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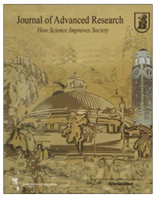


Plants predict the mineral mines – A methodological approach to use indicator plant species for the discovery of mining sites

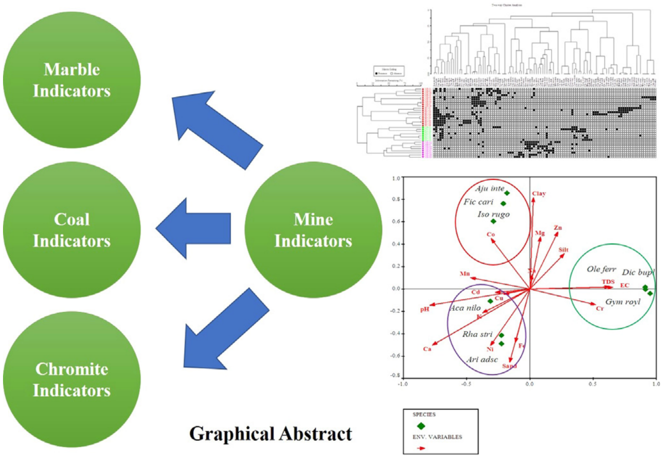
Zeeshan Ahmad [a], Shujaul Mulk Khan [a,*], Sue Page [b], Saad Alamri [c], Mohamed Hashem [c,d]

[a] Department of Plant Sciences, Quaid-i-Azam University Islamabad, Pakistan
[b] Department of Geography, University of Leicester, UK
[c] King Khalid University, College of Science, Department of Biology, Abha 61413, Saudi Arabia
[d] Assiut University, Faculty of Science, Botany and Microbiology Department, Assiut, 71516, Egypt

HIGHLIGHTS

- Plant species predict presence of specific mineral reserves.
- These plants can be used as indicators for economically important mineral reserves.
- Indicator Species and modelling approaches were used for indicators of mineral mines.
- Coal indicators were Olea ferruginea, Gymnosporia royleana and few more.
- These approaches could potentially be applied for exploration of mineral reserves.

GRAPHICAL ABSTRACT



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ABSTRACT

Introduction: There has been limited research conducted on the identifications/methodological approaches of using plant species as indicators of the presence of economically, important mineral resources.

Objectives: This study set out to answer the following questions (1) Do specific plant species and species assemblages indicate the presence of mineral deposits? and (2) if yes, then what sort of ecological, experimental, and statistical procedures could be employed to identify such indicators?

Methods: Keeping in mind these questions, the vegetation of subtropical mineral mines sites in northern Pakistan were evaluated using Indicator Species Analysis (ISA), Canonical Correspondence Analysis (CCA) and Structural Equation Modeling (SEM).

Results: A total of 105 plant species belonging to 95 genera and 43 families were recorded from the three mining regions. CA and TWCA classified all the stations and plants into three major mining zones, corresponding to the presence of marble, coal, and chromite, based on Jaccard distance and Ward's linkage

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Abbreviations: ISA, Indicator Species Analysis; CCA, Canonical Correspondence Analysis; SEM, Structural Equation Model; KPK, Khyber Pakhtunkhwa; CA, Cluster Analysis; TWCA, Two-way Cluster Analysis; EC, electrical conductivity; TDS, total dissolved solids; K, potassium; P, phosphorus; Mn, Manganese; Ni, Nickle; Cu, Copper; Cd, Cadmium; Fe, Iron; Cr, Chromium; Co, Cobalt; Na, Sodium; Mg, Magnesium; Ca, Calcium.

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* Corresponding author.

E-mail address: shujaqau@gmail.com (S. Mulk Khan).

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methods. This comprehended the following indicator species: *Ficus carica*, *Isodon rugosus* and *Ajuga parviflora* (marble indicators); *Olea ferruginea*, *Gymnosporia royleana* and *Dicliptera bupleuroides* (coal indicators); and *Acacia nilotica*, *Rhazya stricta* and *Aristida adscensionis* (chromite indicators) based on calculated Indicator Values (IV). These indicators were reconfirmed by CCA and SEM analysis.

Conclusion: It was concluded that ISA is one of the best techniques for the identification/selection of plant indicator species, followed by reconfirmation via CCA and SEM analysis. In addition to establishing a robust approach to identifying plant indicator species, our results could have application in mineral prospecting and detection.

Introduction

The floristic composition is actually an expression of the abiotic environment. Environmental factors differentially affect the growth and reproduction of plant species, which in turn influence their distribution patterns [1–5]. As a result, the presence or absence of plant species can provide us with information on the cumulative effects of environmental variables prevalent in a particular habitat [6–9] and can also demonstrate the presence of environmental gradients. Plant indicators (also referred to as bio-, phyto- or environmental indicators) can, according to one definition, be described as those species that consistently occur only within a narrow and distinctive environmental range [10]; most can be described as stenotypic (indicating narrow limits of tolerance). Ideal indicators can denote, with a high level of certainty, a specific set of environmental conditions [11–14]. Occasionally, their presence may indicate conditions that have prevailed in the past, e.g. plant indicators of former agriculture or human habitation, or the one that may occur in an ecosystem in the future [15–16]. There have been a minimal number of ecological studies of indicator plant species of non-toxic mineral resources, with a greater emphasis on species that may indicate metals in soils or mining sites.

Changes in the soil composition can evidently bring about changes in the vegetation composition; thus plant communities can, in turn, provide information on the edaphic environment [17]. Examples of plant species which have been reported as indicators of the presence of heavy metals in soils include *Viola calaminaria* and *Thlaspi calaminarium* for zinc [18], *Stellaria setacea* for mercury [19], and *Viscaria alpina*, *Gypsophila patrini* and *Gymnocolia inflata* for copper [20–21], with *Polycarpaea spyrostyles* reportedly formerly used in prospecting for copper ore in Australia [22]. Species of *Allium, Astragalus, Calochortus* and *Eriogonum* are noted as indicators of uranium ore [23–24] and *Aster venustus*, *Oryzopsis* and *Astragalus* spp. as indicators of both selenium and uranium [25] since these two metal ores often occur in the same locations. Plant species listed as indicators of the presence of other metalliferous ores include *Equisetum* spp. and *Papaver libonoticum* as indicators of gold [26,27–29], *Lycium juncus* (a lithium indicator), *Dacrydium caledonicum* and *Betula* spp. (iron indicators), *Ulex aquifolium* (aluminum indicator) [18], *Asplenium viride* (chromium indicator) and *Erigonum ovalifolium* (silver indicator) [30–31].

Some researchers have utilized plant species as indicators of environmental, and specifically edaphic, conditions without a strong conceptual background. In particular, there are limited empirical studies underpinning the identification/selection of plant indicators of the presence of mineral resources. Conventionally, authors have mentioned the concept of dominant or characteristics species [32–33]. Indicator Species Analysis (ISA) can be used to compare the performance of individual indicator species across two or more groups of sampled units [34] based on concepts of both abundance and frequency (concentration of abundance in a particular group and relative frequency within a group). This approach provides a proficient means to explore the complex relationships of plants with abiotic factors, including soil physical and chemical characteristics. It enables the detection of significant environmental factors that elucidate these complications and thus gives proper indicators [10,35]. ISA distinguishes the main patterns in the relationships among species and environmental factors and assists in generating a hypothesis concerning the structure and specificity of indicator species in a particular ecosystem [36–38].

The Hindu Kush-Himalaya range is situated on a fault line of Indian and Eurasian geological plates and hence are rich sites for various minerals. Mineral resources of economic importance include both non-metallic minerals, such as marble and coal (varying from bituminous coal to lignite), and metallic minerals, e.g. chromite, all of which are mined. Among the non-metallic minerals marble is a metamorphic rock made up of carbonates minerals i.e., calcite and dolomite [39]. It generally happen when limestone is exposed to increasing heat and higher pressure. It consist of CaO, Fe_2O_3, P_2O_5, Al_2O_3, Na_2O, TiO_2, SiO_2 and MgO compounds - mainly oxides [40]. Marble exhibit many distinctive utilization i.e., in the architecture, sculpture and pharmaceutical industries. It's also used to lower down the soil acidity of agricultural fields by farmers [41–42]. Coal is a sedimentary rock usually contains carbon plus sulphur, hydrogen, nitrogen and oxygen. It's formed from peat's through the pressure of rocks. Coal deposits are widely distributed in Pakistan especially at western border areas. It varies from high volatile bituminous to lignite forms. It's geological history dates back to the Tertiary and Cretaceous era. The third mineral under consideration in the current article is Chromite which can be found in orthocumulate lenses of chromitite in peridotite from the earth mantle, ultramafic intrusive and metamorphic (serpentinites) rocks. It thrusted above Jurassic to Cretaceous sediments. Different adherents i.e., pillow lavas, plagiogranites, gabbros, pelagic sediments, sheeted dykes and ultramafic rock of aforementioned sequence is established. Chromite lenses range up to 6 m long and 0.5–1 m thick [43].

Different sort of plant species grow in all these different mineral sites, that compel researchers to understand the under ground mechanism. Such mechanism can help geologist and botanist to use plants for mining discoveries if properly understood. Till date, there has been very little work on plant indicators of mining sites or use of indicators for mining discoveries in this region, or more widely in relation to minerals that are not classed as heavy metals. Therefore, keeping this research gap in mind, it was hypothesized that each type of mineral zone e.g., where coal, chromite or marble were abundant (as indicated by mining activity) would have definite plant indicators associated with it that could survive, grow and manifest more tolerance to that specific site as compared to other plants, thereby predicting the presence of a specific type of mineral reserve. For this purpose, the marble, coal, and chromite mines located in the districts of Malakand, Mardan, Buner and Kohat in the Khyber Pakhtunkhwa (KPK) region of northern Pakistan were selected for this study. We focused on these three minerals as they are found abundantly close to the surface and play a vital role in the socioeconomics of the KPK region. Our research approach applied detailed statistical procedures and methods to the identification of indicator plant species. In our approach to Indicator Species Analysis (ISA) we employed both Structural Equation Model (SEM) and Canonical Correspondence Analysis (CCA) in order to identify indicators via statistical evaluation of the correspondence between the hypothesized multivariate model along with the estimation of unobserved conceptual variables from the measured variables. This procedure could also be applied for the identification of indicator plants of any microhabitat type/ ecosystem in any part of the world. Our specific research aim was to apply a robust statistical approach to biotic and abiotic data sets in order to identify plant species indicators of the presence of specific economically important mineral resources of northern Pakistan.

