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Comparative study of plant diversity around water towers in hyper-arid areas (Adrar, Algeria)

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Abstract. Water is a vital compound that determines the life of all organisms, but is often deficient, especially in hyper-arid areas. The rapid development and expansion of modern irrigation systems in these areas has created favourable environments for many plant species adapted to extreme aridity. In this study, to compare plant diversity in the vicinity of 6 water towers in hyper-arid areas, at each site we conducted 5 floristic surveys on the basis of subjective sampling. The floristic data were analysed using biodiversity and statistical parameters. We recorded there 43 species of 22 families, with a good representation of the Poaceae (18.6%) and Asteraceae (14.0%). According to Raunkiaer's classification, the plant cover is mainly composed of therophytes (41.8%), i.e. annual species that complete their development cycle within one growing season. The spectrum of various types of dispersal shows the dominance of flora by anemochorous species (70.7%). A chorological analysis of the vegetation in the area revealed the importance of the Saharo-Arabian element (41.9%), which confirms its adaptation to the environment of the hyper-arid zones of the Sahara. The analysis of abundance classes revealed the existence of 10 rare species (18.1%), 3 very rare species (4.9%), and one fairly rare species (1.3%). In conclusion, the environments surrounding water towers in hyper-arid areas require adequate management measures to preserve biodiversity in Saharan environments.

Key words: adaptation, plant diversity, water towers, preservation, hyper-arid zone

1. Introduction

The Algerian Sahara, representing more than 80% of the surface of Algeria, is characterized by drought, low and irregular rainfall, as well as by the very low renewability of its groundwater resources (Kassah 2002). The total water resources on the planet are estimated at 1.4 billion km^3, consisting of 97.5% salt water and only 2.5% fresh water (Zella & Smadhi 2006). In the Algerian Sahara, the water resources are essentially constituted by groundwater because they are often the only source of potable water (Tabouche & Achour 2004; Bouchahm & Achour 2005). Humans have adapted and exploited the resources of their territory by developing many techniques to draw out ground water. The exploitation techniques vary according to the nature of the resources, their importance, and location (Kassah 2002). The populations of arid zones use fossil water contained in aquifer basins (Terminal Complex and Intercalary Continental), which emerges naturally at the surface of the soil or is artificially recovered using the foggara system (Bellal *et al*. 2016). Another type of exploitation based on the drilling technique is introduced in the development programs via the construction of modern water wells equipped with pumps (Salem & Habil 1988), focused mainly on the storage and supply of the human population and known as water towers (Viviroli *et al*. 2007; Immerzeel *et al*. 2010; Huang *et al*. 2022).

Water towers are found especially in the semi-arid and arid zones of the world (Messerli *et al*. 2004), and are constructed to supply the urban populations of the Sahara with drinking water. In the proximity of the towers, the excess and/or cleansing water is released into nature. This results in the establishment of semi-permanent surface water as well as the formation of small and superficial water areas that are colonized by unique vegetation, differing substantially from the prevailing flora in the surrounding hyper-arid area (Bouallala *et al*. 2020; Souddi & Bouallala 2023).

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The availability of water (both surface water and groundwater) as well as humidity are the main factors limiting the natural distribution of plants in arid areas (Malagnoux *et al*. 2007), where plants mainly use locations with more favourable water supply (Le Houérou 1990; Ozenda 2004).The study of plant diversity in these areas allows us to characterize the state of the ecosystem and to demonstrate its natural or artificial modifications caused by humans.

The spontaneous flora of the Algerian Sahara includes about 500 species of vascular plants and 700 species of cryptogams. It represents about 1/7 of the 3300 species of Algerian vascular flora (Quézel & Bounaga 1974; Bounaga & Brac de la Perriere 1988). The flora of the Algerian Sahara has affinities with the Mediterranean flora (28%), the tropical desert (25%), but most species (47%) are Saharo-Arabian (Bounaga & Brac de la Perriere 1988). The studies devoted to understanding and description of Saharan plant diversity are very numerous, indicating the influence of the factors of the hyper-arid environment on the flora and vegetation (Maire 1933-1940; Guinochet & Quézel 1954; Quézel & Santa 1962-1963; Quézel & Simonneau 1963; Quézel 1978; Barkoudah & Van Der Sar 1982; Benhouhou *et al*. 2001, 2003; Ozenda 2004; Chehma 2005; Chehma *et al.* 2005; Chehma & Youcef 2009; Bradai *et al*. 2015; Bouallala *et al*. 2020, 2022, 2023; Azizi *et al*. 2021; Souddi & Bouallala 2023; Merchala *et al*. 2023).Those studies show that the plant species richness in this hyper-arid environment is due to a large spatial heterogeneity of geomorphological, bioclimatic, and historical factors, as well as a large spatial heterogeneity of natural habitats (Quézel 1985). However, plant diversity in anthropized ecosystems of hyper-arid zones is poorly studied. Some surveys have been carried out in the vicinity of Saguia in the region of Touat (Algerian Sahara) and recently by Bouallala *et al.* (2020), and Souddi & Bouallala (2021, 2022, 2023).

