PATTERNS OF SPATIAL DISTRIBUTION AND DIVERSITY OF INVASIVE PLANTS AND THEIR CORRELATION WITH ENVIRONMENTAL ELEMENTS IN SIX DAM AREAS, AL-BAHA, SAUDI ARABIA

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Abstract. In Saudi Arabia, Al-Baha region is considered the most vulnerable to changes in community structure and biodiversity due to the spread of invasive plants. This study was designed to evaluate the diversity of invasive plants across six dam areas (Medhas, Aljanabeen, Alaqiq, Arada, Alahsaba and Olib). Twenty invasive plants were reported representing 17 genera and 10 families; 35% of them were from the American region, while 55% were therophytes and Asteraceae was the most prevalent family. Species richness ranged from 4 to 13 invasive plants per dam area, higher in Medhas and lower in Alahsaba and Olib dam areas. *Argemone ochroleuca* which was abundantly distributed in all dam areas had the greatest potential to invade this area. The evenness value for Olib dam area (0.92) was markedly high since it was close to one. A higher level of invasive plant diversity was observed in Aljanabeen and Medhas dam areas. This result was confirmed by the highest Shannon (2.19), Simpson (0.88), and Brillouin, (2.16), index values for Aljanabeen, and the highest Margalef (1.86), Menhinick (0.52), and Fisher's alpha (2.31) index values for Medhas dam area. Plant invasion was correlated with soil physical and chemical variables and elevation gradients. Canonical correspondence analysis revealed that total organic matter, electric conductivity, and elevation were the key active environmental factors in the studied areas.
Keywords: *invasive plants alien species, diversity of non-native plants, dam habitats, environmental elements ecological factors, plant communities in Saudi Arabia*

Introduction

Worldwide, biological invasions represent a real threat to global biodiversity and natural habitats (Mack et al., 2000; Pimentel et al., 2005). As a result of globalization of economics and liberty (Pimentel et al., 2001), the invasion of new plants has increased in recent decades, which is widely regarded as the second most serious hazard to natural habitat loss after human interference (Manchester and Bullock, 2000). Invasive plants are living organisms that are introduced intentionally or unintentionally to areas outside their habitats and successfully establish and spread without the help of humans, causing negative impacts on the indigenous flora and the environment (Yair et al., 2005). They have several negative effects on the ecosystem in question by disturbing natural habitats, food chains, community structure, as well as causing the loss of indigenous species (Vilà et al., 2010; Bellard et al., 2016; Macic et al., 2018), physical and chemical properties of soil (Ehrenfeld et al., 2001; Weidenhammer and Callaway, 2010) and communities of microbes (Weidenhammer and Callaway, 2010; Qu et al., 2021). Additionally, the spread of these plants may have substantial negative socioeconomic consequences, obstructing ecosystem functions and adversely affecting human health (Vilà and Hulme, 2017). It has been reported that invasive species have a greater influence on aquatic habitats than terrestrial ones (Vilà et al., 2010). The most prevalent reason for the introduction of alien plants into new ecosystems is human disruption in natural environments, such as the

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removal of indigenous species from plant-rich regions to construct roads (Kingston and Waldren, 2003). According to Alfarhan et al. (2021), 55 invasive or non-native species have been detected in Saudi Arabia; the majority of these are restricted to a maximum of two percent in the places area where they occur, but predictions indicate that they might possibly invade more than 10% or 15% within the next few years. Alharthi et al. (2023) have identified 52 foreign plants in the Kingdom (45 naturalized, 4 casual and 3 invasive). Furthermore, Aljeddani et al. (2021) reported 42 non-native plants across the kingdom's eleven governorates, while Thomas et al. (2016) identified 48.

The building of dams is one of the most dangerous anthropogenic disruptions affecting the environment because it frequently results in major changes in biological traits that allow alien species to invade a new habitat (Ceschin et al., 2015; Ortega et al., 2015). Furthermore, dams can modify hydrological systems, making it easier for exotic species to grow and spread (Bunn and Arthington, 2002; Johnson et al., 2008). Dams have a fundamental role in Saudi Arabian development projects because they provide potable and agricultural water (Pan et al., 2016; Wang et al., 2007). There are 522 dams in the country, with an overall storage space of 2.304.390.647 billion cubic meters for the collection, preservation, and control of flood water (Al-Munqedhi et al., 2022). According to Sayed et al. (2020), the constructed dam of Wadi Jizan affected the soil properties, distribution, and diversity of the local flora, as well as influencing the introduction of non-native plants.

Research on the impact of dam construction on vegetation has increased in the last few years (Mallik and Richardson, 2009; Hand et al., 2018). Dam flooding can have severe effects on ecological systems by reducing biodiversity (Chikodzi et al., 2013; Alla and Liu, 2021) and negatively affecting the reproductive success of certain species (New and Xie, 2008). Dams have major effects on vegetation, animal life, land and the quality of air and water (Alla and Liu, 2021). They disturb groundwater, silt accumulation, nutrients, and soil fertility in valleys, as well as the ecosystem homogeneity (Schmutz and Sendzimir, 2018).

Today, the adverse consequences of dam building, as well as their solutions, are now being addressed in the analysis of environmental problems (Tahmiscioğlu et al., 2007). In aquatic ecosystems, there is a correlation and association between dam construction and alien invasive plants that need additional investigation (Havel et al., 2005). In Saudi Arabia, a few studies have been conducted on the impact of dam construction on the diversity and distribution of plants, especially invasive species. Here, the general hypothesis of this study is that the spread and diversity of invasive plants across dam areas can be affected by different environmental variables. Therefore, this work aimed to study the distribution and diversity of these plants in valleys or streams where six dams were constructed across Al-Baha region, as well as their correlation with soil physicochemical properties and elevation gradients as ecological parameters. The expected data will be used to establish a baseline for monitoring the future spread of these kind of plants in this area and surrounding locations as well as their effects on the diversity of the native plants in the country.

