that receive 100 to 450 mm of annual rainfall. This herb is a strong soil binder and serves as a pioneer species for stabilizing sand dunes (Choudhary et al. 2014). It grows on sand dunes, coastal dunes, and temporary riverbeds and thrives on well-drained sandy soils at altitudes ranging from sea level to 1000 m. It inhibits acacia grassland, deciduous bushland, and grassland in semiarid areas. Additionally, it can tolerate high pH and elevated sodium and potassium levels (Ram 2008).

Accordingly, the current study aimed to investigate the impact of the HOFA landfill at Rabigh governate, Saudi Arabia, on the growth of the indigenous shrubs *Z. coccineum* and *L. pyrotechnica* and their accumulation of heavy metals. The study also evaluated the spatial distribution of heavy metals around the landfill and assessed the phytoremediation potential of the two shrubs in terms of metal uptake and translocation.

Materials and Methods

Two plant species, *Z. coccineum* (Fig. 1A) and *Leptadenia pyrotechnica* (Fig. 1B), naturally growing at the Rabigh landfill were selected, and their efficiency as phytoremediators for removing toxic heavy metals from the landfill site was evaluated.

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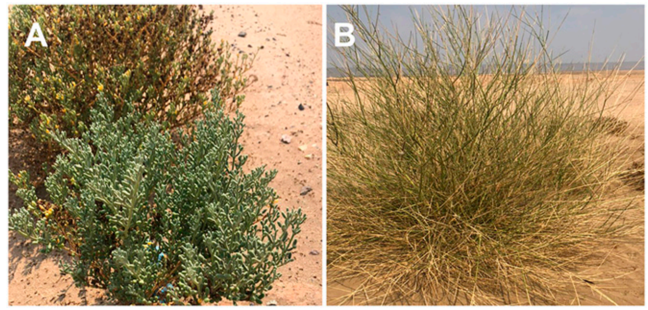

Fig. 1. *Zygophyllum coccineum* L. (**A**) and *Leptadenia pyrotechnica* (**B**) naturally growing in the landfill experimental site that were studied for their phytoremediation ability.

Study area

The landfill selected for the study is located in the Rabigh governorate, Saudi Arabia, which covers an area of 222 m × 1054 m (lat. 20°37′23″N, long. 39°56′4.52″E) (Fig. 2).

Collection and analysis of plant samples

For each plant species, 36 samples (plants) were collected from both inside and outside the landfill at distances of 250, 500, and 1000 m away from the landfill at the north, east, west, and south locations. Sampling locations at the inside and outside of the landfill are illustrated in Figs. 3 and 4, respectively. Plant samples were separated into roots and shoots (aerial parts), and their fresh weights were recorded. The samples were washed with distilled water and dried in an oven at 70 °C. After 48 h, the dried samples were weighed, finely ground, and passed through a 2-mm sieve. Subsequently, 0.5 g of the plant material from each treatment was dry-ashed for 5 h at 550 °C and extracted with 20% HCl in triplicate (Jones et al. 1991). Elemental analyses were conducted for silver (Ag), aluminum (Al), arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), sulfur (S), antimony (Sb), selenium (Se), tin (Sn), thallium (Tl), vanadium (V), and zinc (Zn) in the plant extracts using inductively coupled plasma atomic emission spectroscopy (Ultima 2; Horiba Jobin Yvon, Unterhaching, Germany).

Collection and analysis of soil samples

Soil samples were collected from the same locations illustrated in Figs. 3 and 4 at two depths, 0 to 15 cm and 15 to 30 cm, resulting in a total of 72 soil samples. The collected samples were stored in polyethylene bags for further analysis. Collected soil samples were subjected to the measurements of electrical conductivity (EC; $ds{\cdot}m^{-1}$) and pH.

Statistical analysis. Data were subjected to analysis of variance, and the revised least significant difference test was also performed to quantify the level of significance among treatments ($P > 0.05$) (SPSS version 22; IBM, Chicago, IL, USA).

Results

Soil analysis

Table 1 shows that the soil at the southern location had the highest pH, followed by the soil in the eastern, western, and northern locations, respectively. Regarding soil EC, the highest EC was at the southern location, followed by the eastern, western, and northern locations. According to the distance from the landfill, the highest pH and EC were found in the soil inside the landfill, and then it decreased with an increase in distance from 0, 250, 500, and 1000 m away from the landfill.

Plants growth

Effect of location. The growth of the two species was significantly affected by the different locations at which the plant species were growing and attained different growth rates at different locations (Tables 2 and 3). Plant species growing in the northern direction of the landfill attained the highest values of fresh and dry weights of shoots, roots, and total biomass compared with those of the other plants growing in the other locations (east, west, and south). In the northern location, fresh and dry weights, respectively, of *Z. coccineum* were as follows: shoots, 2034.69 and 905.34 g; roots, 98.38 and 69.02 g; and total biomass, 2133.08 and 974.36 g. Those for *L. pyrotechnica* were as follows: shoots, 2533.5 and 1662 g; roots, 354.5 and 235.5 g; and total biomass, 2888.5 and 2147.5 g. Plants growing in the southern area had the lowest mean fresh and dry weights, respectively, of shoots (936.82 and 572.66 g), roots (52.56 and 31.11 g), and total biomass (989.38 and 603.78 g) for *Z. coccineum*, and of shoots (1461.25 and 1100.5 g), roots (135 and 82.25 g), and total biomass (1621.5 and 1193.25 g) for *L. pyrotechnica*.

