HABITAT PROPERTIES AND MINERAL CONTENTS OF *AERVA JAVANICA* IN ARID LANDS

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Abstract. This study investigates exploring the phytoremediation potential of *Aerva javanica*, an indigenous herbaceous species, for the absorption and sequestration of heavy metals from contaminated soils in Jeddah governorate, Saudi Arabia. Fieldwork involved the collection of soil and plant samples from six distinct locations along the main roads of Jeddah throughout 2023. The investigation focused on examining the levels of various heavy metals, encompassing copper (Cu^{2+}), chromium (Cr^{2+}), nickel (Ni^{2+}), barium (Ba^{2+}), lead (Pb^{2+}), aluminum (Al^{3+}), and cobalt (Co^{2+}) present in both the soil and plant samples, including their leaves and inflorescences. The findings elucidated substantial seasonal fluctuations in the uptake of metals, with the plant showing an increased efficacy in absorbing Ba^{2+} and Co^{2+}, remarkably within its aboveground components. Through the application of bioaccumulation factor (BAF) analysis, the study underscored *A. javanica's* ability to accumulate metals, with discernible significant variances obvious between the polluted and uncontaminated sites. These results underscore the potential of *A. javanica* as a candidate contender for the sustainable phytoremediation of soils contaminated with heavy metals within urban locations, thereby aligning with the environmental preservation objectives outlined in Saudi Arabia's Vision 2030 initiative. Subsequent investigations and field experiments are recommended to refine its utilization under diverse environmental conditions.
Keywords: *Aerva javanica, phytoremediation, bioaccumulation, sustainability, urban contamination*

Introduction

The Kingdom of Saudi Arabia, renowned for its expansive deserts and varied ecosystems, boasts a rich flora comprising approximately 2243 plant species (Osman and Abdein, 2019). These plants have evolved distinct adaptations to thrive in the region's diverse environmental conditions. The biodiversity of Saudi Arabia, notably its indigenous flora, presents unique prospects for environmental conservation and sustainable development. However, the city of Jeddah, nestled along the Red Sea coast, faces with significant environmental challenges due to fast urbanization, industrial growth, and escalating vehicular traffic. These factors contribute to heightened levels of toxic metals in the atmosphere and soil, exerting increased environmental stress on organisms and jeopardizing food safety and human well-being (Adnan et al., 2024).

Aerva javanica (Burm.f.) Juss. Ex Schult is a resilient perennial herb belonging to the Amaranthaceae family, stands out as a crucial player in the realm of phytoremediation, offering a beacon of hope for rejuvenating polluted landscapes worldwide (Batool et al., 2022). Its widespread distribution underscores a remarkable adaptability to a plethora of environmental conditions, a trait that positions it as a frontrunner in the restoration of

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contaminated regions. Aljedaani and Fakhry (2023) reported that *A. javanica* is widely distributed in the arid desert of Jeddah. The plant Aerva javanica is a perennial herb. It can grow to a height of roughly 0.3 to 1.5 meters and is erect, long-lived, and frequently suffruticose (woody at the base). We frequently observe *A. javanica* growing along roadside ditches, in hilly regions, in sandy places, in degraded and disturbed areas, and in extremely dry environments. According to our field findings, *A. javanica* plants maintain their metabolic activity throughout the year. They regularly produce biomass that can be managed and harvested for cleanup. This behavior could suggest that plants of *A. javanica* can be chosen for phytoremediation. Among a diverse array of plant species, *A. javanica* emerges as a key contributor to the rich biodiversity of the region, weaving itself intricately into the needlepoint of vegetation that defines Jeddah's natural heritage. Its role transcends mere botanical significance, encapsulating a narrative of resilience, adaptation, and environmental stewardship, making it an indispensable collaborator in the activity of sustainable remediation strategies for polluted regions. *A. javanica*, through its phytoremediation prowess, effectively targets a spectrum of metals, reflecting its versatility in environmental cleanup. This resilient herb demonstrates proficiency in the remediation of metals such as Pb, Cd, Cr, Cu, Zn, and Ni (Rashed, 2010; Mousavi Kouhi and Moudi, 2020; Batool et al., 2022). Studies have highlighted the ability of *A. javanica* to absorb and accumulate these metals from contaminated soils, thereby mitigating their adverse effects on the ecosystem. The capacity of *A. javanica* to sequester these metals within its tissues aids in reducing soil toxicity levels, offering a sustainable solution to heavy metal pollution (Alghamdi and El-Zohri, 2024). Through mechanisms like phytoextraction and phytostabilization, *A. javanica* actively participates in the remediation of environments tainted by these detrimental metals, revealing its significance as a potent agent of environmental restoration (Mousavi Kouhi and Moudi, 2020).

The primary objective of this study was to investigate the sustainable applicability of *A. javanica* in phytoremediation practices targeting heavy metal contamination in Jeddah, Saudi Arabia.

Materials and methods

Study area and collection of the samples

Leaf and inflorescence samples of *Aerva javanica*, alongside soil samples from diverse locations across Jeddah governorate, Kingdom of Saudi Arabia, were conscientiously procured. This sample acquisition was carried out during August 2023, when *A. javanica* plants were in fruiting stage. Traffic crowding and exhaust emissions were identified as primary contributors to air pollution in the study area. The sampling locations included six distinctive sites within the Jeddah governorate, characterized by elevated traffic-related pollution along the main roads (*Table 1* and *Fig. 1*). The exact collection technique comprised careful harvesting of *A. javanica* leaves and inflorescences (*Fig. 2*), properly packaging them in polyethylene bags with site-specific labels, and instantly storing them in sealed containers before transport to the laboratory. Three replicates, each containing five plants, were sampled for phenological characterization and sample collections for the laboratory analysis. Soil samples were retrieved to a depth of 30 cm using a manual auger following the elimination of the uppermost layer. After collection, the plant samples were promptly transferred to the laboratory, where they were washed many times with tap water to remove surface pollutants, followed by washing with distilled water to eradicate

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residual contaminants. After the washing, the plant samples were air-dried in shaded quarters until a consistent weight was attained. Subsequently, the plant material underwent grinding to a fine consistency and sieving through a 2 mm mesh to ensure uniform particle size and the exclusion of extraneous debris. Plant materials were appropriately maintained in paper bags until the time of analysis.