Materials and methods

Study area

Al Baha area (11221 km^2), southwestern Saudi Arabia, is a region of the Arabian Peninsula on the Hijaz Plateau (*Fig. 1*). It lies at altitudes of 19° 27′ 17″ and 20° 49′ 75″

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N and longitudes of 40° 46′ 30″ and 42° 10′ 10″ E (Alghamdi et al., 2023). The rocky escarpments divided the area into the Tihama region to the east and the Al-Sarawat Mountains to the west (Shrahily et al., 2022). The area has mountains with high and low-elevation mountains, small and big Wadis rich in herbaceous plants, huge trees in the valley floor, small, stunted trees at the edge, plains, and wet and dry regions. It is characterized by significant amount of fog, especially in high-altitude areas, with precipitation throughout the year and cold temperatures in summer and winter (Mobarak et al., 2022). Total precipitation for 2022 was 165 mm, mean annual temperature was 23.9°C, and mean annual air relative humidity was 47.5% (*Table 1*). According to Al-Namazi et al. (2021), Al Baha is a plant hotspot area with a high diversity of plant species that must be conserved. The southwestern region of Saudi Arabia, in which the study area is located, is highly infested by non-native and introduced plants (Aljeddani et al., 2021; Thomas et al., 2016). In Al-Baha Province (250–2500 m above sea level), 25 dams have been constructed mainly for water harvesting and groundwater recharge during rainy seasons (Mahmoud and Alazba, 2015). The present investigation was carried out on the six biggest dams that have been built in different locations within the study area (*Fig. 2*). Dam's name, year of construction, water capacity (El-Hazek, 2014), location, latitude, longitude, and altitude of the studied dams are shown in *Table 2*.

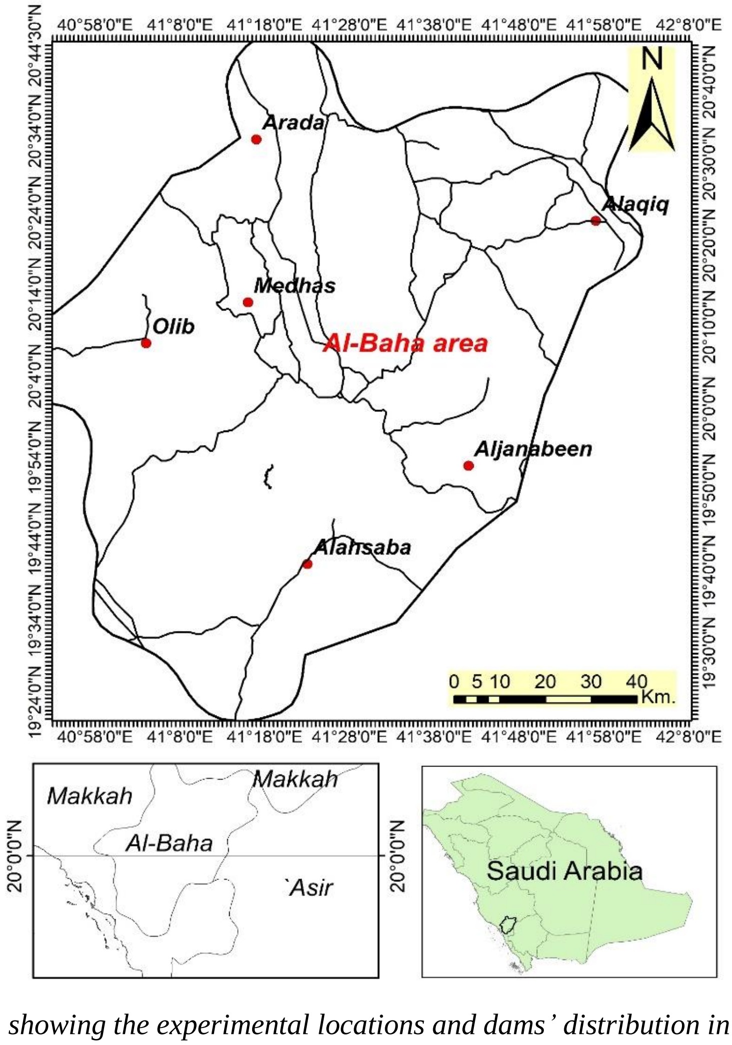

Figure 1. *Map showing the experimental locations and dams' distribution in the study area*

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Figure 2. *Habitats and plant communities surrounding the studied dam areas*

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Table 1. *Monthly variation in air temperature (°C), relative humidity (%) and precipitation (mm) as recorded at Al-Baha meteorological station during Jan–Dec 2022*

Month	Temperature (°C)	Relative humidity (%)	Rainfall (mm)
January	16.7	73	12.6
February	18.4	61	0
March	21.6	45	0.001
April	24.3	43	13.8
May	28	36	16.5
January	30.5	28	3
July	29.6	38	0
August	28.5	50	67.5
September	28	35	2.6
October	23.6	33	3.5
November	20.8	59	2
December	16.6	69	43.6

Table 2. *Name of the dams and their construction year, water capacity, location, coordinates, and elevation*

Dam's name	Dam construction year	Water capacity (m^3)	Location	Latitude (N)	Longitude (E)	Altitude (m)
Aljanabeen	2009	20000000	Baljurashi	19°53′N	41°42′E	1810
Medhas	1986	12000000	Almandaq	20°13′N	41°16′E	1767
Alaqiq	1987	27000000	Alaqiq	20.23′N	41°57′E	1610
Arada	2012	134106178	Alqara	20°33′N	41°17′E	1394
Olib	2011	78095719	Alhajrah	20°08′N	41°04′E	277
Alahsaba	2011	77171490	Almakhwah	19°41′N	41°23′E	270

Field survey

Regular field trips were made to each dam area from January to December 2022. The study covered both the upstream and downstream sites. Each site was divided into 4 stands (100 m × 100 m each), spaced by 50 m and 24 quadrates (5 m × 5 m) were randomly examined in each stand, a total of 8 stands (192 quadrates) for each dam area. Within each stagnant or slow-flowing waterbody, the quadrats were aligned perpendicular to the shore at approximate depths of 0.25 m, 0.5 m, and 0.75 m. Plants were collected using a rake with hooks. Invasive exotic plants were collected from each site and identified using the published texts of the Kingdom of Saudi Arabia's flora (Chaudhary, 1989, 1999, 2000, 2001; Collenette,1999). To update nomenclature and categorize the studied plants as exotic (non-native, non-indigenous plants) or native, reliable electronic sources and authorized worldwide data were used (IPNI, 2023; WFO, 2023).