Materials and methodology

Study area

The Khyber Pakhtunkhwa (KPK) province of Pakistan lies in north-west Pakistan at 31°49′–35°50′N latitude and 70°55′–71°47′E longitude, covering an area of 408 by 279 miles (39,900 square miles; 74, 521 km^2) [44]. The province was targeted for this study as it is well known for its mineral resources and mining activity. KPK province comprises a mixture of rugged mountainous ranges, undulating submontane areas and plains surrounded by hills and the varied climate and landscapes of the province support a diverse flora. It can be divided into four topographical regions; the north-western mountainous Malakand Region (where the Himalayan and Hindu Kush ranges meet), the north-eastern Hazara region (extending to the Himalayan and Karakorum ranges), the Central Zone, and the Southern Zone [45]. A range of mineral resources occurs in this region, including agro-mineral resources (anhydrite deposits, rock gypsum and phosphate), alum, antimony, arsenic, barite, chromite, coal, copper, gemstones, graphite, iron, lead, marble, mercury, petroleum, precious metals (gold, platinum, silver), radioactive mineral resources and zinc [43]. The total reserves of the Dara Adam Khel coalfield are 3.75 metric tons [46]. There are 160 million tons of marble in Pakistan, of which 98% are present in the KPK province [47]. Chromite reserves are approximately 0.67 metric tons consisting of 20% dunite and 80% ultramafic cumulates in the study region. Economically, 20,000 tons of chromite ore is processed every year to produce sodium dichromate (1500 tons), chromite sulphate (8000 tons) and sodium sulphate (300 tons) [43]. In this study, we focused on the regions that were particularly rich in coal, marble and chromite reserves.

Vegetation sampling

Study locations with known marble, coal and chromite reserves were identified by the presence of mines (Fig. 1). Information on the location of mines was obtained from local miners and study sites were chosen based on mining history (>25 years) and scale of operation. Marble, coal, and chromite mines were identified across the districts of Malakand (MK), Mardan (MR), Buner (BU) and Kohat [Dara Adam Khel (DA)] and these were selected for detailed study. All are located in the subtropical region of northern Pakistan.

A total of thirty-three stations were randomly established at a distance of 1–2 km from mines in the mining regions, but avoiding any disturbances caused by mining activities. Quadrat quantitative ecological techniques were implemented for the sampling of vegetation. At each station, different sizes of quadrats i.e., 100 m^2, 25 m^2 and 1 m^2 were taken for trees, shrubs and herbaceous vegetation, respectively. Phytosociological attributes i.e., cover, frequency, density, relative cover, relative frequency, relative density and importance value index were measured for every plant species at each station. The cover and its relative values for tree species were calculated as the basal area of a stem through Diameter at Breast Height techniques. Basal area was calculated using formula = πr^2 (where r = radius) [48–52].

All the reported plant species were collected, appropriately tagged, placed in a newspaper and pressed in a plant presser [10,53–55]. Mercuric chloride and ethyl alcohol solutions were utilized for the poisoning of specimens which were then mounted on standard herbarium sheets [56]. All the plant specimens were identified subsequently with the help of Flora of Pakistan and other expert taxonomists [57]. The geographical coordinates (longitude, latitude and elevation) for each of these stations were recorded using GPS (Garmin etrex). A Geographical Information System (GIS) generated map was prepared for the study region using ArcGIS software [10,58].

Collection of soil samples and soil analyses

Soil samples were collected from all stations (in replicate) at a depth of 0.3 m with the help of a soil sampling instrument. Samples were placed in polythene bags, labeled and subsequently dried at room temperature. The collected samples were analyzed for different physicochemical properties including soil Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS) and Texture (sand, silt & clay), and concentrations of Potassium (K), Phosphorus (P), Manganese (Mn), Nickle (Ni), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Cobalt (Co), Sodium (Na), Magnesium (Mg) and Calcium. Soil EC, pH and TDS were determined following McLean methods [59]. Ten grams of well sieved and air-dried soil were homogenized in 50 mL distilled water using a magnetic stirrer for sixty minutes (1 h.). The solution was filtered using filter paper and EC, pH and TDS were determined using EC (Adwa AD3000), pH (Russel RL060P) and TDS meters, respectively. The soil texture i.e., silt, sand and clay fractions, were determined using the hydrometer method [60]. Concentrations of the elements K, P, Mn, N, Cu, Cd, Fe, Cr, Co, Na, Mg and Ca were analyzed by using standard protocols for Atomic Absorption Spectrophotometry (AAS) [47]. One gram of sieved and dried sample was taken in a 250 mL conical flask. Ten mL of per-chloric ($HClO_4$) and nitric acid (HNO_3) solution in 1:3 ratio were added and left for 24 h. Subsequently, soil samples were digested by placing on a hot plate at an initial temperature of 150 °C for 1 h and finally 235 °C until the red fumes of nitric acid disappeared and were replaced by white fumes. The solution was then filtered after cooling through filter paper (Whatman No. 42) and 40 mL distilled water was added to raise the sample volume. Blank reagents were also prepared. The AAS VARIAN, AA240FS was used for the aforementioned elemental analyses.

Data analyses

All the collected datasets relating to the vegetation and environmental factors were analyzed in order to understand the complex correlation of indicator plants and the presence of mineral resources through multivariate statistical packages devised for ecological data [61]. The absence and presence (0,1) data of all thirty-three stations and 105 plant species were arranged in the MS Excel sheet and according to the software's requirements. The Two-way Cluster Analysis and Cluster Analysis of PCORD V5 were used to identify significant mineral resource zones based on pattern similarity index through Jaccard distance measurement and Wards Linkage Method [10,37,62]. The ISA was carried out

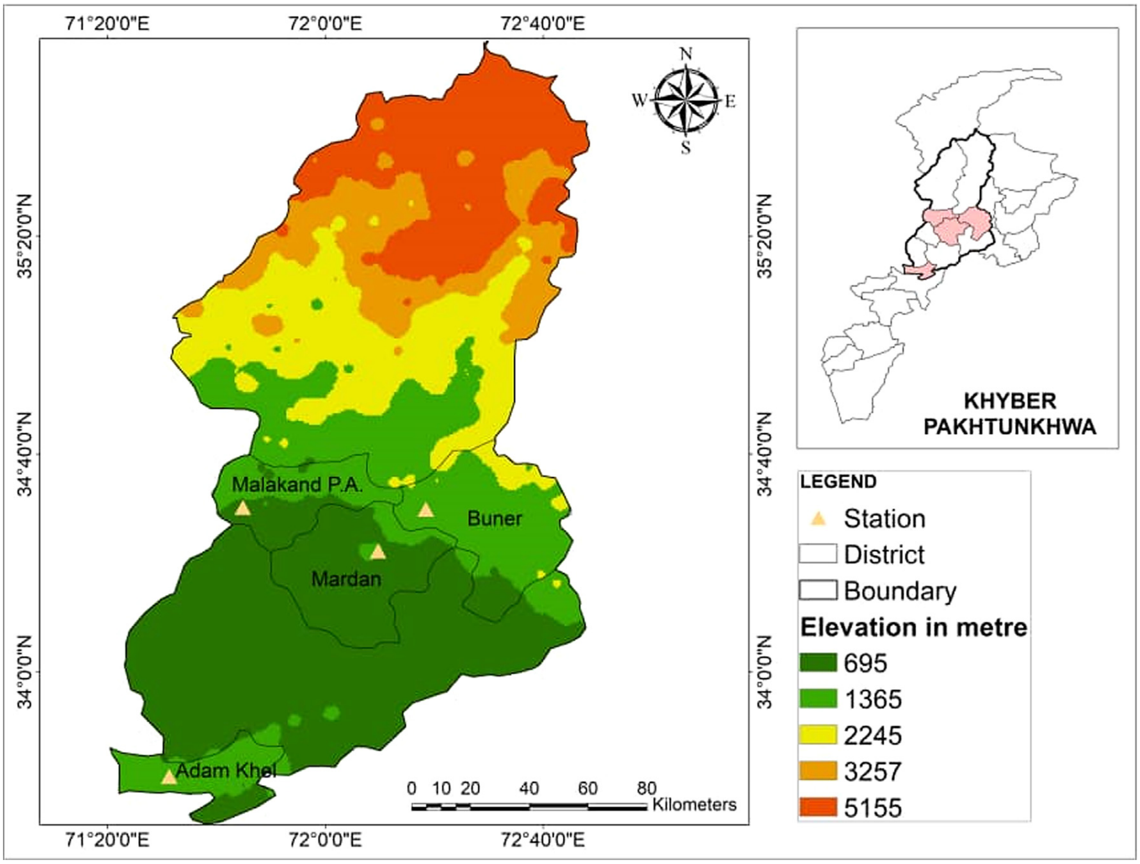

Fig. 1. GIS generated map of the study area showing three mining regions.

to identify indicators of each of the mineral resources present in the mining districts (i.e., marble, coal and chromite). This provided knowledge about species fidelity with the particular habitat of specific mineral zones. A Monte Carlo Test was carried out to test for statistical significance after the determination of Indicator Values (%age of perfect indication established on combining values of relative abundance and frequency) of respective indicators using a method initially adopted in a study by [34].

During ISA, the proportional abundance of a specific plant in a specific group, i.e. its relative abundance in the groups, was calculated using the formula given below:

$$RA_{jk} = \frac{x_{kj}}{\sum_{k=1}^{g} x_{kj}} \tag{1}$$

where RA*jk* = relative abundance, X*kj* = means an abundance of species *j* in group *k, g* = total number of groups.

Then, the relative frequency of a plant in each group was also calculated i.e., the proportion of sample units in each group that contains that plant species using the below formula. The percent/ faithfulness/ constancy of presence in a particular group is also expressed using these procedures.

$$RF_{kj} = \frac{\sum_{i=1}^{nk} b_{ijk}}{n_k} \tag{2}$$

where RF*kj* is relative frequency of plant j in group *k*, b*ijk* is presence or absence of plant *j* in sample *i* of group *k, i* is sample unit.