Table 1. *The geographical coordinates of the sites of A. javanica and soil samples collected from Jeddah Governorate throughout 2023*

Sites	Coordinates
S1	21°36'23.9"N 39°11'41.2"E
S2	21°37'40.8"N 39°11'30.8"E
S3	21°40'04.7"N 39°12'36.9"E
S4	21°42'35.3"N 39°12'04.0"E
S5	21°44'09.4"N 39°12'51.0"E
S6	21°46'59.3"N 39°16'35.1"E

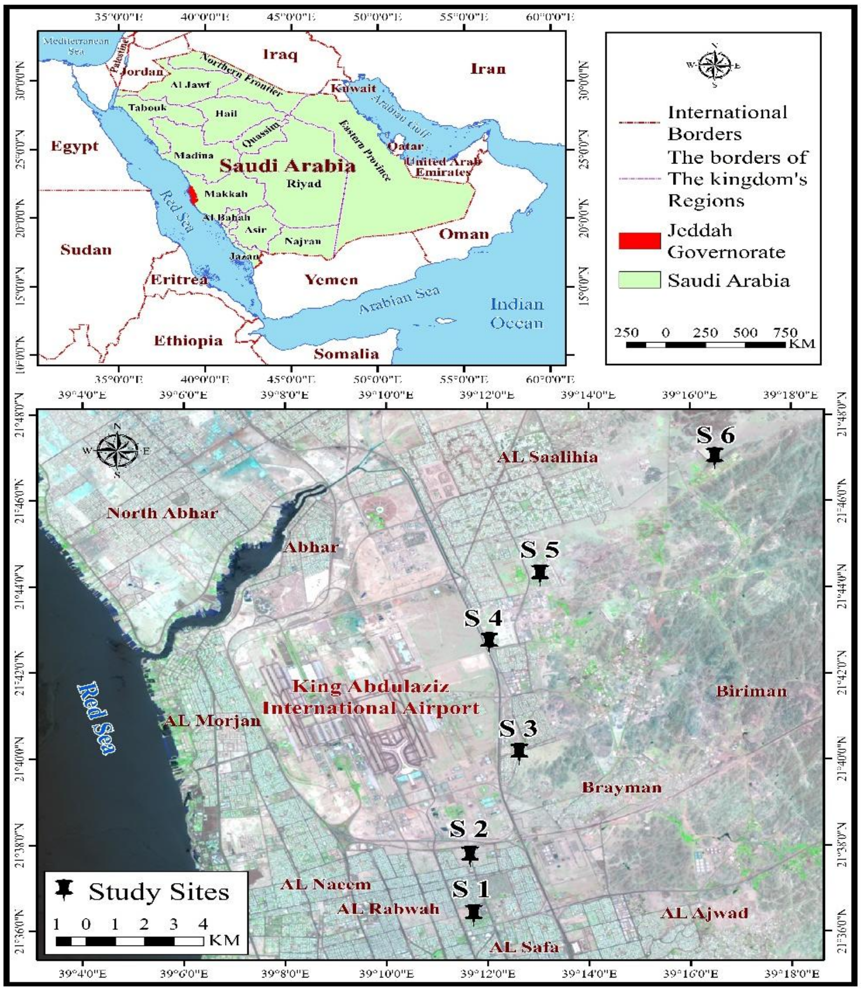

Figure 1. *The investigation area and the sampling sites (S1 – S6)*

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Figure 2. *Image of A. javanica plant captured using an iPhone XS*

Determination of soil texture

The methodology for ascertaining soil texture involved the utilization of the Bouyoucos hydrometer technique as described by Bremner (1965). Initially, a 100-g of the air-dryed soil samples were mixed with 20 ml H_2O_2 and subsequently heated to 100°C. Following this, 200 ml of distilled water and 25 ml of Calgon solution were introduced. The resulting soil suspension was agitated for 3 min. before being adjusted to a volume of 1 liter using a measuring cylinder. Subsequently, the suspension was stirred, and in cases of froth formation, amyl alcohol was introduced. A dry hydrometer was then immersed to capture readings at 40 s (RC1) and 1 h (RC2). Subsequently, the amount of sand, silt, and clay was calculated, and the classification of soil texture was predicated upon the USDA texture triangle, as detailed by Bates et al. (1973) and Beretta et al. (2014) utilizing the percentages obtained from the aforementioned calculations.

Determination of soil organic matter

Soil organic matter content was quantified following the methodology outlined by Walkley (1947). A one-gram portion of air-dried soil samples was deposited into a 500-ml beaker. Subsequently, 10 ml of 1N $K_2Cr_2O_7$ and 20 ml of conc. H_2SO_4 were combined with the soil sample. The mixture was gently agitated and allowed to settle for 30 min. Upon cooling, 200 ml of distilled water and 10 ml of concentrated orthophosphoric acid were introduced. Following this, 10-15 drops of diphenylamine indicator were

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incorporated. The resulting solution was titrated against 0.5 M ferrous ammonium sulfate until the color transitioned from violet-blue to green. The organic matter percentage was computed using *Equation [1]*:

$$Organic\ matter\ (\%) = 10 - \left[1 - \left(\frac{soil\ titration\ value}{blank\ titration\ value}\right)\right] \times 1.34 \qquad \text{(Eq.1)}$$

Preparation of soil extract and soil analysis

A soil paste in water at a 1:5 ratio was accurately prepared and utilized for the quantification of soil minerals following the methodology outlined by Allen et al. (1974). Sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), and chloride (Cl^{-}) were determined following the guidelines provided by the Public Health Association (APHA, 1998). Additionally, the pH levels were assessed using the APH A4500 technique, while the electrical conductivity (EC) was measured using the SMEWW 2510 method, and total dissolved solids (TDS) were quantified through the APHA 2510 procedure as guided by the Public Health Association. Moreover, the prepared soil extract was employed for the analysis of some heavy metals including copper (Cu^{2+}), chromium (Cr^{2+}), nickel (Ni^{2+}), barium (Ba^{2+}), lead (Pb^{2+}), aluminum (Al^{3+}), and cobalt (Co^{2+}) through the utilization of an ICP-MS (Polyscan 61E, Thermo Jarrell-Ash Corp., Franklin, MA, USA) (Dressler et al., 1998). These elemental assessments were carried out at the National Water Company Laboratory in Jeddah, Kingdom of Saudi Arabia.