Floristic data and ordination analysis

The collected plants were listed, and their life forms were assessed (Raunkiaer, 1934). The geographical distribution pattern of the invasive plants was determined as described by Zohary (1973), Wickens (1978), and White and Léonard (1991). Canonical correspondence analysis (CCA) was applied to summarize and evaluate the relationships between the floristic composition of the invasive species and the

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environmental variables using statistical software of MVSP version 5.1. (Ter Braak, 1986). The analyzed variables were total carbon content, electrical conductivity, total nitrogen, and total phosphorus in the soil as well as elevation gradients.

Soil analysis

Five soil samples (0 – 30 cm depth) were collected from each dam site (upstream and downstream sites) at random, mixed thoroughly, dried, ground, and sieved (soil water extracts, 1:5). The collected samples were analyzed using the American Public Health Association (APHA) methods. The pH was determined in accordance with APHA (4500-H + B) and the electric conductivity (EC) was measured following APHA (2510) method. The total organic carbon content (TOC) was quantified by APHA (5310C) method, while the total nitrogen content (TNC) was determined by APHA (4500-N) method. Metals were extracted from soil samples using the United States Environmental Protection Agency (EPA) standard method 3051 (USEPA, 1994). In a 45-mLTeflon, 5 mL of nitric acid were added to 0.5 g of soil sample and heated in Parr microwave digestion bombs (USA) for 3 min at 700 W. The digested sample was diluted to 10% by adding 45 mL of deionized water. Metal concentrations in each sample were detected using thermos Scientific ICP-7000 plus Series ICP-OS inductively coupled plasma-atomic emission spectroscopy (ICP-AES).

Ecological indices

To evaluate species diversity across the dam areas, the statistical software PAST 4.12 (Hammer et al., 2001) was used to calculate various ecological indices (species richness, evenness, Shannon, Simpson, Brillouin, Menhinick, Margalef, Fisher’s alpha and Berger-Parker), which are often used in quantitative ecology. The calculation of the selected indices depends on the number, frequency, and occurrence of invasive plants in the dam area.

Results and discussion

Floristic composition

Twenty species (17 genera) from 10 families were reported in the surveyed six studied dam areas (*Tables 3* and *4*). The dam areas most affected by invasive species were Medhas (13 species), followed by Aljanabeen and Arada (10 species). Only four invasive species (*Dysphania carinata*, *Heliotropium curassavicum*, *Argemone ochroleuca* and *Cenchrus echinatus*) were reported in Olib dam area. The total number of invasive exotic plants recorded in Saudi Arabia by Thomas et al. (2016), Alfarhan et al. (2021), Aljeddani et al. (2021) and Alharthi et al. (2023) were 48, 55, 42 and 52 species, respectively. Most of these plants were identified in the western region of Saudi Arabia. In adjacent Arab countries, 8 invasive plants were discovered in the United Arab Emirates (Soorae et al., 2015), while 111 species were documented in Oman (Patzelt et al., 2022).

In present study *A. ochroleuca* was commonly found in all studied six dam sites. It has been reported as a serious invader plant in Taif Governorate, occupying different habitats such as valleys, dams, and sand plains (Moussa et al., 2012). The study carried out by Assaeed et al. (2020) across multiple ecosystems in an area extending from Al-Taif to Al-Baha in southwestern Saudi Arabia showed that *A. ochroleuca* is widely spread in different types of soil habitats and under diverse environmental conditions. Furthermore, it possesses rapid development and the adaptability to respond to stressful and adverse situations.

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Nicotiana glauca, one of the most aggressive invasive plants in western parts of Saudi Arabia (Assaeed et al., 2021), was not reported in Alahsaba and Olib dam areas, but it was widely spread in the other dam areas. This finding agrees with the fact that *N. glauca* grows well at high altitude areas (Alharthi et al., 2021). According to Assaeed et al. (2021), it can grow in different habitats, including high altitudes, mountain ranges, arid zones, coastal lands, roadsides, and rocky habitats. As a result, it could have adverse impacts on soil nutrients and plant interactions. Furthermore, *N. glauca* has few competitors because it has a harmful pyridine alkaloid compound (anabasine) that is toxic to human beings as well as animals (Scharenberg et al., 2019). *Argemone* spp. and *N. glauca* are currently threatening major conservation areas such as Shada Mountains, Asir National Park, and Raida Nature Reserve in the southwestern regions of Saudi Arbia (Alfarhan et al., 2021).

Datura innoxia predominated in five areas, *Datura ferox* was only found in three dam areas, and *Datura stramonium* was found in Medhas and Arada. *D. innoxia* has been reported as one of the invasive species commonly found outside of the canopy of *N. glauca* in Taif regions, western Saudi Arabia (Assaeed et al., 2021). The invasion of *Xanthium spinosum* and *Lantana camara* was restricted to the Arada and Medhas dam areas, respectively. According to Aljeddani et al. (2021) both species were detected as introduced invasive plants in Al-Baha Governorate and did not exist in Al-Ghat, Bisha, Buraidah, Dammam, Fayfa, Jizan, Jeddah, Tabuk, Taif and Riyadh Governorates. The negative impact of *X. spinosum* on plant diversity and agricultural fields in Saudi Arabia has been reported by Alfarhan et al. (2021).