Finally, the products of equations 1 & 2 were multiplied and the results were expressed as a percentage yielding the indicator value (IV*kj*) for each plant *j* in group *k.*

$$IV_{kj} = 100(RA_{kj} \times RF_{kj})$$

A threshold level of 25% indication and 95% significance ($p \leq 0.05$) was used as a cutoff value for the determination of indicator species. Furthermore, the distribution curves of each identified indicator species were constructed with the help of PCORD software in order to understand their distribution pattern graphically [81–83]. Once the significant indicators had been identified, the direct gradient analysis i.e., CCA was performed using CANOCO software [84,85] to examine and reconfirm the significant and distinct indicators of the presence of each sort of mineral resource. CCA analyzes the indicator plants relation by a multiple linear regression along with environmental gradient and gives us an interpretable graphical presentation of the species response to environmental variables [34,63].

Structural Equation Modeling (SEM)

The Structural Equation Model was designed to examine the structural relation between the observed variables and latent constructs using IBM SPSS AMOS 26.0 software. It uses a combination of Factor Analysis and Multiple Regression Analysis. We have checked the normility of data through Shapiro Wilk test. Multicollinearity was checked through the calculation of Variance Inflation Factor (VIF). There is no multicollinearity problem in our dataset. We assessed Chi-square Statistics (CMIN), Goodness of Model Fit Index (GFI), Comparative Fit Index (CFI) and Standard Root Mean Square Residual (SRMR) for the goodness of model fit for SEM.

Mathematical representations of the general and specific SEM are as follow:

$$Y = \beta_{0+}\beta_{1Z+}\varepsilon_i \tag{3}$$

$$Y = \beta 0 + \sum_{19}^{i=1} \beta i \; (XpH + XEC + XK + XP + Xtexture + XMg + XCr \cdots + XCu) + \varepsilon i \quad (4)$$

The equation (3) shows the general structural equation model and equation (4) the specific model of our study. Where, Y represent indicator species, β_0 denote the intercept of the equation, β_1 disclose the coefficient of latent variable z, ε_i represent the unobserved variations in the model or error term in the equation, βi represents the coefficient of latent variables which ranges from 1 to 19.

Results

A total of 105 plant species belonging to 95 genera and 43 different plant families were recorded from the mineral mine regions of the Malakand, Mardan, Buner and Kohat (Dara Adam Khel) districts. They comprised 70 herbs (67% of the total vegetation), 20 shrubs (19%) and 15 trees (14%). The family Poaceae was the leading family, accounting for 19% of the total species, followed by Amaranthaceae, Compositae and Lamiaceae each with a 7.3% share of the total species.

Cluster Analysis and Two-way Cluster Analysis (CA and TWCA)

CA and TWCA separated all the stations and plants into three major vegetation zones/subtypes i.e., the samples obtained from the marble, coal, and chromite mining sites could be separated based on Jaccard Distance measurements using the Ward linkage method (Fig. 2). The TWCA further comprehended the distribution of each plant species at a particular station and even at the quadrat level for the different mine types (Fig. 3).

Characterizing the vegetation at the mine sites

Vegetation of the marble mines

A total of eighteen stations comprised this vegetation community encompassing 73 plant species. The topmost plant indicators of this vegetation type were *Ficus carica* L., *Isodon rugosus* (Wall. ex Benth.) Codd and *Ajuga parviflora* Benth. which had indicator values ≥ 25 and probability values ≤ 0.05 after ISA (Fig. 4). These were indicators of the moderate extent of Calcium (1.7–7.1 ppm), high Manganese (0.4–4.3 ppm), Cobalt (0.1–0.2 ppm), and Copper concentration (0.6–0.8) in the soils of the study sites. The Mg concentration of this marble vegetation zone ranges from 1.7 to 3.9 ppm along with sandy clay loam soil conditions (Table 1). Other indicators of this mineral mine zone were *Aerva javanica* (Burm.f.) Juss. ex Schult., *Azadirachta indica* A.Juss., *Bromus japonicus* Thunb., *Calotropis procera* (Aiton) Dryand, *Cyperus rotundus* L, *Cynodon dactylon* (L.) Pers., *Debregeasia saeneb* (Forssk.) Hepper & J.R.I. Wood, *Desmostachya bipinnata* (L.) Stapf, *Dysphania ambrosioides* (L.) Mosyakin & Clemants, *Indigofera heterantha* Brandis, *Saccharum bengalense* Retz., and *Verbascum thapsus* L.

Vegetation of the coal mines

This subtype encompassed seven stations along with 37 different plant species. The topmost three indicator species of this vegetation were *Olea ferruginea* Wall. ex Aitch, *Gymnosporia royleana* Wall. ex M.A.Lawson and *Dicliptera bupleuroides* Nees, one each from trees, shrubs and herbs, respectively which had indicator values ≥ 25 and probability values ≤ 0.05 (Fig. 5). The other characteristic species of this vegetation zone were *Adiantum incisum Forssk.*, *Cymbopogon commutatus* (Steud.) Stapf, *Dichanthium annulatum* (Forssk.) Stapf, *Dicliptera bupleuroides* Nees, *Micromeria biflora* (Buch.-Ham. ex D.Don) Benth, *Setaria viridis* (L.) P.Beauv, *Sideroxylon mascatense* (A.DC.) T.D.Penn., and *Withania coagulans* (Stocks) Dunal having IV ≥ 25% and probability ≤ 0.05. These were the indicators of higher chromium (0.2–6.4 ppm), zinc (0.3–1.0 ppm) and a lower amount of calcium (1.1–6.1 ppm) and alkaline soil pH (8.0–9.0) (Table 1). Soil EC of this coal mineral mine zone varies 21.5–681 ppm, TDS ranges from 27 to 846 ppm and Clay 36–38.6%.

Vegetation of the chromite mines

Chromite mine vegetation zone comprised of eight stations and 35 plant species. The topmost plant indicators of this chromite

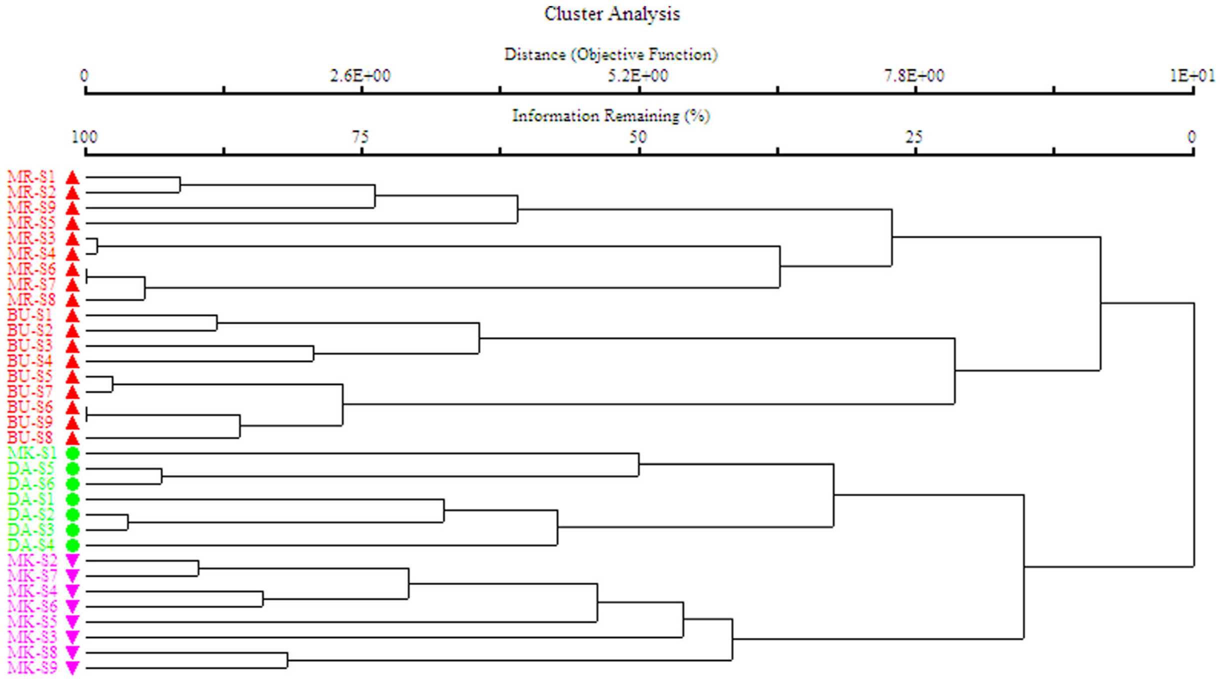

Fig. 2. CA dendrogram using Jaccard Distance Measurement separated all the stations into three vegetation types using ward linkage methods (with narrow single-spaced width).