Plant analyses

The plant stem length and diameter were manually determined in the field at the investigation sites using a measuring tape. In order to calculate the diameter of the canopy using a measuring tape, the widest point of the plant's spread was identified. Subsequently, the the individual leaf area was calculated following the methodology outlined by Sadik et al. (2011). Selected leaves and inflorescences from each plant were carefully collected and placed in a plastic bag, which was then stored in an icebox to maintain sample integrity until their transportation to the laboratory. To prepare the samples for analysis, soil residues and dust on the plant leaves and inflorescences were removed by thorough washing with tap water followed by two rinses with deionized water. The cleaned samples were then air-dried in paper bags in an air-forced oven at 70°C until a constant weight was achieved over five days. Upon reaching complete dryness, the leaf and inflorescence samples were finely ground into a powder using an electric mixer, sieved through a 0.2 mm mesh, and stored in paper bags for subsequent analyses.

Plant ionic content determination

According to the technique prescribed by Havlin and Soltanpour (1980), 1.0 g of plant tissue was carefully weighed and placed into a 50 ml Taylor tube. Subsequently, 10 ml of concentrated nitric acid was introduced, and the sample was left to stand overnight. The following day, the samples underwent heating at 125°C for 4 h, and once fully digested, they were allowed to cool. The volume was then adjusted to 12.5 ml using concentrated nitric acid and further diluted to 50 ml with distilled water. The resultant digestates of *A. javanica* leaves and inflorescences were utilized for the quantification of mineral ions

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(Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}). Additionally, these digestates were employed for the analysis of some heavy metals (Cu^{2+}, Cr^{2+}, Ni^{2+}, Ba^{2+}, Pb^{2+}, Al^{3+}, and Co^{2+}).

Calculation of the bioaccumulation (BAF)

The bioaccumulation factor (BAF) represents the ratio between the heavy metal concentrations within plant tissues (leaves or inflorescences) and those present in the soil. It was calculated by *Equation [2]*.

$$BAF = \frac{Metal\ concentration\ in\ tissue}{Metal\ concentration\ in\ soil} \quad \text{(Eq.2)}$$

Statistical analysis

The data underwent processing using Microsoft Excel 2016, with results depicted as mean values accompanied by their respective standard deviations (SD) derived from three replicates. Subsequently, a one-way analysis of variance (ANOVA) was achieved to assess mean differences, followed by the least significant difference (LSD) as a post-hoc test at a 5% significance level. The statistical analysis was carried out utilizing the SPSS 19.0 software.

Results

The soil physicochemical characters of A. javanica

The data depicted in *Table 2* elucidate the soil texture and organic matter across the surveyed sites. S3 exhibited the highest sand content at an average of 84.0%, contrasting with S5 which displayed the lowest at 79.67%. Notably, S2 recorded the highest silt content (17.0%), with S3 revealing the minimum (10.33%). Furthermore, S5 demonstrated the highest clay content (6.67%), whereas S6 depicted the least at 2.0%. Regarding the total organic matter, S6 showed the highest content (10.21%), contrasting with S2 which displayed the lowest (9.32%).

Table 2. *Variations in soil texture and organic matter (%) at the studied sites*

	Sand	Silt	Clay	Organic matter
S1	79.90 ± 0.17^{b}	15.10 ± 0.17^{b}	5.00 ± 0.01^{c}	1.86 ± 0.12^{c}
S2	80.0 ± 1.01^{b}	17.0 ± 1.02^{a}	3.00 ± 1.04^{e}	1.87 ± 0.37^{c}
S3	84.0 ± 1.02^{a}	10.33 ± 0.58^{d}	5.67 ± 1.15^{b}	1.86 ± 0.37^{b}
S4	82.0 ± 1.61^{b}	$14.0 \pm 1.36b^{c}$	4.00 ± 1.73^{d}	1.96 ± 0.00^{b}
S5	79.67 ± 3.43^{b}	13.67 ± 1.69^{c}	6.67 ± 0.51^{a}	1.9 ± 0.28^{b}
S6	83.33 ± 1.55^{a}	14.67 ± 1.55^{bc}	2.00 ± 0.00^{f}	1.9 ± 0.05^{a}
F	7.8240	46.9701	99.6134	18.3118
P	0.0132 *	0.0001 ***	0.0000 ***	0.0014 **
LSD	1.9686	1.1138	0.6026	0.29175

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

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The variability in the physical (pH, EC, and TDS) and chemical (SO_4^{2-} and Cl^-) attributes of the sampling sites investigated (S1-S6) is presented in *Table 3*. Approximately, the soil pH across the investigated sites ranged from weakly acidic to slightly alkaline. The highest pH value (7.06) manifested in S3, contrasting with the least (6.73) observed in S6. Regarding salinity levels, as indicated by electrical conductivity (EC), the peak EC (2394 µS/cm) was documented in S5, with the lowest (230.3 µS/cm) in S6. In terms of total dissolved solutes (TDS), S5 showed the highest value (1208 mg/Kg), contrasting with S6 recording the lowest value (106.7 mg/Kg). Sulfate concentrations peaked in S5 (120.3 mg/ Kg), whereas S6 exhibited the lowest (16.09 mg/ Kg). Chloride concentrations were maximized in S5 (643.2 mg/ Kg), while S6 displayed the minimum (28.14 mg/ Kg).

Table 3. *Variations in soil pH, electrical conductivity (EC), total dissolved solutes (TDS), sulfate, and chloride ions at the studied sites*

	pH	**EC (µS/cm)**	**TDS (mg/ Kg)**	**Sulfate (mg/Kg)**	**Chloride (mg/ Kg)**
S1	$6.92{\pm}0.02^{a}$	$821.0{\pm}32.9^{cd}$	$395.3{\pm}18.2^{c}$	$18.8{\pm}1.1^{b}$	$151.7{\pm}5.74^{d}$
S2	$6.92{\pm}0.12^{a}$	$1668.7{\pm}34.0^{ab}$	$814.0{\pm}42.3^{b}$	$24.06{\pm}\ 1.2^{a}$	$302.9{\pm}16.10^{b}$
S3	$7.06{\pm}0.06^{a}$	$431.7{\pm}18.3^{d}$	$202.0{\pm}21.4^{cd}$	$8.1{\pm}\ 0.65^{e}$	$84.54{\pm}5.36^{e}$
S4	$6.95{\pm}\ 0.16^{a}$	$1155.7{\pm}10.7^{bc}$	$560.3{\pm}13.2^{c}$	$11.2{\pm}\ 0.51^{d}$	$232.8{\pm}22.02^{c}$
S5	$6.77{\pm}0.43^{a}$	$2394.0{\pm}10.9^{a}$	$1208.0{\pm}15.8^{a}$	$16.1{\pm}\ 0.41^{c}$	$643.2{\pm}36.9^{a}$
S6	$6.73{\pm}0.12^{a}$	$230.3{\pm}21.9^{d}$	$106.7{\pm}10.1^{d}$	$3.2{\pm}\ 0.3^{f}$	$28.14{\pm}1.08^{f}$
F	0.1494	2.7679	9.7081	48.3	968.875
P	0.6383 ns	0.0059 **	0.0001 ***	0.0000 ***	0.0000 ***
LSD	0.1203	140.24798	41.8964	1.5928	2.04393