Table 3. *Floristic characteristics of the invasive plants*

Family	Invasive species	Life forms	Habit	Chorotypes
Aizoaceae	*Sesuvium portulacastrum* (L.) L.	Th	Herb	PAN
Amaranthaceae	*Alternanthera pungens* Kunth	He	Herb	AM
	Amaranthus albus L.	Th	Herb	AM
	Dysphania carinata (R.Br.) Mosyakin & Clemants	Th	Herb	AUS
	Salsola kali L.	Ch	Herb	PL-T
Asteraceae	*Eclipta prostrata* Lour.	Th	Herb	SUB-T
	Tagetes minuta L.	Th	Herb	AM
	Verbesina encelioides (Cav.) A.Gray	Th	Herb	AM
	Xanthium spinosum L.	Ch	Herb	PL-T
	Xanthium strumarium L.	Ch	Herb	PL-T
Boraginaceae	*Heliotropium curassavicum* L.	Ch	Herb	AM
Ceratophyllaceae	*Ceratophyllum submersum* L.	Hy	Herb	ME
Convolvulaceae	*Cuscuta campestris* Yunck.	Pr	Herb	AM
Papaveraceae	*Argemone ochroleuca* Sweet	Th	Herb	SU-ZA
Poaceae	*Cenchrus echinatus* L.	Th	Herb	AM
Solanaceae	*Datura ferox* L.	Th	Herb	SUB-T
	Datura innoxia Mill.	Th	Herb	PL-T
	Datura stramonium L.	Th	Herb	PL-T
	Nicotiana glauca Graham	Ph	shrub	PL-T
Verbenaceae	*Lantana camara* L.	Ph	shrub	NEO

Life form abbreviations: Th; Therophytes, He; Hemicryptophytes, Ch; Chamaephytes, Hy; Hydrophytes, Pr; Parasites, Ph; Phanerophytes. Chorotypes abbreviations: ME; Mediterranean, NEO; Neotropical, PAN; Pantropical, SU-ZA; Sudano-Zambezian, AUS; Australian, PL-T; Plurireginalbor-trop, SUB-T; Subtropical-Tropical, AM; American

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Table 4. *List of presence (+) and absence (-) of invasive plants in the studied dam areas*

Invasive species	Medhas	Aljanabeen	Alaqiq	Arada	Alahsaba	Olib
Alternanthera pungens **Kunth**	-	+	+	-	-	-
Amaranthus albus **L.**	-	-	-	+	+	-
Argemone ochroleuca **Sweet**	+	+	+	+	+	+
Cenchrus echinatus **L.**	-	-	-	-	+	+
Ceratophyllum submersum **L.**	+	-	-	-	-	-
Cuscuta campestris **Yunck.**	+	-	+	-	-	-
Datura ferox **L.**	-	+	-	+	+	-
Datura innoxia **Mill.**	+	+	+	+	+	-
Datura stramonium **L.**	+	-	-	+	-	-
Dysphania carinata **(R.Br.) Mosyakin & Clemants**	+	+	+	+	-	+
Eclipta prostrata **Lour.**	-	+	+	-	-	-
Heliotropium curassavicum **L.**	+	-	-	-	-	+
Lantana camara **L.**	+	-	-	-	-	-
Nicotiana glauca **Graham**	+	+	+	+	-	-
Salsola kali **L.**	+	+	-	-	-	-
Sesuvium portulacastrum **(L.) L.**	+	-	-	-	-	-
Tagetes minuta **L.**	+	-	-	-	-	-
Verbesina encelioides **(Cav.) A.Gray**	-	+	-	+	-	-
Xanthium spinosum **L.**	-	-	-	+	-	-
Xanthium strumarium **L.**	+	+	-	+	-	-
Total	13	10	7	10	5	4

Xanthium strumarium was abundant in Arada while it was less common in Medhas and Aljanabeen area, and non-existent in the other dam areas. It was reported as an introduced and invasive species in two Governates (Al-Baha and Al-Ghat Governorates) out of eleven Governorates in Saudi Arabia (Aljeddani et al., 2021). Because *X. strumarium* can accumulate heavy pollutants, it is a useful invasive plant for biomonitoring and phytoremediation of heavy metals in soil (Ullah and Khan, 2022).

Salsola kali and *Verbesina encelioides* were abundant in Aljanabeen dam area, but Medhas and Arada areas showed fewer numbers of S. kali and *V. encelioides*, respectively. Based on population cover in Taif Governorate, the two species were classified as important invasive herbs with comparatively higher importance values (Assaeed et al., 2021). The two native Saudi Arabian aquatic plants, *Lemna gibba*, and *Potamogeton nodosus* were not detected in all dam areas and were only found in abroad association with *Ceratophyllum submersum* in Medhas area. This is the first time in the Kingdom to report *C. submersum* as an aquatic invasive species. In the Alaqiq dam area, two species, *Forsskaolea tenacissima* and *Euphorbia chamaesyce*, were identified as indigenous accompanied plants among the exotic plants *Alternanthera pungens*, *Eclipta prostrata*, *Cuscuta campestris*, *D. carinata*, *A. ochroleuca*, *D. innoxia* and *N. glauca*.

D. carinata was found in all studied areas except Alahsaba, while *Sesuvium portulacastrum* and C. submersum were only found in Medhas dam area. In the Medhas area, the prominent and extensively distributed native plant was *E. chamaesyce* which was associated with *S. portulacastrum* and *C. campestris*. *Abutilon pannosum* was the most prevalent native indigenous plant in Alahsaba dam area, along with *Amaranthus albus*, A. ochroleuca, *C. echinatus*, *D. ferox* and *D. innoxia* as exotic species. According to Assaeed et al. (2021), exotic species can help spread of indigenous native plants

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directly or indirectly by changing the ecosystems, affecting soil microbial populations, and facilitating pollination. The invasive plants *Argemone Mexicana, Opuntia dillenii, Opuntia ficus-indica, Prosopis juliflora* and *Trianthema portulacastrum* which were widely scattered in southwestern Saudi Arabia (Thomas et al., 2016) were not reported in this study. In addition, *Cylindropuntia rosea* which was an established invasive cactus plant detected around Jebel Hizna (Al-Robai et al., 2018) was not found in the studied dam areas.

Alfarhan et al. (2021) have demonstrated that the introduction of alien plants is a big issue in Saudi Arabia, since their numbers are increasing, and the indigenous species and agricultural plants cannot survive with these foreign plants. The invasion is affecting valleys, escarpments, plant diversity hotspots, and species-rich habitats that are constitutionally protected. Furthermore, these changes might influence other species and alter the ecosystem's structure and function.