Effect of distance from the landfill. The growth of the two naturally occurring plant species was significantly affected by their distance from the landfill. Their growth rates differed as the distance from the landfill increased. The results presented in Table 2 indicate that the plants growing inside the landfill had the least growth parameters, with *Z. coccineum* attaining fresh and dry biomass of 231.13 and 109.72 g for shoots, 25.35 and 11.9 g for roots, and 256.79 and 121.71 g for total biomass, respectively. Likewise, *L. pyrotechnica* had fresh and dry biomass values of 336.5 and 261.5 g for shoots, 90 and 65 g for roots, and 458.75 and 327.5 g for total biomass, respectively (Table 3). However, the highest growth metrics were attained by plants located 1000 m from the landfill. The fresh and dry biomass values of *Z.*

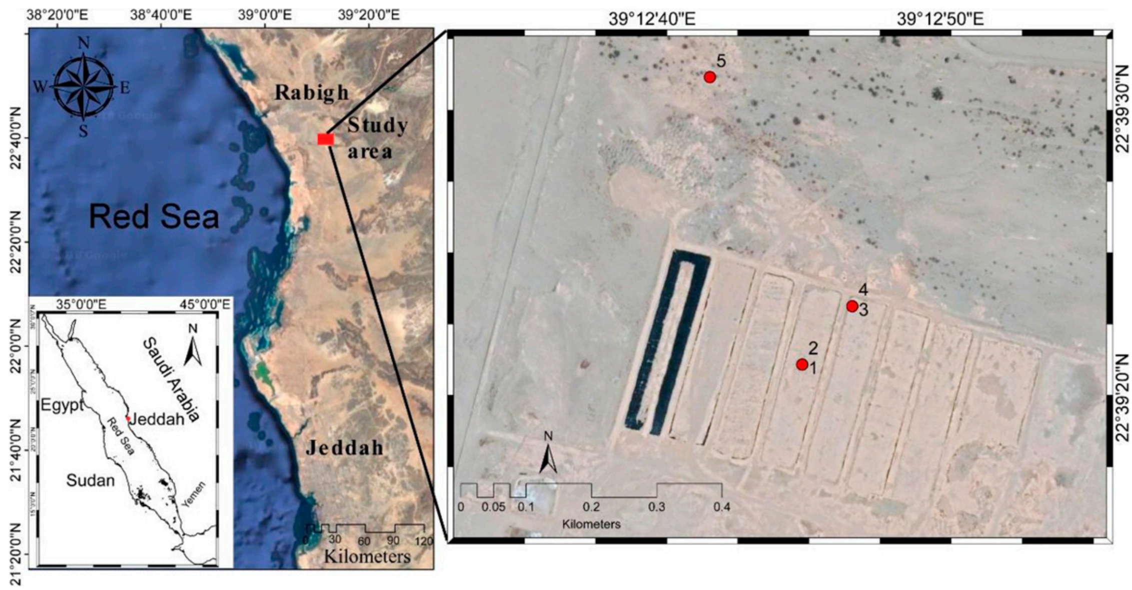

Fig. 2. Map of the study area at the Rabigh landfill located in the Rabigh governorate, Saudi Arabia.

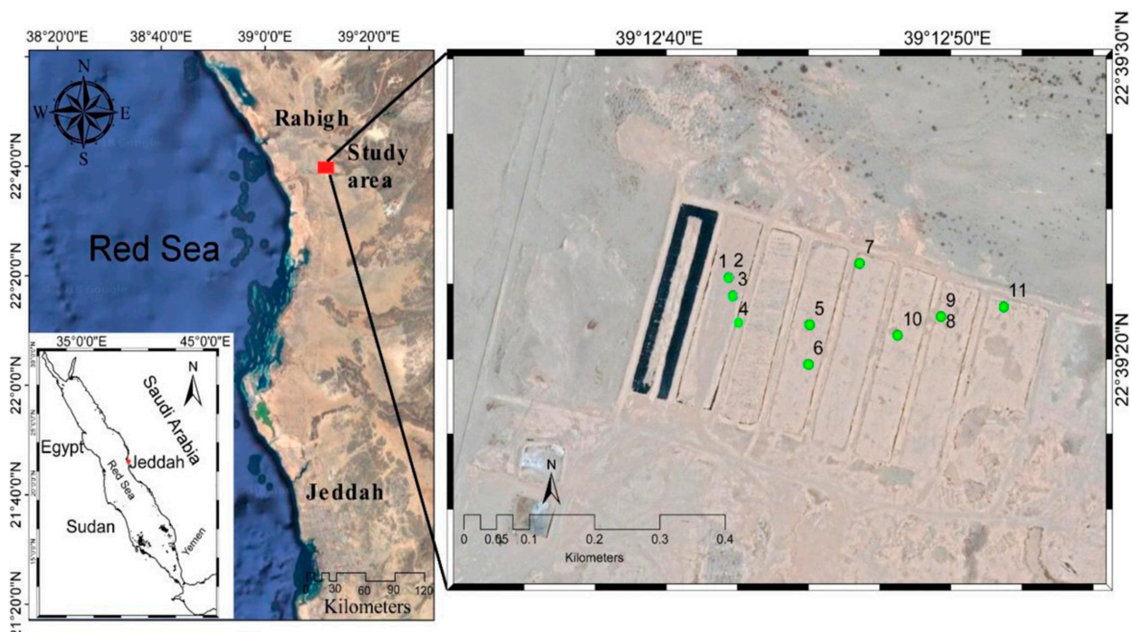

Fig. 3. Sampling locations inside the landfill site. The green numbered circles represent the samples collected from various locations inside the landfill site.

coccineum reached 2237.07 and 1046.1 g for shoots, 122.73 and 75.23 g for roots, and 2359 and 1121.23 g for total biomass, respectively. A similar trend was recorded for *L. pyrotechnica*, with fresh and dry biomass values of 3125.5 and 2092.5 g for shoots, 365.5 and 261.5 g for roots, and 3491 and 2354 g for total biomass, respectively.