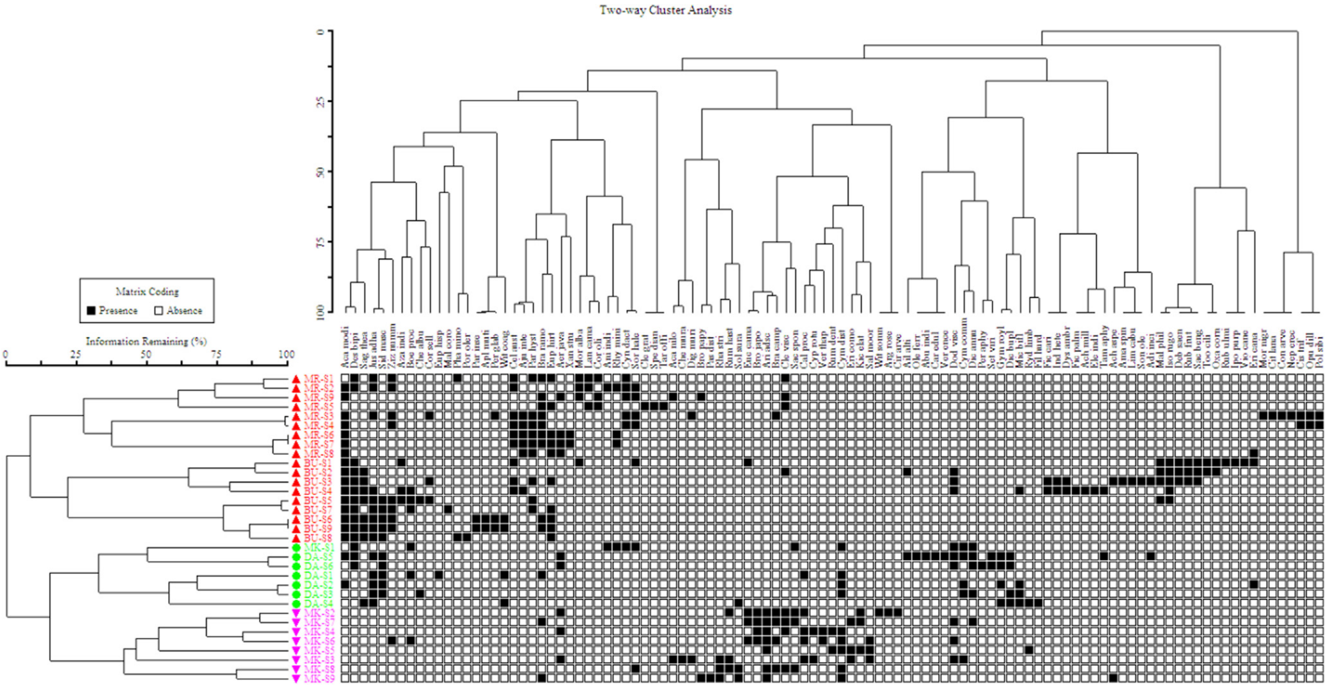

Fig. 3. The TWCA dendrogram comprehended the distribution of one hundred-five plant species in the studied region using Jaccard Distance Measurements with the Ward Linkage method.

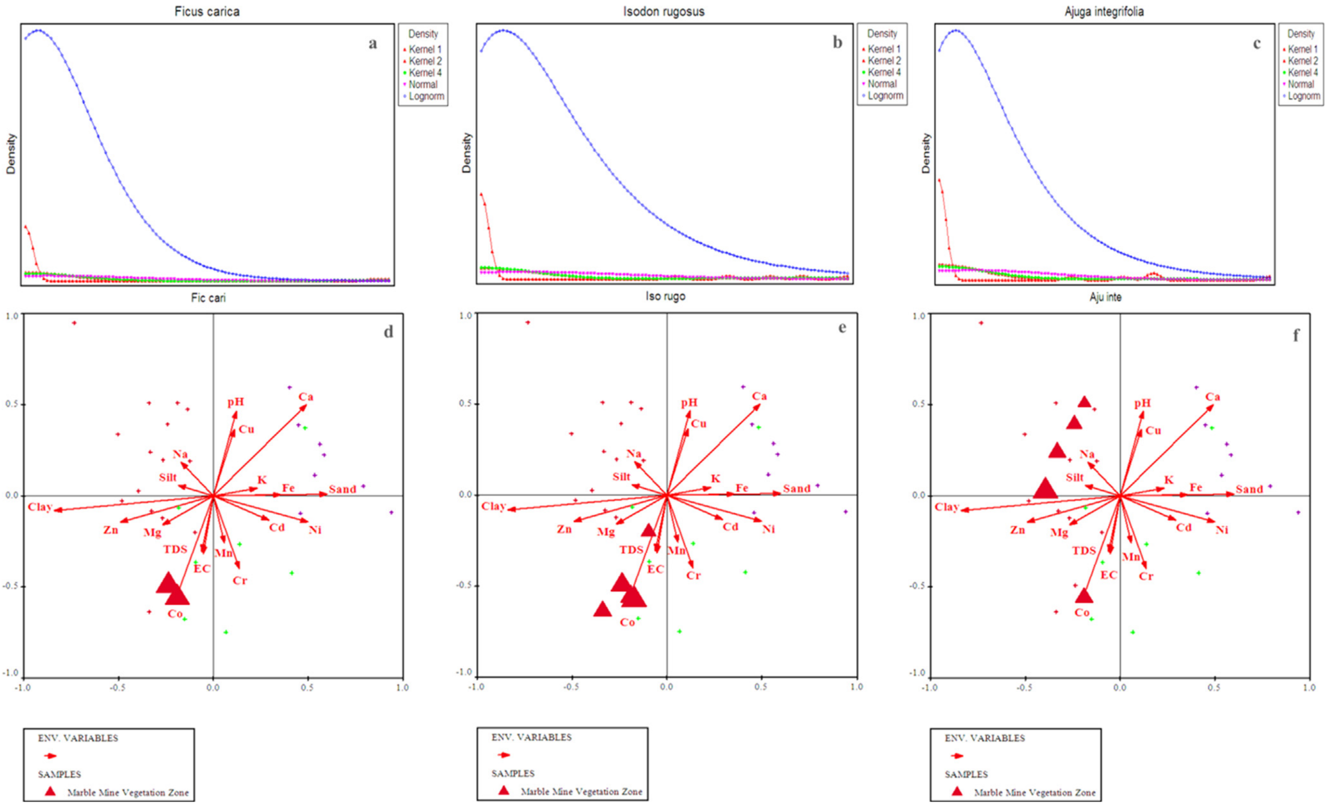

Fig. 4. The distribution curves (a-c) and data attribute plots (d-f) of the topmost three indicator plants of the marble vegetation zone in relation with measured environmental factors after Species Distribution and Canonical Correspondence Analyses of PCORD and CANOCO software's reconfirming the identification of ISA graphically.

subtype were *Acacia nilotica* (L.) Delile, *Rhazya stricta* Decne, and *Aristida adscensionis* L which had indicator values ≥ 25 and probability values ≤ 0.05 after ISA (Fig. 6).

Other characteristics species of this coal mine zone were *Bromus japonicus* Thunb, *Chenopodium murale* L., *Digera muricata* (L.) Mart., *Dodonaea viscosa (L.) Jacq*, *Eucalyptus camaldulensis* Dehnh.,

Table 1

Indicator Species Analysis indicating the topmost indicator species (with bold font) of each mineral mines subtype of vegetation/zone (1–3) in relation with various environmental factors at 25% threshold level of indicators founded on Monte Carlo Test of significance for the observed maximum IV (percentage of perfect indication established on combining values for the relative abundance and frequency for plant species along with probability value ≤ 0.05. [Max grp = Maximum group (group identifier for maximum observed IV), IV = Observed indicator values, p*= Probability value (1 + number of runs>=observed)/(1 + number of randomized runs)].