The most predominant families in the dams' areas were Asteraceae (5 species), followed by Amaranthaceae and Solanaceae (4 species), while the other seven families were represented by only one species. The dominance of Asteraceae in the study area agreed with the recorded data by Alharthi et al. (2023). The Asteraceae family has been reported as one of the most prominent families in different regions of Saudi Arabia (Al-Turki and Al-Olayan, 2003; El-Ghanim et al., 2010; Al-Robai et al., 2017). The dominant status of this family in Saudi Arabia may be attributed to its capacity to disperse seeds and its ecological adaptability (Al-Robai et al., 2017).

The dominant life forms in the studied dam areas were therophytes (55%), followed by chamaephytes (20%), while the least dominant life-forms were hemicryptophytes, parasites, hydrophytes and Phanerophytes (5%). This variation could be caused by environmental factors such topography, salt stress, and drought (Mutairi et al., 2012). The dominance of therophyte plants in the study area agreed with previous studies in Saudi Arabia (Osman and Abdein, 2019; Al Shaye et al., 2020; Obaid et al., 2020; Galal et al., 2021; Elkordy et al., 2022). The least dominant of phanerophytes could be due to salt stress, flooding, or the accumulation of sediments (Ayyad and El-Ghareeh, 1982). The data of life forms could be useful to trace the impact of environmental factors on the distribution and diversity of exotic plants. The investigated exotic plants had a wide geographical range (Australian, Mediterranean, Neotropical, Pantropical, Sudano-Zambezian, Plurireginalbor-trop, Subtropical-Tropical, and American) in the studied areas. Analysis of geographical distributions of the reported exotic invasive species showed that the major invasive species in the study area were native to American region (7 species) followed by Plurireginalbor-trop region (6 species), and Subtropical-Tropical (2 species) whereas, the rest regions were represented by only one species. Previous studies revealed that the geographical range of the plants in Saudi Arabia is a link between Eastern Africa and South Asia (Alfarhan, 1999; Al-Nafie, 2008). Most of the recorded exotic plants (18 species) were classified as herbs, with only two species classified as shrubs.

Soil analysis

The electrical conductivity, pH values, total organic compounds, total nitrogen, and element content of soil samples collected from dam areas are summarized in *Table 5*. The electrical conductivity values which varied significantly ($p < 0.05$) among the studied dam areas, ranged between 155.75 and 2204.5 S/cm, indicating low to moderate concentrations of dissolved salts. The variation in EC suggested that the soil

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texture and the physical properties of the studied areas differed, which could influence the distribution and diversity of the studied plants. Electric conductivity levels are linked to organic matter, amount of clay, and cation exchange capacity in addition to soil salinity (Ortega-Blu and Molina-Roco, 2016). There were no notable variations in the pH values among the analyzed soil samples (7.7 to 8.5). Soil pH level alters the chemical nature of the soil, which influences plant metal absorption as well as plant density and dominance (Blake and Goulding, 2002). The recorded pH values in the current study suggested that the effect of pH levels on the distribution of the studied exotic plants may be effective because it determines the availability of essential plants nutrients.

No significant ($p < 0.05$) differences in organic contents were observed among Medhas, Aljanabeen, and Alaqiq dam areas. They contained an equal amount of total organic compound (0.82%), which is remarkably higher when compared with that of the other areas (0.19-0.64%). The abundance of invading species in Medhas and Aljanabeen areas could be attributed to high levels of the total organic compounds in these areas. This is because organic matter contains essential plant nutrients and provides macro-and micronutrients that enhance plant growth (Park et al., 2019).

Table 5. *Electrical conductivity (EC), pH values, total organic carbon (TOC) and mineral contents (mg/kg) of soil samples from the studied dam areas*

Soil property	Medhas	Aljanabeen	Alaqiq	Arada	Alahsaba	Olib
EC (µS/cm)	2204.5 ± 24.66 a	980.5 ± 14.25 b	218.75 ± 9.39 e	862.8 ± 16.74 c	302.25 ± 11.02 d	155.75 ± 13.98 f
pH	7.75 ± 0.40 ab	7.7 ± 0.14 b	8.45 ± 0.13 ab	8 ± 0.34 ab	8.3 ± 0.5 ab	8.5 ± 0.41 a
TOC (%)	0.82 ± 0.30 a	0.82 ± 0.30 a	0.82 ± 0.15 a	0.55 ± 0.06 ab	0.19 ± 0.02 b	0.64 ± 0.14 a
TNC (mg/kg)	337.45 ± 8.32 b	519.45 ± 8.81 a	76.60 ± 22.64 c	95.05 ± 8.64 c	33.30 ± 9.56 d	36.75 ± 3.77 d
P	635 ± 5.94 a	688.45 ± 83.02 a	470 ± 60.14 b	507 ± 19.61 b	526.50 ± 36.94 b	485.50 ± 16.34 b
S	4207 ± 10.98 a	2226.5 ± 11.07 b	1349 ± 20.86 c	1072.55 ± 15.46 d	240.30 ± 21.47 e	271.05 ± 17.47 e
K	2047.5 ± 17.38 e	2580 ± 25.81 c	1512.5 ± 11.76 f	2202 ± 30.8 d	3293 ± 35.45 b	3611.5 ± 89.27 a
Ca	15390 ± 22.11 a	13749 ± 35.28 b	8545.5 ± 40.08 d	10477.5 ± 37.19 c	5149.5 ± 114.67 f	5479 ± 28.34 e
Mg	10732 ± 23.66 b	11205 ± 8.91 a	10603 ± 35.75 b	9793 ± 176.24 c	8777 ± 34.52 d	9683.5 ± 83.74 c
Fe	24580 ± 20.07 c	27235 ± 22.55 a	23095 ± 206.67 d	24380 ± 46.71 c	22022 ± 858.82 e	25415 ± 140.93 b
Mn	611.9 ± 10.13 d	892.25 ± 32.68 b	1547.75 ± 48.512 a	858.8 ± 26.79 b	451.1 ± 16.12 e	707.8 ± 19.02 c
Cu	34.76 ± 6.65 b	57.725 ± 5.12 a	32.55 ± 6.16 b	51.26 ± 8.76 a	66.91 ± 12.69 a	61.815 ± 10.3 a
Ni	38.28 ± 3.32 ab	40.57 ± 5.57 a	21.22 ± 5.98 c	33.55 ± 6.40 b	23.59 ± 4.01 c	27.37 ± 2.72 bc
Co	15.18 ± 2.85 ab	16.45 ± 1.79 a	10.33 ± 1.56 b	13.9 ± 3.61 ab	12.56 ± 1.76 ab	14.58 ± 1.69 ab
Cr	61.17 ± 6.51 a	64.5 ± 4.83 a	54.7 ± 7.31 a	56.95 ± 4.83 a	38.89 ± 5.7 b	36.49 ± 2.84 b
Na	658.85 ± 17.13 a	221.65 ± 14.54 c	614.6 ± 9.51 b	169.16 ± 12.04 d	608 ± 24.66 b	128.05 ± 10.56 e
Al	18755 ± 91.54 b	19495 ± 39.27 a	14615 ± 281.89 e	17110 ± 91.22 c	15340 ± 418.28 d	17405 ± 70.73 c