Effect of the combination of location and distance from the landfill. There was a gradual increase in the total biomass growth of the two plant species with the increase in distance from 0 to 1000 m away from the landfill at all four locations. Plants located north of the landfill attained the best growth regardless of the distance from the landfill area, while those growing south of the landfill attained the lowest growth compared with that at the other sites (Fig. 5).

Heavy metals accumulated by the two naturally growing plant species: *Z. coccineum* and *L. pyrotechnica*

Effect of location. Tables 4 and 5 list the accumulation of heavy metals (S, Zn, Mn, Cu, Al, Co, Cr, Ni, and V) in the tissues of the two naturally growing plant species across all growth locations. The highest metal accumulation rates were observed in plants growing in the southern location, followed by those growing in the east. Plants growing in the north accumulated the least amount of heavy metals compared with those growing at the other locations. Among all heavy metals, S showed the highest accumulation level (7722.30 and 6265.5 mg/km), followed by Al (1197.60 and 371.71 mg/kg), and Fe (816.68 and 312.40 mg/km) for *Z. coccineum* and *L. pyrotechnica*, respectively. However, the elements with the lowest content in the plants included Zn, Mn, Ni, V, Cr, Cu, and Co.

Effect of distance from the landfill. There was also a significant difference in the accumulated heavy metals content of both plant species growing at different distances from the landfill area (Tables 4 and 5). The amount of accumulated heavy metals in plants decreased with increasing distance from the landfill. A greater concentration of heavy metals was observed in plant species growing

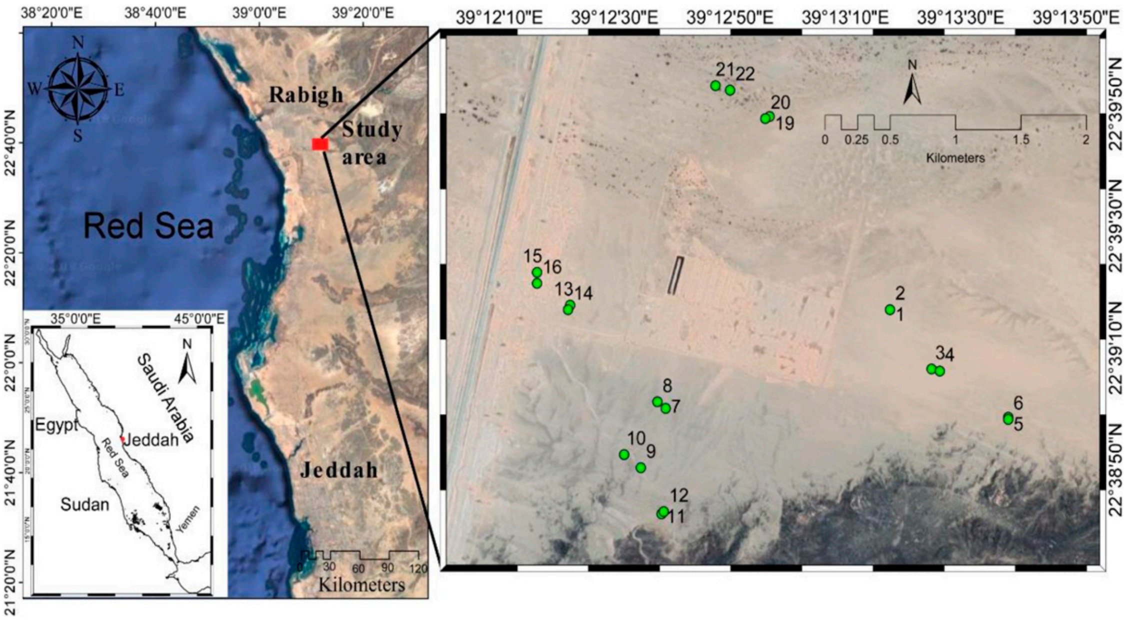

Fig. 4. Sampling locations outside the landfill site. The green numbered circles represent the samples collected from various locations inside the landfill site.

Table 1. Means of pH and electrical conductivity (EC) of soil samples collected from different locations (north, south, west, east), distances (250, 500, and 1000 m), and soil depths (0–15 cm and 15–30 cm) across the landfill site.

	Soil parameters	
Treatments	pH	EC ($dS \cdot m^{-1}$)
Location		
East	7.44 b	905.38 b
West	7.32 c	853.18 c
North	7.33 c	775.70 d
South	7.52 a	973.47 a
LSD	0.017	39.83
Distance (m)		
0	7.56 a	984.39 a
250	7.48 b	904.54 b
500	7.36 c	810.32 c
1000	7.20 d	808.48 c
LSD	0.014	33.54

Means followed by the same letter are not significantly different according to revised least significant difference (LSD) at $P \leq 0.05$.

inside the landfill, and they gradually decreased in plants growing outside the landfill at distances of 250, 500, and 1000 m. The accumulation of metals was significantly higher in the roots compared with that in the shoots of both *Z. coccineum* and *L. pyrotechnica* at all locations and distances away from the landfill. Notably, the concentration of Ni exceeded the permissible limits specified in the Indian standards (Awashthi 2000).

Accumulation of heavy metals in shoots and roots of plants. The results indicated that the two plant species studied accumulated 10 types of heavy metals at a significantly higher rate in their roots than that in their shoots (Tables 4 and 5). Additionally, S was accumulated at rates of 11,238.21 mg/kg in roots and 3149.27 mg/km in shoots of *Z. coccineum*, and at rates of 5775.50 mg/km in roots and 2862.62 mg/km in shoots of *L. pyrotechnica*.

Combined effect of location and distance from the landfill. When the combined effect of the two factors, location and distance, was considered, it was clear that the accumulation of 10 heavy metals was significantly higher in *Z. coccineum* L. and *L. pyrotechnica* L. plants growing inside the landfill site at all locations (south, east, west, and north), and then it gradually decreased with increasing distance from the landfill (250, 500, and 1000 m). The highest metal concentrations were found in plants growing at the southern location at all distances, followed by accumulation in plants growing at the eastern, western, and northern locations, which represent the locations with the lowest accumulation (Figs. 6–15).