S. No.	Botanical Names	Marble Mining community defined based on moderate calcium			Coal Mining community defined based on lower pH			Chromite Mining Community defined by values of Zinc		
		Max grp	IV	p*	Max grp.	IV	p*	Max. grp.	IV	p*
1	*Acacia modesta* Wall	3	27.8	0.173	9	35.2	0.493	6	25.7	0.584
2	[3]***Acacia nilotica*** (L.) Delile	7	20.7	0.672	9	8.0	0.823	1	24.3	0.070
3	*Ailanthus altissima* (Mill.) Swingle	1	14.7	0.446	8	11.0	0.392	7	16.7	0.512
4	*Azadirachta indica* A.Juss.	4	38.5	0.066	9	12.0	0.582	6	21.4	0.492
5	*Broussonetia papyrifera* (L.) L'Hér. ex Vent	6	20.7	0.685	9	8.0	0.823	6	7.1	1.000
6	*Celtis australis subsp. caucasica* (Willd.) C.C.Towns.	5	11.7	0.905	9	20.0	0.453	6	19.5	0.611
7	*Eucalyptus camaldulensis* Dehnh.	8	80.7	0.002	8	8.9	1.000	1	26.9	0.326
8	[1]***Ficus carica*** L.	4	50.0	0.041	8	11.3	0.226	7	11.8	0.899
9	*Ficus palmata* Forssk.	4	25.0	0.657	9	4.0	1.000	6	7.1	1.000
10	*Mallotus philippensis* (Lam.) Müll.Arg	4	27.2	0.161	8	6.5	1.000	7	23.1	0.419
11	*Morus alba* L.	3	22.8	0.373	9	16.0	0.568	6	28.6	0.280
12	*Morus nigra* L.	5	20.0	0.816	9	4.0	1.000	6	7.1	1.000
13	[2]***Olea ferruginea*** Wall. ex Aitch	1	25.0	0.656	8	34.3	0.017	6	7.1	1.000
14	*Tamarix aphylla* (L.) H.Karst.	1	13.1	0.934	8	11.4	0.217	6	7.1	1.000
15	*Toona ciliata* M.Roem.	3	13.2	0.844	9	8.0	1.000	7	12.7	0.897
16	*Abutilon indicum* (L.) Sweet	1	25.0	0.656	8	14.3	0.217	5	21.6	0.375
17	*Calotropis procera* (Aiton) Dryand	6	21.6	0.348	9	8.2	1.000	5	9.2	0.964
18	*Debregeasia saeneb* (Forssk.) Hepper & J.R.I.Wood	3	11.3	0.583	8	7.1	1.000	7	26.1	0.291
19	*Dodonaea viscosa* (L.) Jacq	8	55.8	0.012	8	19.2	0.625	1	31.1	0.285
20	[2]***Gymnosporia royleana*** Wall. ex M.A.Lawson	1	56.5	0.018	8	39.3	0.013	9	66.7	0.010
21	*Indigofera heterantha* Brandis	4	50.0	0.061	8	10.4	0.406	7	10.6	1.000
22	[1]***Isodon rugosus*** (Wall. ex Benth.) Codd	4	45.2	0.046	9	7.8	1.000	7	20.3	0.501
23	*Justicia adhatoda* L.	2	10.9	0.961	8	33.3	0.373	9	51.6	0.051
24	*Lantana camara* L	4	16.5	0.636	9	12.0	0.725	5	21.6	0.375
25	*Parthenocissus inserta* (A.Kern.) Fritsch	6	12.9	0.940	9	8.0	1.000	6	14.3	0.796
26	*Periploca aphylla* Decne.	1	25.0	0.668	8	14.3	0.218	9	17.0	0.109
27	[3]***Rhazya stricta*** Decne.	7	28.8	0.293	9	12.0	0.575	1	47.6	0.032
28	*Rubus fruticosus*	3	15.7	0.465	9	5.4	1.000	7	21.6	0.386
29	*Rubus ulmifolius* Schott	3	25.0	0.672	9	4.0	1.000	6	7.1	1.000
30	*Rydingia limbata* (Benth.) Scheen & V.A.Albert	7	21.4	0.684	8	5.3	1.000	5	20.5	0.367
31	*Sageretia thea* (Osbeck) M.C. Johnst.	4	29.1	0.150	8	15.9	0.777	7	26.8	0.298
32	*Sideroxylon mascatense* (A.DC.) T.D.Penn.	2	15.8	0.610	8	44.0	0.030	9	40.0	0.109
33	*Withania coagulans* (Stocks) Dunal	6	26.1	0.267	8	9.0	0.780	9	60.8	0.021
34	*Withania somnifera* (L.) Dunal	5	20.0	0.822	8	14.3	0.220	5	25.0	0.317
35	*Ziziphus nummularia* (Burm.f.) Wight & Arn.	5	18.0	0.587	9	21.7	0.434	5	14.4	0.847
36	*Achillea millefolium* L.	4	25.0	0.657	9	4.0	1.000	6	7.1	1.000
37	*Achyranthes aspera* L	6	17.4	0.740	8	8.7	0.402	7	16.7	0.511
38	*Adiantum incisum* Forssk.	1	14.4	0.724	8	28.6	0.043	7	16.7	0.511
39	*Aerva javanica* (Burm.f.) Juss. ex Schult.	1	30.3	0.141	8	28.1	0.263	6	33.5	0.168
40	[1]***Ajuga parviflora*** Benth.	4	29.6	0.019	9	16.0	0.560	6	19.2	0.527
41	*Amaranthus spinosus* L.	4	25.0	0.658	8	14.3	0.226	7	16.7	0.511
42	*Anisomeles indica* (L.) Kuntze	5	40.0	0.138	9	8.0	1.000	7	8.7	1.000
43	*Apluda mutica* L	6	12.8	0.940	9	8.0	1.000	6	14.3	0.796
44	*Argyrolobium roseum* (Cambess.) Jaub. & Spach	5	20.0	0.822	8	14.3	0.220	5	25.0	0.317
45	[3]***Aristida adscensionis*** L	8	55.0	0.011	9	18.4	0.443	1	54.5	0.042
46	*Boerhavia procumbens* Banks ex Roxb	4	14.3	0.711	9	9.0	0.937	7	19.1	0.578
47	*Brachiaria ramosa* (L.) Stapf	6	27.1	0.195	9	48.0	0.058	6	16.4	0.838
48	*Brassica campestris*	8	69.2	0.001	9	10.4	0.652	1	72.7	0.014
49	*Bromus japonicus* Thunb.	8	64.0	0.009	8	7.1	0.893	1	23.0	0.427
50	*Caralluma edulis* (Edgew.) Benth. ex Hook.f.	1	25.0	0.656	8	14.3	0.217	7	8.7	1.000
51	*Chenopodium album* L.	4	14.9	0.445	8	11.2	0.211	6	7.1	1.000
52	*Chenopodium murale* L.	7	25.0	0.661	9	4.0	1.000	6	7.1	1.000
53	*Cirsium arvense* (L.) Scop.	5	20.0	0.822	8	14.3	0.220	5	25.0	0.317
54	*Cissus trifoliata* (L.) L.	5	20.0	0.816	9	4.0	1.000	5	25.0	0.312
55	*Citrullus lanatus* (Thunb.) Matsum. & Nakai	5	20.0	0.816	9	4.0	1.000	6	7.1	1.000
56	*Clematis grata* Wall.	4	25.0	0.675	9	4.0	1.000	5	25.0	0.302
57	*Cleome viscosa* L	8	12.1	0.831	9	18.8	0.488	1	49.7	0.065
58	*Convolvulus arvensis* L.	5	20.0	0.816	9	4.0	1.000	6	7.1	1.000
59	*Corchorus olitorius* L.	3	10.7	0.818	9	12.0	0.580	5	15.9	0.659
60	*Cortaderia selloana* (Schult. & Schult.f.) Asch. & Graebn.	4	45.4	0.033	8	9.8	0.871	7	9.8	0.963
61	*Cymbopogon commutatus* (Steud.) Stapf	3	10.8	0.848	8	18.8	0.445	9	26.9	0.266
62	*Cymbopogon distans* (Nees ex Steud.) W.Watson	6	25.5	0.227	9	23.0	0.483	9	27.5	0.272
63	*Cynodon dactylon* (L.) Pers.	5	31.5	0.067	9	20.0	0.449	5	11.8	0.890
64	*Cyperus rotundus* L.	6	13.3	0.851	9	8.0	1.000	6	14.3	0.768
65	*Desmostachya bipinnata* (L.) Stapf	4	16.0	0.698	8	30.8	0.479	7	58.9	0.012
66	*Dichanthium annulatum* (Forssk.) Stapf	1	23.5	0.329	8	39.7	0.014	1	43.2	0.076
67	[2]***Dicliptera bupleuroides*** Nees	1	61.5	0.013	8	57.1	0.001	9	33.3	0.175
68	*Digera muricata* (L.) Mart.	7	17.5	0.430	9	8.0	1.000	6	14.3	0.768

(*continued on next page*)

Table 1 (*continued*)

S. No.	Botanical Names	Marble Mining community defined based on moderate calcium			Coal Mining community defined based on lower pH			Chromite Mining Community defined by values of Zinc		
		Max grp	IV	p*	Max grp.	IV	p*	Max. grp.	IV	p*
69	*Dysphania ambrosioides* (L.) Mosyakin & Clemants	4	50.0	0.061	8	7.4	1.000	7	6.9	1.000
70	*Eleusine indica* (L.) Gaertn.	4	25.0	0.657	9	4.0	1.000	6	7.1	1.000
71	*Eragrostis cilianensis* (All.) Janch.	3	31.8	0.158	9	8.0	1.000	9	26.2	0.265
72	*Eriophorum comosum* (Wall.) Nees	7	30.2	0.201	9	12.0	0.579	1	24.0	0.317
73	*Euphorbia hirta* L.	2	19.6	0.407	9	16.6	0.685	6	17.8	0.684
74	*Euphorbia hispida* Boiss.	6	25.0	0.674	9	4.0	1.000	9	33.3	0.174
75	*Filago hurdwarica* (Wall. ex DC.) Wagenitz	1	25.0	0.679	8	14.3	0.220	9	33.3	0.175
76	*Ipomoea purpurea* (L.) Roth	3	25.0	0.672	9	4.0	1.000	6	7.1	1.000
77	*Kickxia elatine* (L.) Dumort.	8	21.9	0.353	8	8.3	0.858	5	29.1	0.192
78	*Limonium cabulicum* (Boiss.) Kuntze	4	25.0	0.658	8	14.3	0.226	7	16.7	0.511
79	*Malvastrum coromandelianum* (L.) Garcke	2	16.7	1.000	8	14.3	0.236	7	16.7	0.509
80	*Micromeria biflora* (Buch.-Ham. ex D.Don) Benth	3	10.8	0.798	8	21.5	0.137	9	64.0	0.011
81	*Nepeta erecta* (Royle ex Benth.) Benth.	5	20.0	0.816	9	4.0	1.000	6	7.1	1.000
82	*Opuntia dillenii* (Ker Gawl.) Haw	5	20.0	0.816	9	4.0	1.000	5	25.0	0.312
83	*Oxalis corniculata* L	3	10.3	1.000	9	8.0	1.000	7	13.9	0.871
84	*Parthenium hysterophorus* L.	2	18.3	0.298	8	13.7	0.852	6	17.1	0.750
85	*Paspalum distichum* L.	6	25.0	0.673	9	4.0	1.000	7	26.1	0.291
86	*Persicaria glabra* (Willd.) M.Gómez	3	10.2	0.700	9	12.0	0.577	6	21.4	0.497
87	*Phalaris minor* Retz.	7	10.8	0.973	9	8.0	1.000	7	13.7	0.862
88	*Polygala sibirica* L.	5	20.0	0.816	9	4.0	1.000	5	25.0	0.312
89	*Portulaca oleracea* L.	2	16.7	1.000	9	4.0	1.000	7	16.7	0.530
90	*Rhynchosia minima* (L.) DC.	5	20.7	0.480	9	16.0	0.549	6	13.6	0.786
91	*Rumex hastatus* D. Don	7	38.4	0.046	8	8.2	1.000	1	30.0	0.190
92	*Rumex dentatus* L.	7	14.8	0.741	9	8.0	1.000	5	20.9	0.400
93	*Saccharum bengalense* Retz.	2	7.7	1.000	8	7.3	0.866	7	29.9	0.203
94	*Saccharum spontaneum* L.	8	19.0	0.456	8	7.4	0.891	1	80.9	0.008
95	*Salvia moorcroftiana* Wall. ex Benth	8	26.2	0.306	9	12.0	0.586	5	13.3	0.795
96	*Setaria viridis* (L.) P.Beauv.	1	50.0	0.053	8	28.6	0.041	7	16.7	0.530
97	*Solanum surattense* Burm. f.	1	8.9	0.965	8	9.5	0.851	1	27.3	0.252
98	*Sonchus oleraceus* (L.) L.	4	25.0	0.658	8	14.3	0.226	7	16.7	0.511
99	*Sorghum halepense* (L.) Pers.	5	31.3	0.098	9	24.0	0.301	1	12.1	0.892
100	*Spergularia diandra* (Guss.) Heldr.	4	25.0	0.675	9	4.0	1.000	5	25.0	0.302
101	*Taraxacum officinale* L.	4	25.0	0.675	9	4.0	1.000	5	25.0	0.302
102	*Verbascum thapsus* L.	8	22.1	0.232	9	8.0	1.000	7	8.0	1.000
103	*Verbesina encelioides* (Cav.) Benth. & Hook.f. ex A.Gray	1	25.0	0.656	8	14.3	0.217	7	6.9	1.000
104	*Viola canescens* Wall.	3	25.0	0.672	9	4.0	1.000	6	7.1	1.000
105	*Xanthium strumarium* L.	2	33.3	0.216	9	8.0	1.000	6	14.3	0.796

Justicia adhatoda L., *Portulaca oleracea* L., *Sideroxylon mascatense* (A. DC.) T.D.Penn., and *Saccharum spontaneum* L. These were the indicator of higher iron (0.4–1.0 ppm), nickel (1.8–5.8 ppm), calcium (5.1–8.2 ppm), moderate chromium (0.03–2.0) and lower zinc amount (0.1–0.7 ppm) in the chromite mine region (Table 1). When environmental factors change it sustains growth of various indicator species. The soil Mn concentration of this chromite mine vegetation zone deviates from 0.3 to 5.4 ppm, K range from 1.4 to 2.9 ppm along with loamy sand soil conditions.