Results are presented as mean with SD (±); n = 4. Statistical differences were assessed by one-way ANOVA and Tukey's post hoc multiple comparison test ($p < 0.05$) using Graph Pad prism software version 0.5. Means followed by different letters in the same row are significantly different; Zn, Mo, As, Cd and Pb elements were not detected in the tested soil samples

A clear variation was observed among the tested soil samples in their element contents (*Table 5*). All the soil samples tested from dam areas had substantial levels of phosphorus (470-688.45 mg/kg). The soil samples from Alahsaba had the lowest amounts of S, Ca, Mg, Mn, and Fe, but the highest concentration of Cu (66.91 mg/kg). The highest amounts of S, Ca, and Na content were found in the Medhas area, which had the highest level of invasive plant richness. Soil samples from Aljanabeen area had

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significantly ($p < 0.05$) higher nitrogen concentrations compared to other dam areas. In addition to nitrogen, this area showed high levels of P, Fe, Mg, Co, Ni, Al, and Cr contents. The relatively high invasive plant richness pattern of this area may be due to high levels of these minerals in the soil. Alaqiq, Arada, Alahsaba, and Olib areas had extremely low levels of nitrogen (33.3-95.05 mg/kg) when compared with Medhas (337.45 mg/kg) and Aljanabeen (519.45 mg/kg) areas. This could be the reason why these areas had remarkable moderate or low species richness values. In regions with a temperate climate, soil nitrogen, and phosphorus are often the limiting factors influencing plant species richness as well as having a negative impact on the richness of native plants. Moreover, soil nitrogen and phosphorus are important regulators of plant development and influence a wide range of environmental processes (Hrivnák et al., 2015). Soil P, K, and Mg concentrations were among the more effective indicators of plant species diversity and P has a substantial adverse impact on species richness (Hejcman et al., 2010). The diversity of the invasive plants in the studied region may be primarily impacted by the variations in the physicochemical properties of the soil among the dam areas, or it may be influenced by other ecological factors. However, variations in plant diversity among the dam areas might be caused by other factors not addressed in this study, including anthropogenic activities, local biota, age and water capacity of the dams, nutrient cycling in soil-plant system, seed dispersal, and species interactions.

Heavy and trace elements, Zn, Mo, As, Cd, and Pb were not detected in all evaluated soil materials. This could be correlated to the interaction mechanism between the invasive plants and the contaminants in the soil. However, some invasive plants could absorb, adsorb, accumulate, and immobilize the heavy metals and thus decrease the concentrations of these elements in the soil and thereby enhance soil remediation (Li et al., 2022). On the other hand, other environmental factors that affect metal transport and accessibility, as well as plant species, may alter the level of heavy metal toxicity in the soil (Alvarez et al., 2003).

Environmental variables analysis

Canonical Correspondence Analysis (CCA) was used to find the relation between plant distribution and total organic matter, total nitrogen, phosphorus, electrical conductivity, and pH values as soil variables (*Fig. 3*). In the CCA biplot, variables are represented by arrows pointing in the direction of maximal variation, with length proportional to the rate of change. The obtained results indicated a substantial relationship between the diversity of the invasive plants and the tested soil parameters displayed in the biplot. It was clear that total organic matter and electrical conductivity are the most important soil variables, which are strongly correlated with ordination axis 1 and thus with the frequency of the plants. Total organic matter and electrical conductivity were correlated with the first axis and increasing along a gradient from right to left. Total nitrogen and phosphorus had a considerable positive influence on the frequency of the species along the second axis, while total organic matter and electric conductivity had a negative influence.

X. strumarium, D. carinata, C. echinatus, D. innoxia, D. ferox, D. stramonium, X. spinosum, A. albus and A. ochroleuca were correlated with pH value. S. kali, N. glauca, A. pungens, E. prostrata and V. encelioides were correlated with total nitrogen and phosphorus contents. Tagetes minuta, C. submersum, C. campestris, L. camara and H. curassavicum were strongly correlated with total organic matter and electric conductivity.