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

The fluctuation in the ionic composition of the studied sites encompassing Ca^{2+}, Mg^{2+}, Na^+, and K^+ throughout the different sites is shown in *Table 4*. The paramount Ca^{2+} content was determined in S5 (27.94 mg/Kg), compared with the minimal concentration (3.31 mg/Kg) identified in S6. Concerning Mg^{2+}, the peak concentration was documented in S5 (2.71 mg/Kg), while the lowest was observed in S6 (0.51 mg/Kg). Na^+ levels peaked at S5 at 36.22 mg/Kg, while the lowest value was ascertained in S6 at 1.66 mg/Kg. K^+ concentrations were maximal in S1 (4.17 mg/Kg), whereas the minimum was detected in S3 (0.71 mg/Kg).

The variability in the concentration of some heavy metals across the sites investigated, comprising Cu^{2+}, Cr^{2+}, Ni^{2+}, Ba^{2+}, Pb^{2+}, Al^{3+}, and Co^{2+} throughout the different sites, is portrayed in *Table 5*. The data elucidated that the most prevalent pollutive ions in the soil of the studied sites were Al^{3+} and Ba^{2+}. A thorough analysis of diverse heavy metal contents at the collection sites revealed that, Cu^{2+} concentrations peaked at S1 (0.32 mg/Kg), and were lowest at S4 (0.27 mg/Kg). In terms of Cr^{2+}, the highest concentration was detected at S5 (0.40 mg/Kg), with the lowest at S4 (0.32 mg/Kg). Ni^{2+} concentrations peaked at S1 (0.47 mg/Kg) and were lowest at S4 (0.36 mg/Kg). According to our findings, barium (Ba^{2+}) concentrations were maximal at S1 (0.74 mg/Kg), and minimal at S4 (0.43 mg/Kg). Pb^{2+} concentrations peaked at S6 (1.65 mg/Kg) and were minimal at S1 (0.28 mg/Kg). For Al^{3+}, the highest concentration

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was observed at S1 (9.83 mg/Kg), with the lowest at S2 (4.57 mg/Kg) among the investigated sites. Co^{2+} concentrations reached their peak at S4 (0.34 mg/Kg) and were lowest at S2 (0.29 mg/Kg).

***Table 4.** Variations of soil macronutrients (mg/Kg) in the sites investigated*

	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
S1	$11.18{\pm}5.1^{d}$	$1.47{\pm}0.10^{b}$	$14.6{\pm}0.51^{d}$	$4.17{\pm}0.21^{a}$
S2	$24.88{\pm}1.2^{b}$	$2.1{\pm}0.13^{b}$	$27.26{\pm}1.7^{b}$	$2.09{\pm}0.17^{b}$
S3	$5.53{\pm}8.1^{e}$	$0.55{\pm}0.06^{d}$	$7.10{\pm}0.36^{e}$	$0.71{\pm}0.30^{de}$
S4	$13.77{\pm}2.1^{c}$	$1.61{\pm}0.10$	$16.56{\pm}1.03^{c}$	$1.40{\pm}0.11^{c}$
S5	$27.94{\pm}1.2^{a}$	$2.71{\pm}0.31^{a}$	$36.22{\pm}1.1^{a}$	$0.92{\pm}0.14^{e}$
S6	$3.31{\pm}5.1$	$0.51{\pm}0.09^{d}$	$1.66{\pm}0.2^{f}$	$0.81{\pm}0.04^{d}$
F	380.817	47.603	202.341	264.952
P	0.0000***	0.0000***	0.0000***	0.0000***
LSD	1.0461	0.0116	1.048	0.128

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

***Table 5.** Variation in heavy metal concentrations (mg/Kg) in soil extracts at the investigated sites*

	Cu^{2}	Cr^{2}	Ni^{2+}	Ba^{2+}	Pb^{2+}	Al^{3+}	Co^{2+}
S1	$0.32{\pm}0.06^{a}$	$0.38{\pm}0.04^{ab}$	$0.47{\pm}0.05^{a}$	$0.74{\pm}0.09^{ab}$	$0.28{\pm}0.02^{d}$	$9.83{\pm}0.21^{a}$	$0.31{\pm}0.03^{b}$
S2	$0.28{\pm}0.07^{bc}$	$0.39{\pm}0.02^{a}$	$0.43{\pm}0.08^{b}$	$0.70{\pm}0.04^{a}$	$0.29{\pm}0.03^{bc}$	$4.57{\pm}0.5^{d}$	$0.29{\pm}0.08^{c}$
S3	$0.31{\pm}0.07^{a}$	$0.34{\pm}0.04^{bc}$	$0.41{\pm}0.06^{b}$	$0.54{\pm}0.11^{bcd}$	$0.29{\pm}0.02^{cd}$	$6.95{\pm}0.04^{b}$	$0.31{\pm}0.05^{d}$
S4	$0.27{\pm}0.02^{c}$	$0.32{\pm}0.03^{c}$	$0.36{\pm}0.02^{b}$	$0.43{\pm}0.03^{d}$	$0.32{\pm}0.02^{cd}$	$6.96{\pm}0.05^{b}$	$0.34{\pm}0.06^{b}$
S5	$0.31{\pm}0.03^{a}$	$0.41{\pm}0.01^{a}$	$0.41{\pm}0.03^{c}$	$0.57{\pm}0.09^{abc}$	$0.32{\pm}0.02^{ab}$	$6.73{\pm}0.03^{c}$	$0.30{\pm}0.06^{a}$
S6	$0.29{\pm}0.01^{b}$	$0.40{\pm}0.03^{a}$	$0.40{\pm}0.04^{b}$	$0.45{\pm}0.03^{cd}$	$1.65{\pm}0.01^{a}$	$6.67{\pm}0.02^{bc}$	$0.31{\pm}0.01^{bc}$
F	4.4852	1.0626	29626	1.65716	2.6958	48.0939	15.854
P	0.0008***	0.0122*	0.0030**	0.0139*	0.0047**	0.0000***	0.0000***
LSD	0.0157	0.05109	0.0398	0.1120	0.0278	0.4387	0.0150