In this context, the objective of this work is to compare plant diversity between the environments of different water towers in hyper-arid zones on the basis of species richness, functional traits (plant life-forms, morphological types, and dispersal types), chorological spectra, and classes of abundance.

2. Material and methods

2.1. Study area

Field research was conducted in the Wilaya of Adrar, located in south-western Algeria, in the Sahara. It is the second-largest wilaya, covering 424 948 km^2, limited to the north by Timimoune, to the east by In Salah, to the west by Tindouf and Beni Abbes, and to the south by BordjBadji Mokhtar (Fig. 1). The study was carried out at 6 sites (water towers) in 3 municipalities: Tamentit, Tamest, and Fenoughil (Fig. 1). These water towers are characterized by the presence of specific vegetation

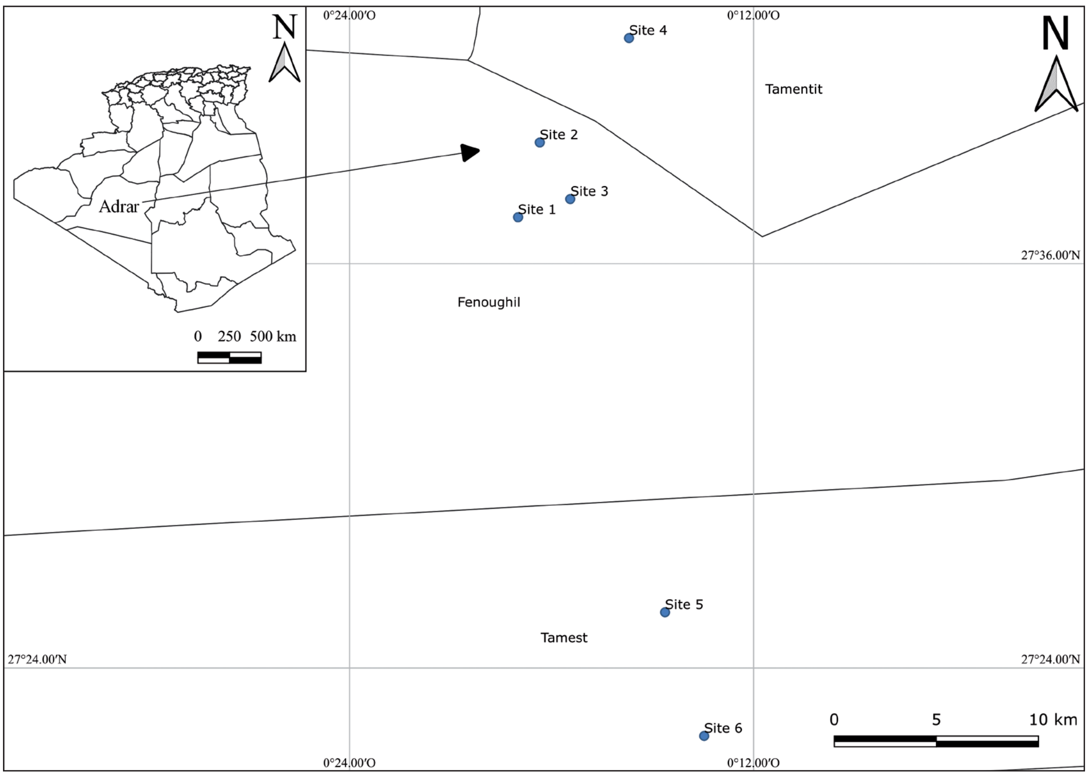

Fig. 1. Geographic location of the study sites in the Algerian Sahara

Table 1. Characteristics of the study sites in the Algerian Sahara

No.	Municipality	Geographic coordinates	Altitude [m]	Description	Dominant plant species
1	Fenoughil	27°37′23″N, 0°18′06″W	202.1	new submersion	*Zygophyllum album*, *Senecio massaicus*, *Launaea glomerata*, *Asphodelus tenuifolius*
2	Fenoughil	27°39′36″N, 0°18′20″W	199.0	new submersion	*Imperata cylindrica*
3	Fenoughil	27°37′55″N, 0°17′26″W	197.9	new submersion	*Zygophyllum album*, *Senecio massaicus*
4	Tamentit	27°42′40″N, 0°15′42″W	216.2	new submersion	*Phragmites communis*
5	Tamest	27°25′39″N, 0°14′38″W	206.3	traces of animal grazing	*Zygophyllum album, Pergularia tomentosa*, *Senecio massaicus*
6	Tamest	27°21′59″N, 0°13′28″W	181.9	traces of animal grazing	*Zygophyllum album, Pergularia tomentosa*, *Asphodelus tenuifolius*

in the depressions located in their immediate vicinity (Table 1).

The analysis of climatic data provided by InfoClimat (www.infoclimat.fr) for 37 years (1985-2022) indicates that the area is hyper-arid. The average annual precipitation during the study period was only 9.2 mm. The study area is characterized by a mean minimum temperature of 5.4°C in January and a mean maximum temperature of 46°C in July.

2.2. Sampling and floristic surveys

Six water towers were selected based on subjective sampling in the study area to compare the plant diversity that develops in their environments. The surveys were carried out in spring (February-May 2022), which coincided with the flowering phase of most plants (Ozenda 1982). At each site, 5 surveys of an area of 100 m^2 each (in total 500 m^2) were conducted; the choice was based on the concept of minimum area adopted for studies of the diversity of Saharan plants (Benhouhou *et al*. 2003; Bouallala 2013; Bouallala *et al*. 2020, 2022, 2023; Azizi *et al*. 2021; Souddi & Bouallala 2023; Merchala *et al*. 2023). The Braun-Blanquet approach for classification and description of vegetation was used. During each survey, we recorded the list of species with their cover-abundance (Braun-Blanquet 1964).