Table 2. Means of the total fresh weight and dry weight of *Zygophyllum coccineum* under the effects of location (north, south, west, east) and distance (250, 500, and 1000 m) across the landfill site.

	Fresh wt (g/plant)			Dry wt (g/plant)		
Treatment	Shoot	Root	Total	Shoot	Root	Total
Location						
East	1620 c	75.21 c	1695 c	706 c	45.09 b	751 c
West	1695 b	83.93 b	1779 b	772 b	63.14 a	835 b
North	2035 a	98.38 a	2133 a	905 a	69.02 a	974 a
South	937 d	52.56 d	990 d	573 d	31.11 c	604 d
LSD	36	1.76	37.48	10.89	6.77	12.85
Distance (m)						
0	231 d	25.35 d	257 d	109.72 d	11.98 d	121 d
250	1633 c	67.15 c	1701 c	774.24 c	55.71 c	830 c
500	2185 b	94.84 b	2280 b	1025.99 b	65.45 b	1091 b
1000	2237 a	122.73 a	2360 a	1046.18 a	75.23 a	1121 a
LSD	36.96	1.92	38.35	17.03	7.13	19.50

LSD = least significant difference.

Discussion

This study was conducted to investigate the distribution of heavy metal contents in a HOFA-deposited landfill at Rabigh governorate, Saudi Arabia, and its impact on plant growth inside and outside the landfill area. Two naturally growing indigenous plant species, *Z. coccineum* and *L. pyrotechnica*, were selected for this study, and their phytoremediation capabilities were evaluated.

There was a negative impact of proximity to a landfill on plant growth, with the healthiest plants found at a distance of 1000 m from the landfill. Northern locations showed the strongest growth, while southern locations showed the weakest growth. Overall, growth improved as the distance from the landfill increased in all directions. These results are consistent with those of Attalage et al. (2023), who reported that landfill leachate reduced plant growth. Dobson and Moffat (1999) observed growth inhibition of alder trees, willows, and poplars when planted in four landfill sites in Merseyside. Wong (1995) reported reduced plant growth of plants growing in landfills in Korea. Because it contains considerable amounts of heavy metals and is mostly deposited in landfills, HOFA is considered hazardous waste (Bakkar et al. 2023). Rainwater percolates through the HOFA deposited in the landfill, and the waste becomes moist and undergoes decomposition, resulting in the formation of a liquid effluent called landfill leachate (Costa et al. 2019). Many contaminants

Table 3. Means of the total fresh weight and dry weight of *L. pyrotechnica* under the effects of location (north, south, west, east) and distance (250, 500, and 1000 m) across the landfill area.

	Fresh wt (g/plant)			Dry wt (g/plant)		
Treatment	Shoot	Root	Total	Shoot	Root	Total
Location						
East	1791 c	235 c	2025 c	1270 c	162 c	435.1 c
West	1538 b	225 b	1777 b	945 b	202 b	1174 b
North	2534 a	355 a	2888 a	1662 a	236 a	2148 a
South	1461 d	135 d	1621 d	1100 d	82 d	1193 d
LSD	36.19	1.76	37.48	10.89	6.77	12.85
Distance (m)						
0	336 d	90 d	459 d	262 d	65.75 d	327.5 d
250	1615 c	272 c	1885 c	1191 c	192.5 c	1383.5 c
500	2811 b	319 b	3129 b	1905 b	223.25 b	2133 b
1000	3125 a	366 a	3491 a	2093 a	261.5 a	2354 a
LSD	36.96	1.92	38.35	17.03	7.13	19.50

LSD = least significant difference.

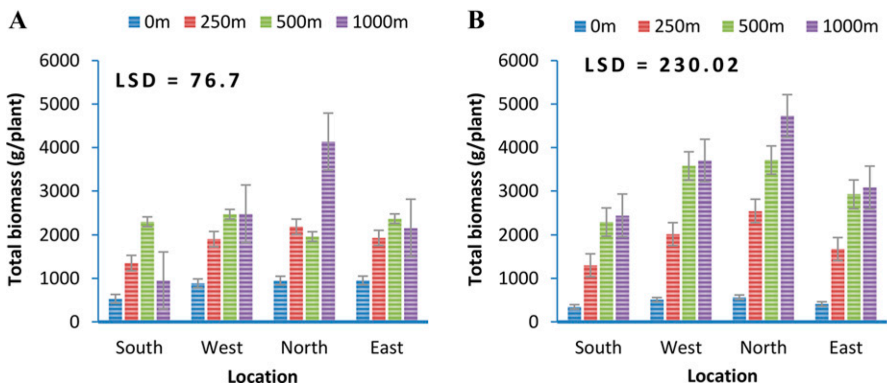

Fig. 5. Plant total biomass under the effect of the combination of location and distance from the landfill: (**A**) *Zygophyllum coccineum* and (**B**) *Leptadenia pyrotechnica*. Values are represented as the mean ± standard error indicated by the vertical bars.

have been identified in landfill leachate, including organic carbon, fatty acids, inorganic compounds, chlorides, ammonium, phosphates, nitrates, heavy metals, benzene, phenols, and phthalates (Kumari et al. 2016). Attalage et al. (2023) reported that HOFA landfill methane displaces oxygen in plant root zones, resulting in stunted plant growth because oxygen is below the required levels for healthy plant growth. Methane produced in the HOFA landfill reduces dissolved oxygen, thus hampering plant growth (Bhalla et al. 2013). Wong and Yu (1989) reported plant toxicity of landfill leachate caused by high nitrogen concentrations, various trace metals, and reduced oxygen. Accordingly, it is more likely that the concentration of these contaminants decreases with increasing distance from the landfill; therefore, plant growth is less affected by these contaminants. The percolation of rainwater through landfill wastes results in leaching, which extends and moves out of the landfill, mostly toward the southern location, resulting in lower growth of the two naturally growing plant species *Z. coccineum* and *L. pyrotechnica* at the southern location compared with those at the northern, eastern, and western locations.