Having identified the different plant indicators of the mineral mines through ISA, the results were reconfirmed by applying direct gradient analysis using CCA and Structural Equation Model (SEM) analysis.

Direct gradient Analysis using CCA for mining indicator plants

The ordination of indicator plant species through a CCA bi-plot shows differential and similarity indices for the indicators. The results show that the environmental variables i.e., Iron, Clay, Potassium, Magnesium, Nickel, Zinc, Calcium, Cobalt, Copper, Manganese, pH, Chromium, Electrical Conductivity, Total Dissolved Solids all have a significant effect ($p \leq 0.002$) on the composition and distribution pattern of indicator species around the mineral mines (Table 2). The CCA bi-plot reconfirms our observation from the ISA. The topmost indicators of the marble mine vegetation zone were clustered under the impact of higher soil concentrations of Co, Mn, Mg and clay fraction along with lower concentrations of Cr and Fe. Whereas the indicator species of the coal mine vegetation were under the influence of higher concentrations of Cr, and of higher EC and TDS, but lower concentrations of Ca and Mn and pH. The indicators of the chromite mine vegetation zone were assembled under the effect of higher soil pH, higher Ca, Fe, Ni, Cr, K and sand fraction, and lower amounts of Zn and Mg, and lower EC and clay fraction (Fig. 7).

Structural Equation Modeling (SEM) and Goodness of Model Fit

Based on the aforementioned results, SEM was carried out to further examine or verify the indicators of each mine vegetation zone. Our hypothesized model for mining indicators was based on equation (4) which showed the relationship between observed variables and latent constructs simultaneously. The SEM revealed that the indicators of the chromite mine vegetation zone have a positive and significant relationship with soil Fe, Mn, Ni, Ca, and K, but a negative and significant relationship with Zn and clay fraction (Table 3; Fig. 8). Whereas, the indicators of the marble mine vegetation showed a positive and significant alliance with Mg, pH and Co along with a negative relation with Ni as compared to the other mining zones. Furthermore, indicators of the coal mine vegetation disclosed a significant relation with soil EC, Cr, pH and TDS along with a lower Ca concentration (Table 3; Fig. 8). The SEM analysis again reconfirmed our observation/hypothesis based on the results of ISA and CCA.

Tables 4 and 5 comprehend the analyses of co-variance, co-relation and variance of the significant environmental variables. As far as the measurement of Goodness of Model Fit of SEM are

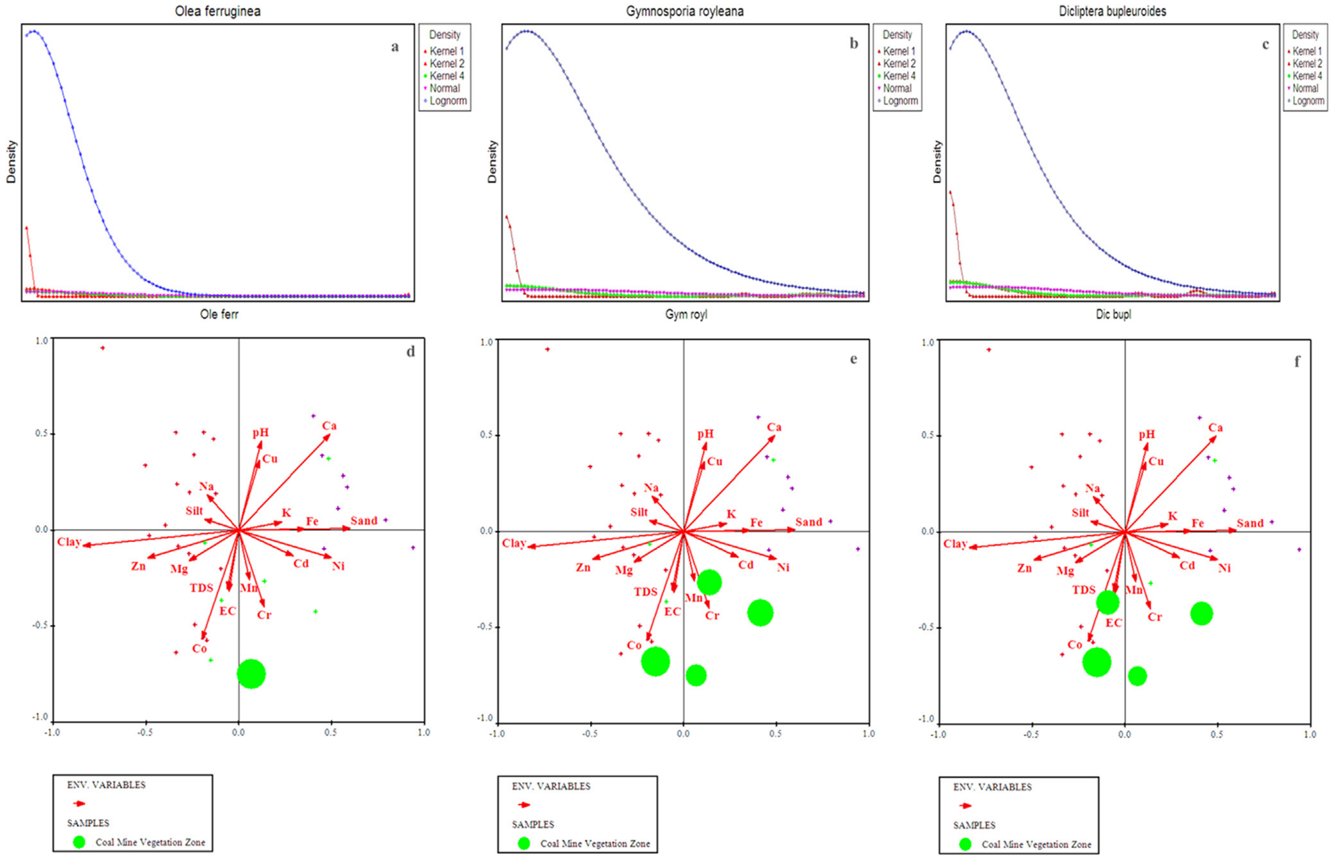

Fig. 5. Distribution curves (a-c) and data attribute plots (d-f) for the topmost three indicators i.e., *Olea ferruginea* (first indicator), *Gymnosporia royleana* (2nd indicator) and *Dicliptera bupleuroides* (3rd indicator) of the coal mine vegetation zone in relation to different environmental factors using Species Distribution and Canonical Correspondence Analyses of PCORD and CANOCO softwares.

concerned, our model is considered as a good fit because all the values (i.e., CMIN/DF < 5.0; GFI = 0.981; CFI = 0.965; SRMR = 0.022) show significant results (Table 6).

Discussion

The current study has identified a number of plant species that can be considered indicators of mineralization and, in particular, of the coal, chromite and marble mining terrains in the Khyber Pakhtunkhwa province of northern Pakistan. It was observed that the majority of the indicators belong to the families Poaceae, Amaranthaceae, Compositae and Lamiaceae. The dominance of few specific families can be coined with their tolerating nature and uptake ability of certain heavy metals present at mining sites. There is a wide knowledge gap of plant indicator species of mining sites in Pakistan, with only a few recent studies on the vegetation around chromite mines in northern Pakistan undertaken. These identified 32 medicinal and fodder plants in relation to cadmium and lead accumulation [64]. Further afield, Donggan et al. [65] studied the vegetation of a coal mining area in Shanxi Province, China and reported Compositae as the dominant plant family followed by Leguminosae, Umbelliferae and Ranunculaceae. Woch et al. [66] also studied the coal mine vegetation in Trzebinia, southern Poland and reported Asteraceae, Fabaceae, Poaceae and Rosaceae as the most prevalent families.

In our study, distinctive plant indicators were identified for each of the three mining zones. For the marble mining zone, indicator species were *Ficus carica*, *Isodon rugosus* and *Ajuga parviflora*. *Olea ferruginea*, *Gymnosporia royleana* and *Dicliptera bupleuroides* were the indicators of the coal mining zone, while *Acacia nilotica*, *Rhazya stricta* and *Aristida adscensionis* were the indicators of the chromite mining zone. The indicators for each zone were different, likely due to differences in soil physicochemical properties. These indicators were identified using ISA techniques which provided information regarding species fidelity [34]. A threshold level of 25% with 95% significance ($p \leq 0.05$) was used as a cutoff value for the determination of indicators for each mining zone, which is in close harmony with the methods proposed by [34,63]. The ISA must have higher values for the relative abundance and frequency in each category (Mc-Cune and Grace 2002), which was also satisfied in the case of our indicators. Practical, sensible indication of species for each zone or association linked with a particular set of environment can further be utilized for exploration of mines as well [67]. Unlike to our study, two species of *Acacia viz.-mangium* and *auriculiformis* along with *Cassia seamea* and *Dalbergia sissoo* were found to be growing satisfactory in the Coal mine zones, India [68–69].