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

Variation of vegetative attributes of A. javanica in the different sites

The data delineated in *Table 6* elucidate the dynamic fluctuations in the growth characteristics of *A. javanica* across six distinct collection sites (S1-S6). The data unveiled a spectrum of plant heights varying from 61.67 to 76.67 cm. Notably, site S4 exhibited the maximum average height at 76.67 cm. Moreover, the plant diameter oscillated between 50.0 and 75.0 cm throughout. Site S4 possessed a top diameter of 75.0 cm. Leaf area measurements spanned from 2.22 to 4.76 cm². Site S4 exhibited the maximal leaf area of 4.76 cm². Conversely, the most diminutive leaf area of *A. javanica* within the assessed sites was documented at site S6, revealing values of 2.22 cm².

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***Table 6.** Variations of the stem height, width, and leaf area of A. javanica in the investigated sites*

	Height (cm)	Width (cm)	Leaf area (cm^2)
S1	66.0±2.58^c	62.33±5.82^c	3.41±0.27^b
S2	61.67±3.66^d	50.0± 5.00^d	3.11±0.86^b
S3	68.67±2.31^b	69.0±1.15^b	3.63±0.53^b
S4	76.67±5.28^a	75.0±1.03^a	4.76±0.62^a
S5	65.00±2.66^c	55.00±3.23^d	4.37±0.03^{ab}
S6	63.33±3.08^d	68.33±1.07^b	2.22±0.29^b
F	95.106	79.0262	4.5089
P	0.0000***	0.0000***	0.0472*
LSD	1.7919	3.8142	2.2310

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

Variations of ionic content in A. javanica leaves in the different sites

The variation in the concentrations of four ionic components (Ca^{2+}, Mg^{2+}, Na^+, and K^+) in the leaf powders of *A. javanica*, collected from different localities (S1-S6) in *Table 7*. The data indicated that the significance of the ions in leaf powders was ranked as follows: Ca > Na > K > Mg. Data indicated that Ca^{2+} concentrations in the leaves were maximal in S1 (1.37 mg/Kg) and minimal in S2 (0.87 mg/Kg). Mg^{2+} concentrations were highest in S4 at 0.28 mg/Kg and lowest in S2 at 0.11 mg/Kg. Sodium (Na^+) concentrations exhibited significant fluctuation all investigation sites. Sodium was observed at its peak concentration in S5 (0.74 mg/Kg) and its lowest in S6 (0.61 mg/Kg). Potassium (K^+) concentrations were highest at S1 (0.25 mg/Kg) and lowest at S4 (0.17 mg/Kg).

***Table 7.** Variations in macronutrients (mg/Kg) in A. javanica leaves in the investigated sites*

	Ca^{2+}	Mg^{2+}	Na^+	K^+
S1	1.37± 0.01^a	0.12± 0.01	0.74± 0.02^b	0.25± 0.02^a
S2	0.87± 0.01^d	0.11± 0.01^d	0.62± 0.02^c	0.19± 0.02 ^{b}
S3	1.06± 0.02^c	0.18± 0.01^b	0.87± 0.03^a	0.18± 0.01^{bc}
S4	1.21± 0.02^b	0.28± 0.01^a	0.80± 0.03^{ab}	0.17± 0.01^c
S5	1.25±0.02^{ab}	0.17± 0.01^b	0.87± 0.01^a	0.25± 0.01^a
S6	0.89± 0.01^d	0.14± 0.02^c	0.61± 0.02^c	0.17± 0.01^c
F	2.3658	13.125	1.3056	3.3119
P	0.0001***	0.0000***	0.0011**	0.0001***
LSD	0.114	0.0133	0.974	0.0138

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

Variations of ionic content in A. javanica inflorescences in the different sites

The fluctuations in the levels of four ionic constituents (Ca^{2+}, Mg^{2+}, Na^+, and K^+) in the inflorescence powders of *A. javanica*, sampled from several localities (S1-S6) in *Table 8*. The concentration of the analyzed ions was ranked as $Ca^{2+} > Na^+ > K^+ > Mg^{2+}$.

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In detail, the concentrations of Ca in the inflorescences were highest in S1 (4.67 mg/Kg), and lowest in S4 (0.54 mg/Kg). Mg^{2+} concentrations peaked at 0.05 mg/Kg in S6 and reached a nadir of 0.04 mg/Kg in S4. Sodium (Na^+) concentrations in the inflorescence were highest in S2 (0.37 mg/Kg) and lowest in S3 (0.24 mg/Kg). Potassium (K^+) exhibited the maximum concentration (0.10 mg/Kg) in S5 and the lowest concentration (0.01 mg/Kg) in S1.

Table 8. *Variations in macronutrients (mg/Kg) in A. javanica inflorescences in the investigated sites*

	Ca^{2+}	Mg^{2+}	Na^+	K^+
S1	4.67± 0.11^a	0.03± 0.01^c	0.36± 0.01^a	0.01± 0.01^d
S2	0.99± 0.07^b	0.04± 0.01^b	0.37± 0.01^a	0.05± 0.01^b
S3	0.59± 0.12^c	0.04±0.01^b	0.24± 0.02^c	0.04± 0.01^c
S4	0.54± 0.11^c	0.02±0.01^c	0.26± 0.01^c	0.06± 0.01^b
S5	0.54± 0.13^c	0.03± 0.01^b	0.27± 0.02^b	0.10± 0.01^a
S6	0.59± 0.10^c	0.05± 0.10	0.25± 0.02^c	0.09± 0.02^a
F	126.170	2.8939	5.5709	12.378
P	0.0000***	0.0003***	0.0000***	0.0000***
LSD	0.1146	0.0103	0.0386	0.0199