Plants near the landfill area showed higher heavy metal accumulation, particularly in the roots, with levels decreasing as the distance from the landfill increased. The southern area had the highest metal accumulation and lowest plant growth, while the northern area had the opposite trend. The most commonly accumulated metals were S, Al, and Fe, but all levels remained below harmful thresholds set

Table 4. Accumulation of heavy metals in shoots and roots of *Z. coccineum*.

	S	Zn	Mn	Cu	Fe	Al	Co	Cr	Ni	V
Source of variation	(mg/kg)									
Location										
South	7722 a	39.13 a	25.94 a	9.85 a	816.68 a	1197 a	0.659 a	8.65 a	16.46 a	9.68 a
West	7034 c	28.20 c	19.43 c	6.32 c	533.18 c	775 c	0.537 c	6.25 c	10.67 c	5.87 c
North	6662 d	22.56 d	15.54 d	5.20 d	387.21 d	563 d	0.485 d	5.14 d	9.31 d	5.12 d
East	7356 b	33.82 b	22.90 b	8.07 b	686.75 b	980 b	0.604 b	7.78 b	14.14 b	7.96 b
LSD	270	0.072	0.043	0.02	116.19	174	0.0016	0.016	0.033	0.021
Distance (m)										
0	8187 a	34.85 a	23.36 a	8.86 a	807.65 a	1077 a	0.927 a	9.58 a	15.83 a	9.19 a
250	7522 b	33.25 b	21.94 b	8.00 b	693.57 b	942 b	0.653 b	7.84 b	13.94 b	7.88 b
500	6910 c	30.48 c	20.31 c	6.96 c	588.54 c	819 c	0.400 c	6.08 c	11.95 c	6.50 c
1000	6156 d	25.12 d	18.20 d	5.62 d	334.06 d	679 d	0.305 d	4.32 d	8.86 d	5.05 d
LSD	525	0.04	0.01	0.007	84.81	106	0.0024	0.011	0.02	0.01
Plant part										
Shoot	3149 b	24.01 b	17.90 b	4.76 b	528.96 b	697 b	0.536 b	4.68 b	9.57 b	4.19 b
Root	11,238 a	37.85 a	24.00 a	9.95 a	682.96 a	1061 a	0.607 a	9.23 a	15.72 a	10.12 a
LSD	305.64	0.03	0.01	0.008	50.16	57	0.001	0.009	0.012	0.01
Indian standards (Awashthi 2000)		500		30		—	—	20	1.5	—
World Health Organization/Food and Agriculture Organization (2023)	—	60	—	40	—					

Al = aluminum; Co = cobalt; Cr = chromium; Cu = copper; Fe = iron; LSD = least significant difference; Mn = manganese; Ni = nickel; S = sulfur; V = vanadium; Zn = zinc.

Table 5. Accumulation of heavy metals in shoots and roots of *L. pyrotechnica*.

	S	Zn	Mn	Cu	Fe	Al	Co	Cr	Ni	V
Source of variation	(mg/kg)									
Location										
South	6266 a	58.60 a	63.48 a	13.59 a	312 a	372 a	0.450 a	3.70 a	17.10 a	5.05 a
West	3667 c	30.59 c	48.10 c	6.80 c	239 c	283 c	0.376 c	2.82 c	6.66 c	3.08 c
North	2297 d	17.49 d	40.05 d	3.39 d	206 d	237 d	0.333 d	2.25 d	1.68 d	1.92 d
East	5047 b	44.56 b	54.71 b	9.80 b	278 b	328 b	0.417 b	3.23 b	12.04 b	4.11 b
LSD	1126	10.67	6.19	2.83	24.19	32.46	0.022	0.36	4.86	0.70
Distance (m)										
0	7369 a	61.28 a	73.50 a	15.69 a	348 a	434 a	0.599 a	4.78 a	16.29 a	6.34 a
250	5203 b	43.00 b	59.08 b	10.92 b	291 b	346 b	0.472 b	3.24 b	11.25 b	4.31 b
500	3304 c	30.36 c	44.17 c	5.56 c	233 c	266 c	0.330 c	2.40 c	7.44 b	2.46 c
1000	1399 d	16.61 d	29.58 d	1.40 d	164 d	175 d	0.176 d	1.59 d	2.51 c	1.04 d
LSD	13.28.	11.43	7.69	3.43	39.14	50.72	0.032	0.52	4.7	0.94
Plant part										
Shoot	2862 b	31.75 b	36.62 b	7.39 b	187 b	198 b	0.327 b	2.37 b	6.49 b	2.14 b
Root	5775 a	43.87 a	66.55 a	9.39 a	331 a	412 a	0.461 a	3.63 a	12.25 a	4.94 a
LSD	1814	9.93	16.10	1.43	27.25	37.96	0.034	0.28	2.23	0.38
European Union (2002)	—	—	—	—	—	—	—	0.2	1.5	12
World Health Organization/Food and Agriculture Organization (2023)	—	60	—	40	—			20	1.5	
Indian standards (Awashthi 2000)	—	30		500	—					

Al = aluminum; Co = cobalt; Cr = chromium; Cu = copper; Fe = iron; LSD = least significant difference; Mn = manganese; Ni = nickel; S = sulfur; V = vanadium; Zn = zinc.