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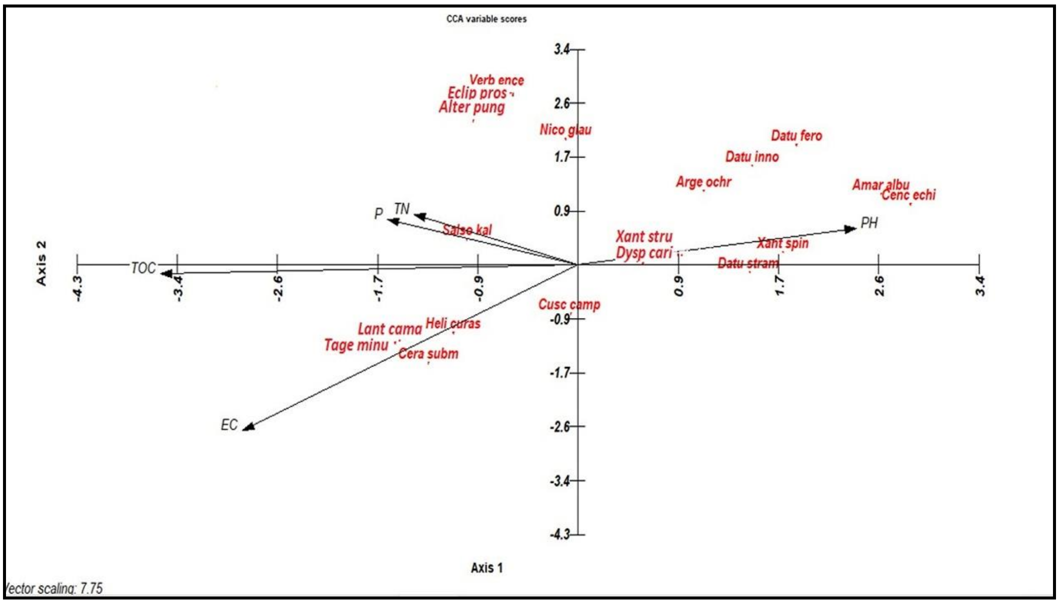

Figure 3. *Biplot canonical correspondence analysis (CCA) showing the correlation between soil variables and distribution of invasive plants in the studied dam areas. Axis 1 and Axis 2 represent the first and second ordination axes of CCA, respectively. Arrows represent the soil data, TOC: total organic carbon, EC: electrical conductivity, P: phosphors content, TNC: total nitrogen content and pH value. Invasive plants are indicated by four letters of genus and species, respectively (see Table 3 for full names)*

The Canonical correspondence analysis ordination diagram (*Fig. 4*) shows the distribution of invasive plants along the elevation gradients. It was clear that elevation was an important environmental factor that affects the distribution of these plants in the studied dam areas. *S. kali*, *T. minuta*, *N. glauca*, *S. portulacastrum*, *A. pungens* and *V. encelioides* were strongly correlated with the high altitude. *D. carinata*, *C. echinatus*, *D. innoxia*, *D. ferox*, *D. stramonium*, *X. spinosum*, *A. ochroleuca*, and *A. albus* were correlated with low altitude. The distribution of *X. strumarium C. campestris* and *H. curassavicum* was correlated with middle altitude. According to Alexander et al. (2011), exotic species are first brought and become established at low-altitude regions before spreading to highlands. However, exotic plants' establishment differs along altitudes and ecosystem types, offering managers of land crucial data for preventing biological invasions (Pollnac et al., 2012). Low and high elevations are among other environmental factors that affect the dispersion, richness, and diversity of both indigenous and non-indigenous plants in different habitats (Haider et al., 2022).

Diversity analysis

Species richness and evenness, Shannon-Weiner, Simpson, Brillouin, Menhinick, Margalef, Fisher's alpha and Berger-Parker indices were used to analyze the diversity of the invasive plants in the studied dam areas. These metrics are recommended useful quantitative tools to measure, compare, and express the distribution and diversity of plants in various ecosystems (Bibi and Ali, 2013). *Table 6* summarizes the numerical species richness, evenness and species diversity indices calculated for the different dam areas. The recorded data varied greatly among the six studied dam areas. Dam areas showed various degrees of species richness, ranging from 4 to 13 invasive plants.

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Medhas dam area had the highest variety of cover, while both Olib and Alahsaba areas showed the fewest numbers of invasive plants. Aljanabeen and Arada dam areas exhibited the same species richness pattern with 10 different exotic plants. Variations in species richness values among the studied dam areas can be attributed to differences in underlying species richness, relative abundance distribution, and individual numbers (Gotelli and Colwell, 2001). Moreover, species richness is affected by sample size; as sample collection expands, additional individuals and species are expected to be discovered and reported (Williams et al., 2005).

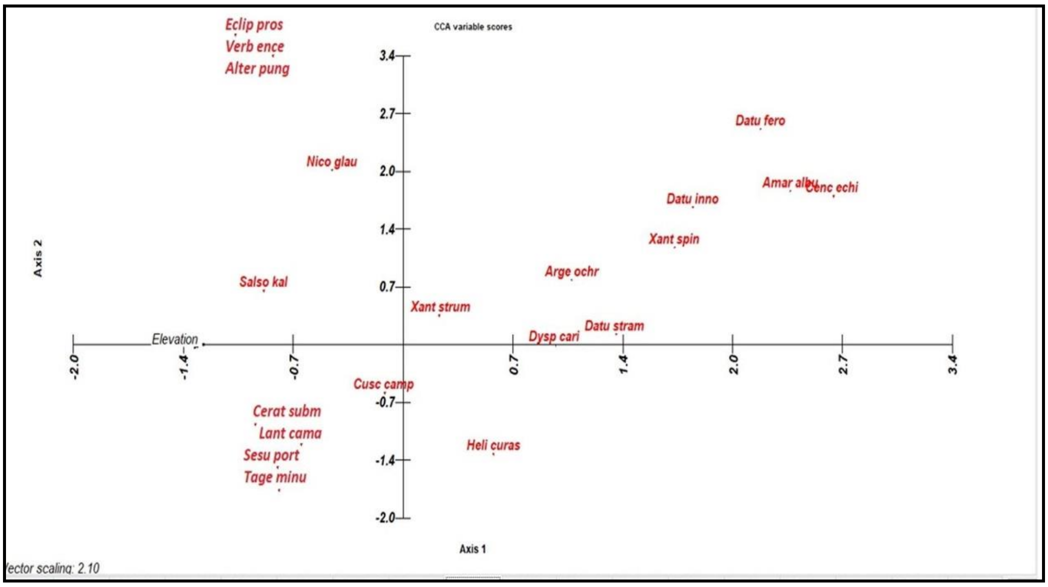

Figure 4. *Canonical correspondence analysis (CCA) ordination diagram of invasive plants along elevation gradient as an environmental variable. Axis 1 and Axis 2 represent the first and second ordination axes of CCA, respectively. Invasive plants are indicated by four letters of genus and species, respectively (see Table 3 for full names)*