Differences and relationships between the vegetation and soil characteristics were worked out using a combination of multivariate statistical techniques, i.e., ISA, SEM, CCA, TWCA and CA [10]. Sequentially, we started with CA and TWCA used to identify potential mineral zone vegetation subtypes based on pattern similarity via Jaccard distance measurements. These techniques resulted in the identification of three specific vegetation types that corresponded to the three mining locations and their specific indicators and edaphic characteristics. The marble mine vegetation zone was characterized by higher Ca, Mn, Co, and Cu concentrations in the soil. The coal mine vegetation zone was differentiated by a lower

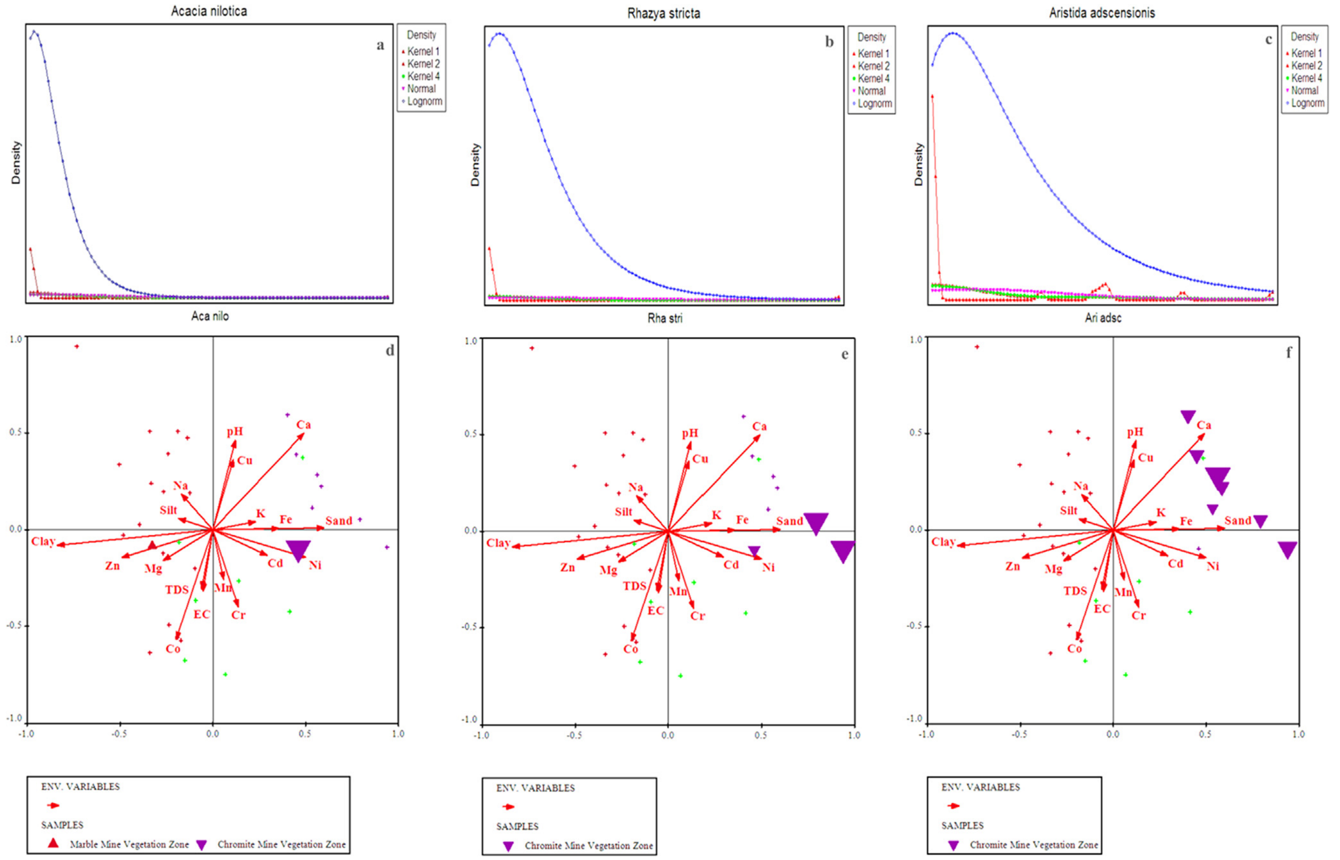

Fig. 6. Species Distribution curves (a-c) and data attribute plots (d-f) for the top three indicators of the chromite mine zone together with measured environmental factors using after PCORD and CANOCO software's.

Table 2
CCA summary of the entire mines' vegetation zone and their distinct indicators in relation to measured environmental variables.

Axes	1	2	3	4
Eigenvalues	0.98	0.95	0.76	0.598
Species-environment correlations	0.99	0.98	0.99	0.894
Cumulative percentage variance of species data	19.5	38.4	53.6	65.5
Cumulative percentage variance of species-environment relation	21.4	42.1	58.8	71.8
Sum of all eigenvalues				5.018
Sum of all canonical eigenvalues				4.578
Test of significance of first canonical axis			Test of significance of all canonical axes	
Eigenvalue	0.98		Trace	4.578
F-ratio	1.21		F-ratio	3.063
P-value	0.04		P-value	0.002

concentration of Ca, soil pH, and higher Cr and Zn concentrations. The chromite mine vegetation zone exhibits higher Fe and Ni concentrations, a moderate Cr concentration, and a lower Zn concentration in the rhizosphere.

As the next step, CCA was used to determine the relationship between the various mine indicators and the measured environmental variables. Correlation of the canonical axes and explanatory matrix along with the significance of each species were determined via a permutation procedure. The hypothesized relationship between the response and explanatory variables were tested by standardizing the axis scores and centering on the unit variance and axes scaled to optimize the representation of each species. The results reconfirmed our observation regarding the indicator species' and the underlying environmental (edaphic) mechanisms. The topmost indicators of the marble mine vegetation zone were clustered under the impact of higher clay and Mg concentration along with the lower concentration of Cr and Fe environmental variables in addition to Ca, Cu and Co mentioned before. Whereas the indicator species of the coal mine vegetation were under the influence of higher Cr, EC, TDS, and lower Ca, pH and Mn variables. The acidic soils (pH range between 4 and 5) associated with coal mining regions was also reported by Maiti [68]. Indicators of chromite mine vegetation zone were assembled under the effect of higher pH, Ca, Fe, Ni, Cr, K, and sand, and a lower amount of Zn, Mg, EC and clay fraction. The impact of marble mining in relation to soil was investigated previously by Adewole and Adesina [70] in southwestern Nigeria. They reported higher pH, a decrease in total soil porosity, organic matter, P, and N, and increase in Ca, Mg, Na, K, Fe, Mn, Cu, Zn and bulk density from southwestern Nigeria. Loamy sand along with Acidic to basic pH, lower EC and mod-

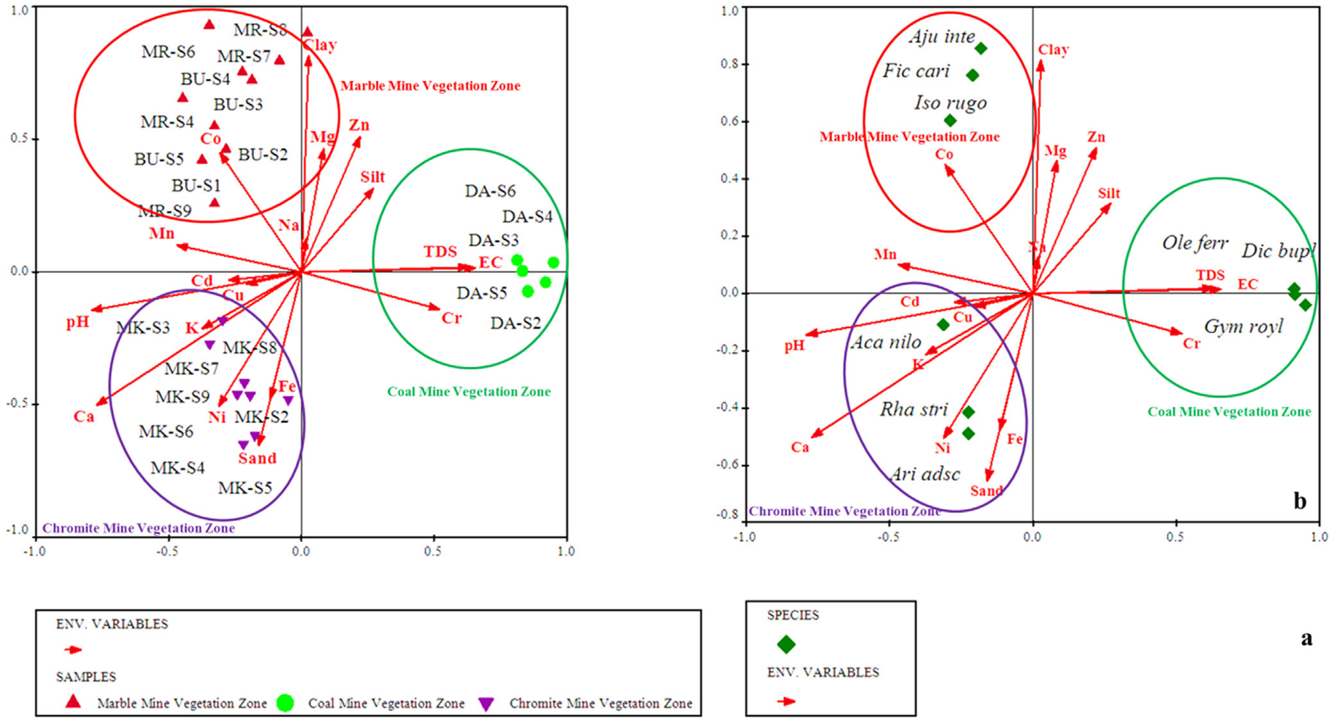

Fig. 7. CCA biplot showing the distribution of (a) all mine stations and (b) different mine vegetation zones along with their respective indicators in relation to measured environmental gradients.

Table 3
Standardized and Unstandardized Coefficients of the topmost indicator species of each subtypes of vegetation after SEM analysis.