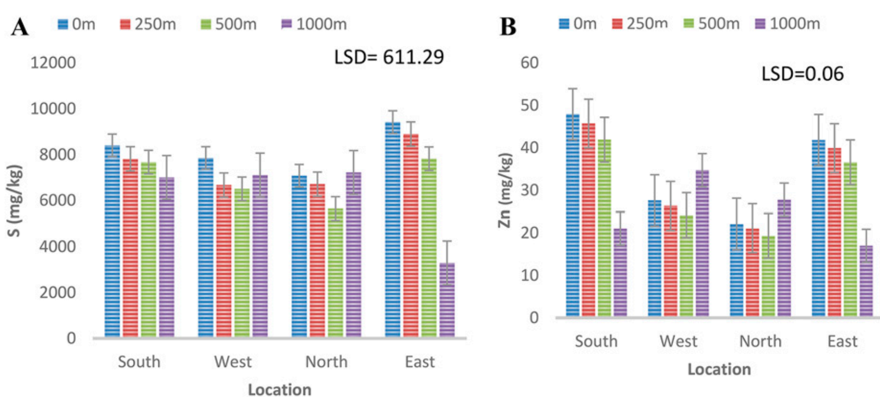

Fig. 6. Concentrations of sulfur (**A**) and zinc (**B**) in tissues of *Z. coccineum* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

by the European Union. The wind direction likely contributes to higher metal levels in the south and east, indicating greater toxic hazards in these areas. The results obtained in this study are consistent with those of other studies. Hredoy et al. (2022) found concentrations of Cr of 2.26 mg/kg and Co of 1.72 mg/kg in all tested plant samples and determined that these values are higher than the allowable limit. Barasarathi et al. (2022) planted *Cordyline fruticosa*, *Duranta variegated*, *Tradescantia spathacea*, and *Chlorophylum comosum* species at landfill sites

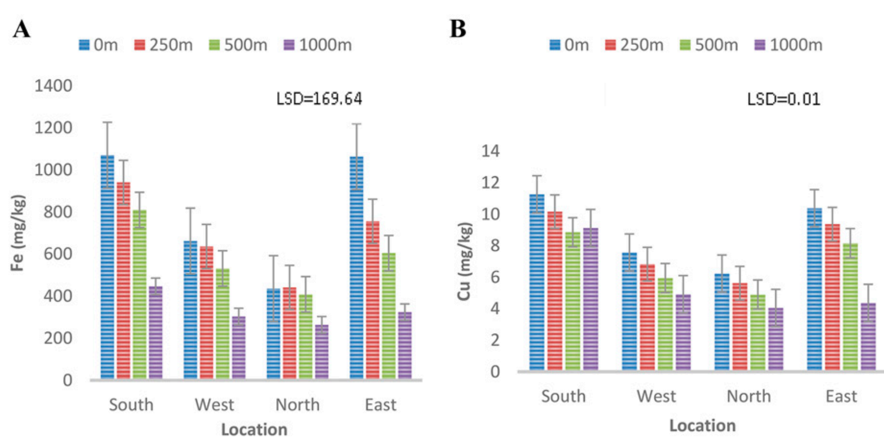

Fig. 7. Concentrations of iron (**A**) and copper (**B**) in tissues of *Z. coccineum* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

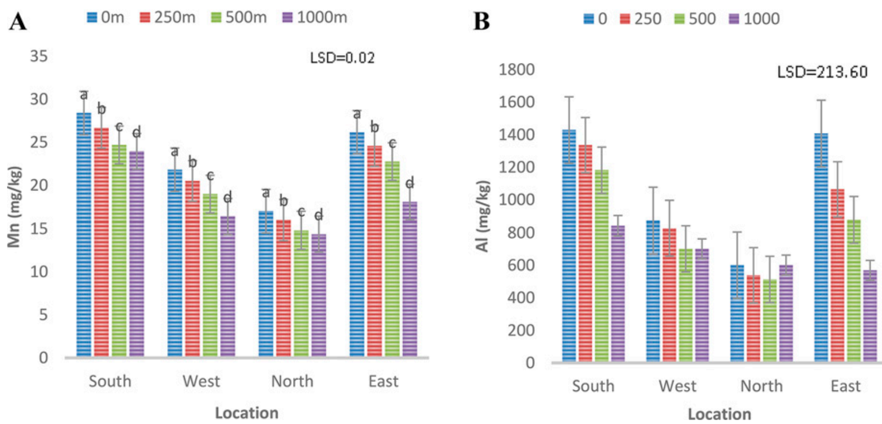

Fig. 8. Concentrations of manganese (**A**) and aluminum (**B**) in tissues of *Z. coccineum* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

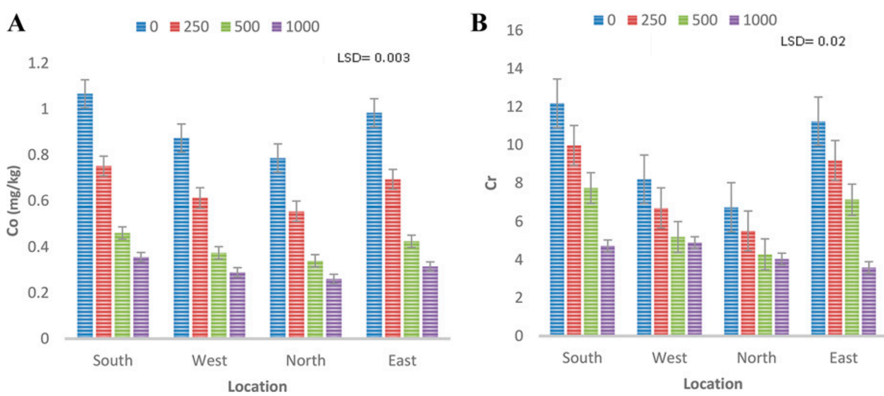

Fig. 9. Concentrations of cobalt (**A**) and chromium (**B**) in tissues of *Z. coccineum* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