Table 6. *Invasive plant diversity indices for the six dam area*

Index	Medhas	Aljanabeen	Alaqiq	Arada	Alahsaba	Olib
Species richness	13	10	7	10	5	4
Individuals	635	1049	318	523	402	95
Simpson_1-D	0.86	0.88	0.50	0.83	0.70	0.71
Shannon_H	2.12	2.19	1.1	1.95	1.37	1.31
Evenness_e^H/S	0.64	0.89	0.43	0.70	0.78	0.92
Brillouin	2.06	2.16	1.05	1.90	1.33	1.22
Menhinick	0.52	0.31	0.39	0.44	0.25	0.41
Margalef	1.86	1.29	1.04	1.44	0.67	0.66
Fisher's alpha	2.31	1.53	1.27	1.75	0.80	0.85
Berger-Parker	0.2	0.21	0.69	0.26	0.45	0.37

The evenness was higher in Olib dam area (0.92), followed by Aljanabeen dam area (0.89) and the overall evenness average across the studied areas was relatively high (0.73). Evenness index values seek to express the unequal distribution of species in

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comparison to a hypothetical sample in which all species are equally prevalent. When all plants are evenly distributed, the evenness index is equal to one, and it drops toward zero when the relative abundance of plants deviates away from evenness (Williams et al., 2005).

Simpson and Shannon indices are the most often used metrics for measuring species diversity in an ecosystem. They are related to species richness and species frequency or abundance (Luis Hernandez-Stefanoni and Ponce-Hernandez, 2004). The highest values of Simpson (0.88) and Shannon (2.19) indices were recorded in Aljanabeen dam area, while the lowest (0.50 and 1.1, respectively) were detected in Alaqiq dam area. These findings suggested that Aljanabeen dam area was an ecosystem with a high diversity of invasive plants, while the least diverse was Alaqiq dam area. Higher diversity indices in Medhas and Aljanabeen dam areas may indicate that total nitrogen, phosphorus content and total organic carbon are key factors for invasive plant diversity. According to Ortega et al. (2004), Shannon diversity index increases when communities are diverse and is more effective than species richness and the Simpson indices in evaluating plant diversity at a land level. This could be because it can express landscape structure in the gamma diversity without losing its concavity structure.

The Brillouin diversity indices at Medhas dam area (2.06) and Aljanabeen dam area (2.16) were relatively higher than in the other dam areas (1.05-1.90). This could be due to Brillouin's sensitivity to the overall individuals in an ecosystem, and hence displays diversity in terms of species heterogeneity (Anand et al., 2022) or other ecological factors. However, this index compared the diversity of plant species found in each area to the maximum diversity of the sample. Menhinick index values showed that species diversity was greatest in Medhas dam area (0.52), followed by Arada dam area (0.44). Variations in Menhinick index values across the studied dam areas may be due to their differences in species richness and abundance (Spatharis and Tsirtsis, 2010). As expected, Margalef's richness index in Medhas dam area (1.86) was notably high when compared with that in the other dam areas (0.66-1.44). This index correlated with the total number of species in an ecosystem, and its values increase as the number of species increases (Saha et al., 2009). Fisher's alpha diversity was higher in Medhas dam area (2.31), whereas Alahsaba (0.80) and Olib (0.85) dam areas exhibited comparable patterns. When compared to other diversity measures, Fisher's alpha index is unaffected by the size of the studying ecosystem and is less influenced by the abundance of the least prevalent or most common species (Kalema and Witkowski, 2012). The Berger-Parker index showed dissimilarity trends with Shannon, Simpson and Margalef indices, it was markedly high in Alaqiq dam area (0.69). This dissimilarity might be because Berger-Parker index was one of the most unsatisfactory diversity metrics and was rarely applied to measure species diversity (Yeom and Kim, 2011).

The increasing threat that invasive plants pose to the composition and function of aquatic ecosystems has led to an increase in research on the consequences of plant invasion on biodiversity (Wang et al., 2022). According to Yang et al. (2022), the harmful influence of these plants on the biomass and plant cover in grassland habitats should be controlled. The southwest of Saudi Arabia is incredibly rich in indigenous plants which could be endangered by the spreading of invasive plants. Based on the field observations, the reported invasive plants were appeared in most of the studied dam areas. It is expected that they will scatter to many nearby localities. The rapid growth of these plants in the surveyed vicinities could result in ecological and conservation problems, as invasive plants have the potential to disrupt the terrestrial and

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aquatic plant communities. Additionally, there are multiple other threats such as the decline or extinction of native plants, loss of biodiversity, and negative impact on the economy and society. Therefore, comprehensive action plans are needed to manage and reduce the spread of invasive plants in this habitat. Without suitable integrated financial and constitutional plans, it is difficult to effectively protect ecosystems with significant ecological value from exotic plants.

Conclusion

In Saudi Arabia, especially in the southwestern regions invasive plants threaten the natural habitats and diversity of native flora. This work was the first attempt in Al-Baha region to assess the diversity of invasive plants and their correlations with different ecological parameters in selected dam areas. Most of the reported invasive plants were herbs, therophytes and of American phytogeographical origin. The family and genus richest in invasive plant species were Asteraceae and Datura, respectively. The invaded dam areas showed notable variation in species richness and evenness. The highest values of species richness (13) and evenness (0.92) were detected in Medhas and Olib dam areas, respectively. The greatest index values of the applied diversity metrics indicated higher invasive species diversity in Medhas dam area. Results of CCA demonstrated that elevation and soil components were influential factors affecting the distribution and diversity of the invasive plants. High-altitude invaders were *A. pungens*, *V. encelioides*, *N. glauca*, and *S. kali*, while low-altitude areas included *C. echinatus* and *A. albus*. The diversity of the invasive plants in the studied dam areas were associated with the levels of electrical conductivity, nitrogen, phosphorus, and total organic carbon contents. Understanding the consequences of invasive plants on different ecosystems is a key step toward establishing conservation plans for the invaded ecosystems. The results of this research might provide baseline information for future monitoring of the distribution and diversity patterns of these invaders in dam-built areas.

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