Chi-square = 312.552 Probability level = 0.089	Indicators	Unstandardized Coefficients					Standardized Coefficients
		Variables	Beta	S.E.	C.R.	P	Beta
Chromite Mines' Vegetation	*Acacia nilotica*	Fe	27.769	14.215	1.953	0.041	0.311
		Mn	3.288	1.754	1.874	0.051	0.299
	Rhazya stricta	Ni	8.515	3.071	2.773	0.006	0.375
		Zn	−65.638	17.004	−3.860	0.001	−0.522
	Aristida adscensionis	Ca	0.964	0.429	2.247	0.025	0.288
		K	4.553	1.593	2.858	0.004	0.336
		Clay	−0.370	0.095	−3.892	0.001	−0.498
Marble Mines' Vegetation	*Ficus carica*	Co	199.173	57.640	3.455	0.001	0.521
	Isodon rugosus	Co	370.589	56.311	6.581	0.001	0.758
	Ajuga parviflora	Ni	−2.011	0.738	−2.726	0.006	−0.359
		Mg	3.778	1.505	2.510	0.012	0.330
		pH	6.708	1.940	3.458	0.001	0.455
Coal Mines' Vegetation	*Olea ferruginea*	pH	1.569	0.728	2.154	0.031	0.118
		TDS	0.040	0.002	18.967	0.001	1.040
	Gymnosporia royleana	Ca	−0.954	0.453	−2.104	0.035	−0.269
		EC	0.581	0.132	4.407	0.001	8.842
		TDS	−0.450	0.106	−4.253	0.001	−8.476
	Dicliptera bupleuroides	Cr	1.114	0.296	3.757	0.001	0.266
		Ca	−0.433	0.198	−2.194	0.028	−0.183
		pH	−2.626	1.181	−2.223	0.026	−0.213
		EC	0.485	0.056	8.665	0.001	11.105
		TDS	−0.384	0.045	−8.573	0.001	−10.864

S.E = Standard error; C.R = Critical ratio, P = Probability.

erate soil organic matter has also been reported from Chromite mine, Pakistan by [64]. Maiti et al. [71] worked on the bioaccumulation of metals in edible plants (*Syzygium cumini*, *Psidium guajava*, *Anacardium occidentale*, *Mangifera indica*, and *Artocarpus heterophyllus*) and timber trees (*Acacia mangium*, *Techtona grandis*, *Eucalyptus* spp. and *Gravellia robusta*) in a coal mining region and reported higher metal accumulation in the edible plants viz Fe > Mn > Zn > Cu > Cd > Ni. Based on theirs as well as ours findings it could be very interesting if the indicators, we have worked out are studied for their ability to uptake the heavy metals, their possible physiological and genetic pathways [72]. Such studies may help in managing the industrial pollution where the raw materials obtained from such mines are used.

The observations obtained through the ISA and CCA were again reconfirmed by the SEM using a goodness of model fit through CMIN/DF, GFI, CFI and SRMR. The SEM revealed that the indicators of the chromite mine vegetation zone have a positive and significant relationship with Fe, Mn, Ni, Ca, and K, while a negative and

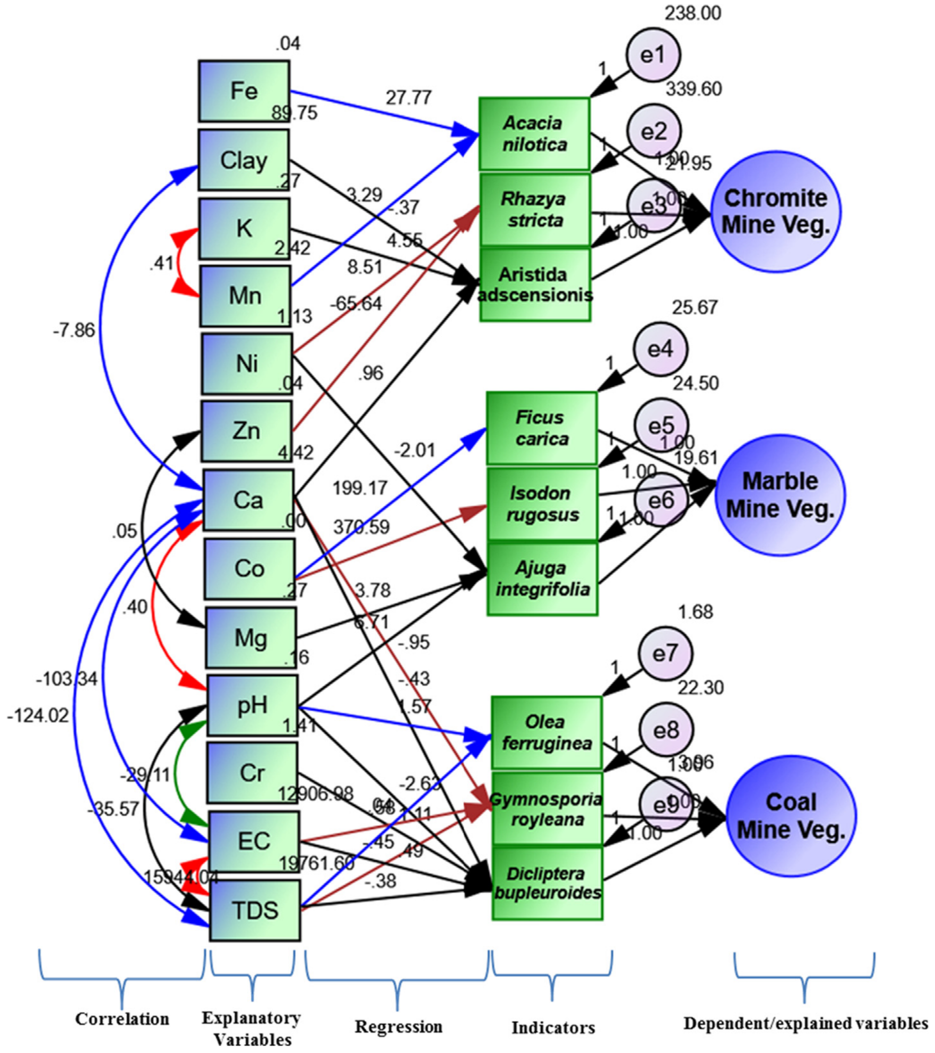

Fig. 8. Structural Equation Model - Analyses of the three mineral mines vegetation each with a distinct plant indicator in relation to different environmental variables.

Table 4
Detail results of covariance and correlation analyses among the significant environmental variables of the Marble, Coal and Chromite mineral mines.

Variables	Covariances				Correlations
	Beta	S.E.	C.R.	P	Beta
pH < –> EC	−29.110	9.598	−3.033	0.002	-0.635
pH < –> TDS	−35.569	11.834	−3.006	0.003	-0.627
pH < –> Ca	0.400	0.155	2.582	0.010	0.471
EC < –> TDS	15944.036	3989.341	3.997	0.001	0.998
EC < –> Ca	−103.335	42.872	−2.410	0.016	-0.433
TDS < –> Ca	−124.023	52.763	−2.351	0.019	-0.420
K < –> Mn	0.406	0.160	2.541	0.011	0.503
Zn < –> Mg	0.046	0.019	2.384	0.017	0.465
Ca < –> Clay	−7.859	3.289	−2.390	0.017	-0.395

significant relationship with Zn and clay soil condition. Whereas, the indicators of the marble mine vegetation showed a positive and significant alliance with Mg, pH and Co along with a negative relation with Ni as compared to the other mining zones. Indicators of the coal mine subtypes of vegetation disclosed a significant relation with EC, Cr, pH, TDS along with the lower amount of Ca concentration. SEM has also been adopted by a number of other researchers in the field of vegetation ecology for the investigation of the complex relationship between plants and environmental gradients [73–78]. We have observed that it could be a better fit to evaluate the indicators of mining or pollution sites as discussed in few of the other studies related to ecological indicators [79,80]. Our findings contribute to the achievements of four of the Sustainable Development Goals (SDGs) i.e., (i) industry, innovation & infrastructure, (ii) decent work & economic growth, (iii) responsible consumption & production and (iv) partnership for the goals. Our findings may provide a baseline for many others to identify and utilize indicator plants to identify mining sites, combating industrial pollution, and managing radioactive elements in the surroundings.

Table 5
Variance matrix of all significant environmental factors affecting plant indicators in the subtropical mineral mines region KPK, Pakistan.

Variables	Beta	S.E.	C.R.	P
K	0.270	0.068	4.000	0.001
pH	0.163	0.041	4.000	0.001
EC	12906.976	3226.744	4.000	0.001
TDS	19761.603	4940.401	4.000	0.001
Ca	4.418	1.055	4.189	0.001
Mn	2.416	0.604	4.000	0.001
Zn	0.037	0.009	4.000	0.001
Mg	0.270	0.068	4.000	0.001
Clay	89.753	22.438	4.000	0.001
Fe	0.037	0.009	4.000	0.001
Ni	1.125	0.281	4.000	0.001
Co	0.000	0.000	4.000	0.001
Cr	1.406	0.352	4.000	0.001

Table 6
Chi-square statistics (CMIN) for Goodness of Model Fit of SEM

Model	NPAR	CMIN	P	CMIN/DF
Default model	53	312.552	0.089	1.563
Saturated model	253	0.0001	0.0001	
Independence model	22	840.146	0.0001	3.637

NPAR = Number of parameters.

Conclusion

Edaphic factors and their impact on plant communities generally and the occurrence of specific plant indicators specifically have been elaborated comprehensively in numerous studies around the globe. In our current study all the other factors, i.e., latitude, altitude, mean annual temperature, rainfall and humidity, were more or less the same across the study sites. We therefore have confidence that differences in the vegetation were strongly determined by the chemical and physical properties of the soils in the different mining zones. Our results suggest that it may be possible to use vegetation and specific indicator plant species to reveal the presence of economically-important mineral resources, namely coal, marble and chromium, in northern Pakistan. Identification of plant communities specific to the different mineral zones could also provide a basis for phytoremediation measures for mine waste restoration. Through the application of various statistical procedures we were able to demonstrate a high affinity for a number of species for the environmental conditions associated with these three mining zones. Further study would be required to elucidate the mechanisms behind these vegetation differences, which may relate to preferential uptake or tolerance of certain soil minerals, e.g. heavy metals, as well as differences in other soil characteristics, including pH, water holding capacity and availability of macro-nutrient elements.

CRediT authorship contribution statement

Zeeshan Ahmad: Conceptualization, Methodology, AMOS Software, Data analyses & curation, Writing – original draft, Visualization of data. **Shujaul Mulk Khan:** Methodology, CANOCO and PCORD Softwares, Validation of the experiment, Investigation of data, Resources and lab management, Writing – review & editing, Visualization of the figures, Over all Supervision, Project administration. **Sue Page:** Validation of article, revision & editing, Supervision during IRSIP. **Saad Alamri:** Data curation, Partial Funding acquisition. **Mohamed Hashem:** Validation, Data curation, Funding acquisition partly for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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