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

Variations of heavy metals in A. javanica leaves in the different sites

The accumulation of the quantified heavy metals (Cu^{2+}, Cr^{2+}, Ni^{2+}, Ba^{2+}, Pb^{2+}, Al^{3+}, and Co^{2+}) in the leaf powders of *A. javanica* collected from six sites (S1-S6) in *Table 9*. Concerning the content of Cu^{2+} across the sites under investigation, the highest level of Cu^{2+} was detected in S2 (0.07 mg/Kg), while the lowest concentration was observed in S1 (0.05 mg/Kg). As for chromium (Cr^{2+}), the highest levels were found in S3, contrasting with the lowest in S2 (0.08 and 0.06 mg/Kg, respectively). Nickel (Ni^{2+}) concentrations peaked in S6 (0.09 mg/Kg) and were lowest in S1 and S5 (0.06 mg/Kg. Barium (Ba^{2+}), the most prevalent heavy metal in *A. javanica* leaves, showed the highest concentration (0.48 mg/Kg) in S3 and the lowest (0.19 mg/Kg) in S4. Lead (Pb^{2+}) accumulation was highest in S2 and S3 (0.08 mg/Kg) and lowest in S1 (0.06 mg/Kg). In terms of aluminum (Al^{3+}) accumulation in *A. javanica* leaves, the highest levels were in S6 (0.73 mg/Kg), while the lowest was in S5 (0.21 mg/Kg). Finally, for cobalt (Co^{2+}), the highest levels were found in S6 (0.60 mg/Kg) and the lowest in S3 (0.17 mg/Kg).

Variations of heavy metals in A. javanica inflorescences in the different sites

The study details the accumulation of the quantified heavy metals (Cu^{2+}, Cr^{2+}, Ni^{2+}, Ba^{2+}, Pb^{2+}, Al^{3+}, and Co^{2+}) in the inflorescence powders of A. *javanica* collected from six different localities (S1-S6) in *Table 10*. The highest concentration of Cu^{2+} was identified in the inflorescences of S3 (0.08 mg/Kg), while the lowest was observed in S2 and S6 (0.06 mg/Kg). Regarding Cr^{2+}, the peak concentration was discerned in S3 (0.51 mg/Kg), contrasting with the nadir in S1 (0.06 mg/Kg). Ni^{2+} concentration reached its peak in S5 (0.10 mg/Kg) and its lowest value in S3 (0.06 mg/Kg). Ba^{2+}in *A. javanica* inflorescences displayed its apex content (0.79 mg/Kg) in S5 and its minimum (0.06 mg/Kg) in S1. The

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superior concentration of Pb^{2+} was noted in S3 (0.07 mg/Kg). Al^{3+} demonstrated active accumulation in the inflorescences of S3 (2.02 mg/Kg), whereas accumulation was minimal in the inflorescences of S5 (0.89 mg/Kg). Concerning Co^{2+} accumulation, the highest levels were apparent in S4 (0.84 mg/Kg), contrasting with the lowest in S1 (0.07 mg/Kg).

Table 9. *Variation in heavy metal concentrations (mg/Kg) in A. javanica leaves in the studied sites*

	Cu^{2+}	Cr^{2+}	Ni^{2+}	Ba^{2+}	Pb^{2+}	Al^{3+}	Co^{2+}
S1	0.05± 0.01^{d}	0.07± 0.01^{d}	0.06± 0.02^{d}	0.42± 0.11^{a}	0.07± 0.01^{c}	1.25± 0.21^{d}	0.27± 0.02^{c}
S2	0.07± 0.01^{a}	0.06± 0.01^{e}	0.08± 0.01^{a}	0.46± 0.09	0.08± 0.01^{ab}	0.51± 0.9^{d}	0.56± 0.01^{a}
S3	0.06± 0.01^{b}	0.08± 0.01^{a}	0.07± 0.01^{b}	0.48± 0.12^{a}	0.08± 0.01^{ab}	0.61±0.02^{a}	0.17± 0.01^{b}
S4	0.06± 0.01^{c}	0.07± 0.01^{ab}	0.07± 0.01^{c}	0.19± 0.02^{b}	0.06± 0.01^{b}	0.44± 0.01^{ab}	0.34± 0.01^{b}
S5	0.06± 0.01^{b}	0.07 ± 0.01^{c}	0.06± 0.02^{d}	0.21± 0.01^{b}	0.06±0.01^{ab}	0.21± 0.01^{c}	0.40± 0.02^{c}
S6	0.06± 0.02^{ab}	0.08± 0.02^{b}	0.09± 0.01^{a}	0.41± 0.13^{a}	0.061± 0.01^{a}	0.73± 0.02^{bc}	0.60± 0.01^{a}
F	2.709	5.115	11.391	1.613	0.0214	1.5798	3.6636
P	0.0001***	0.0000***	0.0000***	0.0005***	0.0172 *	0.0003 ***	0.0000***
LSD	0.05142	0.0533	0.0681	2.0415	0.1495	0.0996	0.09370

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

Table 10. *Variation in heavy metal concentrations (mg/Kg) in A. javanica inflorescence in the studied sites*

	Cu^{2+}	Cr^{2+}	Ni^{2+}	Ba^{2+}	Pb^{2+}	Al^{3+}	Co^{2+}
S1	0.08± 0.01^{ab}	0.06± 0.01^{e}	0.08± 0.01^{c}	0.06± 0.01^{c}	0.06± 0.01^{b}	1.64± 0.11	0.07± 0.01^{e}
S2	0.06± 0.02^{cd}	0.06± 0.01^{d}	0.07± 0.01^{d}	0.07± 0.01^{c}	0.06± 0.01^{ab}	1.10± 0.10^{c}	0.67± 0.02^{b}
S3	0.08± 0.01^{a}	10.07± 0.02^{b}	0.06± 0.01^{e}	0.06± 0.01^{c}	0.07± 0.01^{a}	2.02± 0.06^{a}	0.20± 0.03^{d}
S4	0.07± 0.02^{bc}	0.07± 0.01^{b}	0.08± 0.01^{b}	0.61± 0.01^{b}	0.07± 0.01^{b}	1.13± 0.07	0.84± 0.03^{a}
S5	0.08± 0.01^{a}	0.07± 0.01^{a}	0.10± 0.02^{a}	0.79± 0.10^{a}	0.06± 0.01^{a}	0.89± 0.07^{d}	0.28± 0.03^{c}
S6	0.06± 0.01^{d}	0.07± 0.02^{c}	0.07± 0.02^{cd}	0.64± 0.10^{b}	0.06± 0.01^{ab}	1.71± 0.03^{b}	0.62± 0.08^{b}
F	1.2460	10.791	5.123	26.0635	0.282	8.391	15.434
P	0.0053 **	0.0000 ***	0.0000 ***	0.0000***	0.0286 *	0.0000 ***	0.0000 ***
LSD	0.01	0.0001	0.001	0.05	0.017	0.118	0.061