They found that they accumulated Cu, Mn, Cr, Zn, Fe, and Ni metals at rates higher than the prescribed limits and found that Mn was the highest element removed by plants. Marañón et al. (2020) reported a significantly higher accumulation of trace elements in the roots than in the shoots of native shrubs in Spain (*Populus alba* L., *Celtis australis* L., *Fraxinus angustifolia* Vahl, and *Pinus pinea* L.). Banerjee et al. (2020) found that the accumulation of Zn, lead (Pb), Cu, Ni, and Cd in *Saccharum spontaneum* was higher in the roots than in the shoots. Pathak et al. (2019) found that heavy metals accumulated in the roots of indigenous plants *Prosopis juliflora*, *Ipomea carnea*, and

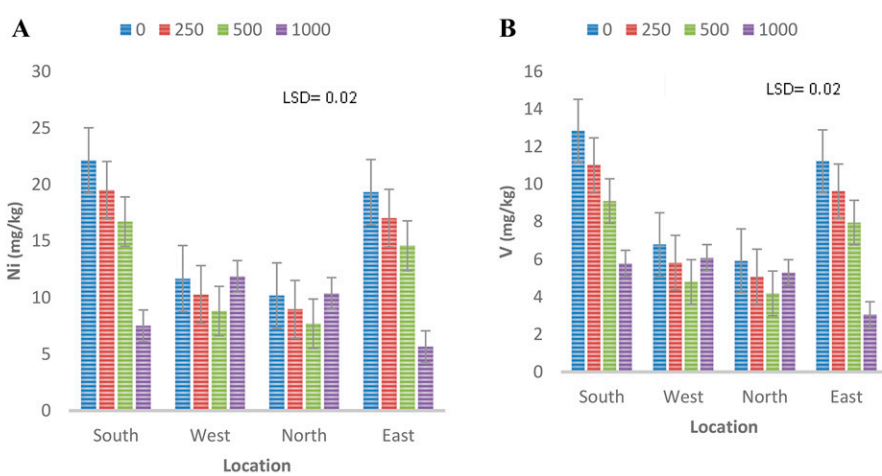

Fig. 10. Concentrations of nickel (**A**) and vanadium (**B**) in tissues of *Z. coccineum* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

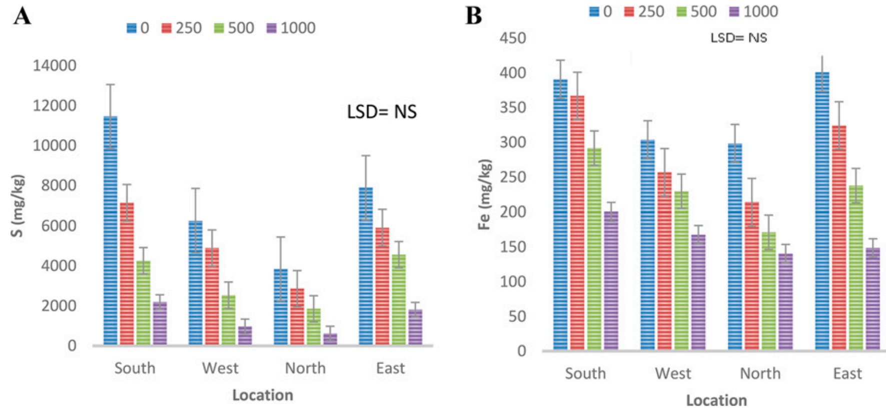

Fig. 11. Concentrations of sulfur (**A**) and iron (**B**) in tissues of *L. pyrotechnica* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

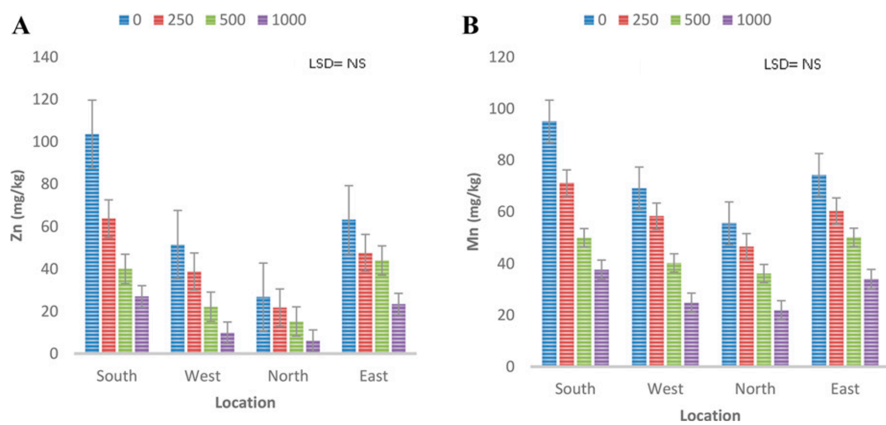

Fig. 12. Concentrations of zinc (**A**) and manganese (**B**) in tissues of *L. pyrotechnica* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

Calotropis procana at a higher rate than that in shoots. Aggarwal and Goyal (2007) planted *Rephamus sativus*, *Amaranth* sp. *Zey mays*, *Cucurbita pepo*, and *Brassica juncea* Oleiformis in a landfill area, resulting in Oleiformis accumulating high concentrations of Cd, Ni, Cu, Cr, and Zn. Al-Solaimani et al. (2024) planted lemongrass and common sage plants under HOFA landfill soil and found that the two species accumulated heavy metals in their roots at a higher rate than that in shoots. Moreover, an extensive analysis of heavy metal concentrations and translocation in *Avicennia marina* mangroves grown in the Red Sea has been performed, and the results of studies in the Yanbu region showed that Fe, Cr, Cu, Ni, and Zn concentrations were highest in fine roots and lowest in aboveground biomass (Abohassan 2013; Al-Solaimani et al. 2022). Rainfall penetrates the deposited HOFA waste, causing decomposition and degradation and releasing many elements, particularly heavy metals. These harmful and toxic elements are high inside the landfill soil, and