The data are presented as the average of three replicates ± standard deviation. Different superscript letters within the same column denote significant differences at the 5% level

Variations of heavy metals bioaccumulation factor in A. javanica leaves and inflorescences in the different sites

Table 11 presents the bioaccumulation factor (BAF) for heavy metals (Cu^{2+}, Cr^{2+}, Ni^{2+}, Ba^{2+}, Pb^{2+}, Al^{3+}, and Co^{2+}) in *A. javanica* leaves and inflorescences. BAF is the ratio of metal concentration in the plant to that in the soil, reflecting metal uptake. The BAF serves as a quantitative measure of the plant's ability to uptake heavy metals from the soil and accumulate them in its aboveground tissues. During the Cu^{2+} exhibited varying BAF values in the leaves, with the highest recorded in S2 (1.02) and the lowest in S1 (0.73). In the inflorescence, the highest BAF for Cu^{2+} occurred in S4 (1.14). For Cr^{2+}, the leaves

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showed the highest BAF in S4 (1.21) and the lowest in S2 (0.67). In the inflorescence, the highest BAF was recorded in S4 (0.93). The leaves of *A. javanica* exhibited the highest BAF for Ni^{2+} in sampling site S6 at 0.93, while the lowest BAF was observed in S1 at 0.59. In the inflorescence, the highest BAF for Ni^{2+} was documented in S5 at 1.01, whereas the lowest was recorded in S3 at 0.64.

Table 11. *Variations in the bioaccumulation factor (BAF) of heavy metals in leaves and inflorescences of A. javanica in the studied sites*

	Cu^{2+}	Cr^{2+}	Ni^{2+}	Ba^{2+}	Pb^{2+}	Al^{3+}	Co^{2+}
S1	0.73	0.72	0.59	2.27	0.84	0.03	0.90
S2	1.02	0.67	0.87	2.68	0.98	0.06	1.26
S3	0.87	1.01	0.74	3.55	0.94	0.05	1.31
S4	0.96	1.02	0.81	1.82	0.90	0.05	0.92
S5	0.86	0.73	0.66	1.39	0.85	0.05	0.80
S6	0.97	0.81	0.93	3.57	0.86	0.05	1.21
S1	1.03	0.63	0.69	0.35	0.88	0.67	0.90
S2	0.92	0.66	0.68	0.40	0.89	0.96	9.16
S3	1.13	0.90	0.64	0.51	1.01	1.17	3.44
S4	1.14	0.93	0.96	5.68	0.87	0.65	10.62
S5	1.08	0.76	1.01	5.53	0.87	0.53	3.29
S6	0.90	0.73	0.77	5.64	0.81	1.03	8.15

Concerning Ba^{2+}, the leaves displayed the highest BAF in S6 (3.57) and the lowest in S5 (1.39). In the inflorescence, the greatest BAF occurred in S4 (5.68), while the lowest was identified in S1 (0.35). In the case of Pb^{2+}, the leaves exhibited the highest BAF in S2 (0.98) and the lowest in S1 (0.84). Within the inflorescence, the maximum BAF was recorded in S3 (1.01), whereas the minimum was in S6 (0.81). For Al^{3+}, the leaves showed the highest BAF in S2 (0.06) and the lowest in S1 (0.03). Within inflorescences, the highest BAF was recognized in S3 (1.17), while the lowest was in S5 (0.53).

Discussion

A. javanica exhibits a number of adaptation traits, such as smaller leaves and a C4 photosynthetic mechanism with two types of assimilatory parenchyma (Ehleringer et al., 1997). The plant's versatility and resilience in harsh environments underscore its importance not only in traditional medicine but also in ecological restoration projects aimed at delaying desertification and promoting sustainable land management practices. Apart from its ability to withstand drought, *A. javanica* also acts as a soil binder and lessens soil erosion. It is categorized as a native plant suitable for urban landscaping by the Global Sustainability Assessment System (Phondani et al., 2015). It is also said to help re-vegetate degraded rangelands through its application in desert dune stabilization (Hammiche and Maiza, 2006). Early, it was recorded that *A. javanica* is able to withstand high temperatures and dry conditions while maintaining photosynthetic efficiency (Ehleringer et al., 1997). Moreover, *A. javanica* serves as a soil binder, resists drought, and reduces soil erosion. It is classified as one of the natural plants appropriate for urban landscaping by the Global Sustainability Assessment System (Phondani et al., 2015). The plant's ability to adapt and endure in challenging conditions highlights its significance in

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ecological restoration initiatives meant to slow down desertification and support sustainable land management techniques.

In a recent study of an area contaminated with heavy metals in Jeddah Governorate, Saudi Arabia, it was suggested that *Amaranthus retroflexus* has the potential to be a promising bioremediatory and stress-tolerant plant at the same time; moreover, defense and detoxification mechanisms were uncovered (Alsherif et al., 2022). It was recorded that a wealth of tolerant species can be found in the vegetation of contaminated sites, such as *A. retroflexus, Echinochloa colona,* and *Prosopis juliflora*, which showed the capacity to colonize areas near the sewage in our research area. Additionally, the latter showed high tolerance to heavy metal toxicity, and they were dispersed throughout the four polluted regions under study. In addition, they recorded that *A. retroflexus* displayed the highest frequencies and relative densities at contaminated sites among the identified tolerant species, so we chose it. It can withstand the toxicity of accumulations of various heavy metals, including Ni, As, and Cu (Alsherif et al., 2022).