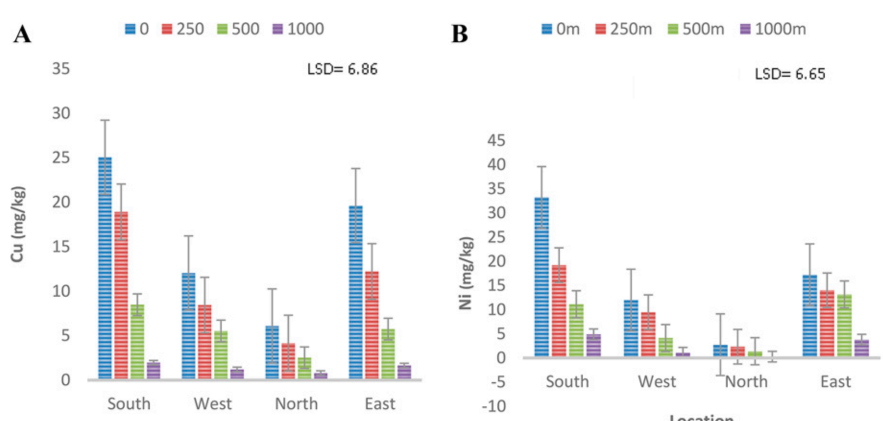

Fig. 13. Concentrations of copper (**A**) and nickel (**B**) in tissues of *L. pyrotechnica* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

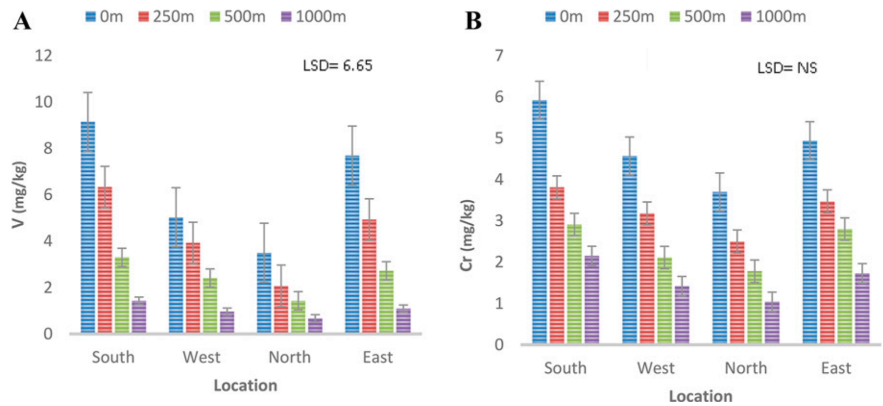

Fig. 14. Concentrations of vanadium (**A**) and chromium (**B**) in tissues of *L. pyrotechnica* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

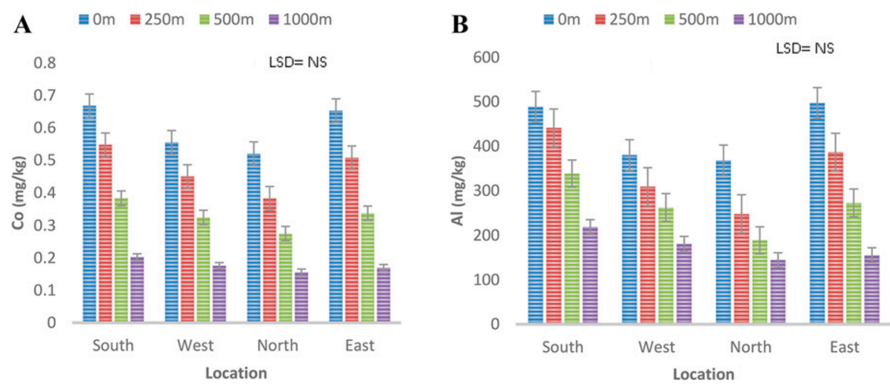

Fig. 15. Concentrations of cobalt (**A**) and aluminum (**B**) in tissues of *L. pyrotechnica* under the effects of the interaction between location and distance across the landfill site. Values are represented as the mean ± standard error indicated by the vertical bars.

through their distribution and movement, rainwater decreases gradually with increasing distance from the landfill. This explains the reduction in *Z. coccineum* and *L. pyrotechnica* growing away from the landfill. *Z. coccineum* was able to absorb these 10 studied heavy metals from the soil of the HOFA landfill in its roots and shoots at a rate higher than that of *L. pyrotechnica*. According to Vargas et al. (2016), the naturally growing plant species *Z. coccineum* and *L. pyrotechnica* are phytoremediators and stabilizers.

Conclusion

Often high in toxic metal content and acidic, HOFA is generated from power stations and water desalination plants and is deposited in landfills. In the current study, the bioaccumulation ability of two naturally growing plants, *Zygophyllum coccineum* and *Leptadenia pyrotechnica*, inside a HOFA landfill was proven, indicating the future potential to exploit such plants in environmental remediation. Growth and metal accumulation by the plants were significantly affected by the distance from the landfill and location. The weakest plant growth rate correlated with the highest metal accumulation by those plants collected from the northern location, which were those with the least accumulation, whereas the opposite was correct for those at the southern location. The highest heavy metal accumulation occurred in plants growing inside the landfill, then it gradually decreased with increasing distance from the landfill at all locations, with S, Al, and Fe being the metals with the highest accumulation. This negatively correlated with the plant growth, whereby the weakest plant growth was recorded inside the landfill and gradually improved with a progressive increase in distances (250, 500, and 1000 m) away from the landfill. The heavy metals accumulated in plant roots at a significantly higher rate than that in the shoots, resulting in a translocation factor of less than one. This indicates that plants use mechanisms of phytoremediation and phytostabilization and can be considered effective in these roles.

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