Soil properties play a significant role in understanding the dynamic nature of soil ecosystems (Chen et al., 2021). Soil analysis revealed distinct variations in sand, silt, and clay content across the sites during both seasons. The ionic composition of the soil within the studied sites, including Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, varied significantly across sites and seasons. Also, heavy metal concentrations differed among sites, with Al^{3+} and Ba^{2+} being notably prevalent. The concentrations of heavy metals varied across sites, highlighting the presence of these pollutants in the soil. The variations in the concentrations of heavy metals across different sites can be attributed to several factors. Heavy metals can originate from natural geological processes such as the weathering of rocks and minerals (Arshad et al., 2025). Also, industrial processes, mining, agriculture, and urbanization can introduce heavy metals into the soil. These activities may vary in intensity across sites, leading to differing levels of contamination. Different land use practices, such as the application of fertilizers, pesticides, and sewage sludge, as well as transportation of heavy metals through water runoff, wind erosion, and atmospheric deposition can also play a role in the distribution of these pollutants across sites (Minhas and Qadir, 2025).

The study reported notable fluctuations in plant height, width, and leaf area measurements, revealing how these characteristics vary in the different sites. S4 demonstrated the highest average height, likely due to optimal photosynthetic efficiency and extended photoperiods enhancing growth (Shibaeva et al., 2022). plant diameter oscillated between sites, with S4 boasting the largest plant width, suggesting site-specific microclimatic influences. Leaf area measurements exhibited a similar trend, with S4 displaying the largest leaf area, consistent with enhanced transpiration-driven cell elongation, Conversely, S6 consistently exhibited the smallest leaf area values across seasons, possibly due to soil nutrient deficiencies or water stress.

Furthermore, the concentrations of metal ions (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) revealed distinct patterns of fluctuation across the leaves and the inflorescences. This fluctuation could be attributed to the edaphic influences on ion uptake efficiency. These findings underscore the complex interplay between seasonal physiological demands, microenvironments, and ion homeostasis in plant tissues. The accumulation of heavy metals in plant tissues such as leaves and inflorescences has been a subject of significant interest due to the potential of plants to act as bioaccumulators or bioremediators of metals in the environment. In the case of *A. javanica*, the findings regarding the variations of heavy metal accumulation in both leaves and inflorescences shed light on the differential capacities of these plant parts to sequester various heavy metals. *A. javanica* leaves

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showed variability across sites, with distinct trends observed. Similar variability was observed in inflorescences, but with differing accumulation levels compared to leaves, suggesting differential uptake or storage mechanisms. In an earlier investigation, Rashed (2010) documented that the bioaccumulation parameters for soil–plant indicated that *A. javanica* serves as an effective indicator for heavy metal contamination in polluted soil. Consequentially, analysis of heavy metal accumulation in *A. javanica* leaves and inflorescences from different sites in Jeddah governorate provides valuable insights into the seasonal variations and site-specific dynamics of heavy metal uptake by the plant. These findings underscore the importance of considering factors when assessing the potential of *A. javanica* as a bioaccumulator or bioremediator of heavy metals in the environment. Further research into the mechanisms underlying these accumulation patterns could enhance our understanding of phytoremediation strategies for heavy metal pollution mitigation.

The variations of heavy metal bioaccumulation factors (BAF) in *A. javanica* leaves and inflorescences provide crucial insights into its ability to uptake heavy metals from the polluted soil. The BAF values, reflecting metal concentrations in the plant relative to the soil, highlight the seasonal dynamics of metal uptake by *A. javanica*. According to our results, Cu^{2+} exhibited varying BAF values in both leaves and inflorescences, with distinct site-specific patterns observed. Cr^{2+} showed contrasting BAF values across different sites, emphasizing the variability in metal uptake by the plant (Ullah et al., 2025). Ni^{2+} exhibited notable BAF variations, with peak values in specific sites, underscoring the dynamics of Ni^{2+} accumulation. Likewise, Ba^{2+} demonstrated significant BAF differences between, with distinct accumulation patterns in leaves and inflorescences. Pb^{2+} and Al^{3+} also displayed varying BAF values, indicating differential metal uptake by *A. javanica* in different sites and seasons. Notably, Co^{2+} showed consistently high BAF values, particularly in site S4, suggesting a strong affinity for metal accumulation in both leaves and inflorescences. Overall, *A. javanica* in S2 stood out as a strong accumulator site for multiple metals in leaves and inflorescences. The significant BAF values for Co^{2+} in both leaves and inflorescences, particularly in S4, highlight the potential of A. javanica for effective metal uptake and accumulation. These results underscore the importance of considering seasonal and site-specific factors in studying heavy metal bioaccumulation in *A. javanica*, contributing to our understanding of phytoremediation strategies and environmental metal pollution mitigation. Furthermore, variations in heavy metal accumulation imply that environmental conditions like temperature, moisture, and pollution levels can impact the efficacy of the plant's phytoremediation capabilities (Yang et al., 2021).

Previously, it was documented that certain metals from the soil, particularly Mn, Cr, Cu, and Zn, can be concentrated by plants like and *Aerva javanica* (Rashed, 2000). Studies on mine-tailings vegetation can yield valuable insights into species tolerance, accumulation, and translocation characteristics that may be relevant at sites with moderate contamination. High quantities of Co, Cu, Cr, Hg, Mn, and Ni are accumulated by *A. javanica*, indicating that this plant was very tolerant of these metals (Rashed, 2000).

Conclusions

In conclusion, the study underscores the significant potential of *A. javanica* as a valuable phytoremediation species in Saudi Arabia, particularly in urban settings such as Jeddah. Its remarkable capacity to accumulate heavy metals, including Cu^{2+}, Cr^{2+}, Co^{2+},

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Ni^{2+}, Pb^{2+}, Ba^{2+}, and Al^{3+} positions it as a promising solution for addressing soil contamination resulting from urbanization and industrial activities. To optimize the phytoremediation efficacy of *A. javanica*, future research efforts should concentrate on fine-tuning conditions that enhance heavy metal uptake. Exploring the plant's responses to diverse soil treatments, irrigation methods, and planting densities could yield insights into maximizing its remediation potential. Also, large-scale field trials are essential to evaluate its long-term sustainability and ecological impact comprehensively. Integrating *A. javanica* into urban planning and reforestation initiatives not only aids in soil detoxification but also fosters green space expansion and environmental preservation.

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Author contributions. Sara Alhazmi – Conceptualization, Data curation, Methodology. Ghalia Aljeddani – Conceptualization, Data curation, Funding acquisition, Investigation, Supervision, Validation, Writing – original draft. Abeer Mahmoud Kutby – Conceptualization, Investigation. Ameina Almoshadak – Conceptualization, Data curation, Investigation, Writing – review & editing. All authors read and approved the final manuscript.

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