2.3. Flora analysis

The plant species were identified based on the works of Quézel & Santa (1962-1963), Ozenda (2004), and the TelaBotanica website (tel-botanica.org).

Species richness (*S*) is the total number of species present within a defined area. To compare the richness of the sites, we used the scale of Daget & Poissonet (1991), adopted to the Saharan regions as follows: very species-poor (≤10), species-poor (11-20), moderate (21-30), fairy species-rich (31-40), species-rich (41-50), and very species-rich flora (>50).

We analysed both the raw spectra, which are based on species richness, and the real spectra, which are based on the average cover obtained by the conversion of the cover-abundance classes of Braun-Blanquet into average percentages. For class 5, average cover was 87.5%; for class 4, it was 62.5%; for class 3, the average was 37.5%; for class 2, it was17.5%; for class 1, species, the average was 5%; and for class +, average cover was 0.1% (Gounot 1969). These average cover values were also used in the statistical analysis and summed up (as if they were not percentages) to calculate the overall vegetation cover (VC).

Functional traits are necessary to define biodiversity more precisely. They are used to understand better the relationship between plant communities and their environment (McGill *et al*. 2006).

The determination of the biological types of the recorded species was based on the classification established by Raunkiaer (1934). He classified plant life-forms according to the position of survival organs during unfavourable periods. The life-forms of species recorded in this study were determined using the flora of Algeria (Quézel & Santa 1962-1963), the flora of the Sahara (Ozenda 2004), and the database of TelaBotanica.

The determination of morphological types (annual vs. perennial species) was based on the works of Quézel and Santa (1962-1963); Ozenda (2004), and the database of TelaBotanica.

Van der Pijl (1982) classified plants according to the agent involved in the dissemination of diaspores into 5 categories, namely anemochorous, autochorous, barochorous, hydrochorous, and zoochorous. Plant dispersal types for the identified species were determined according to Jauffret (2001), Vela (2002), Bouallala *et al*. (2020), and the database of TelaBotanica.

The chorological types of the recorded species were determined based on the flora of Algeria (Quézel & Santa 1962-1963) and a book on the vegetation of the Sahara from Chad to Mauritania (Quézel 1965).

The classes of abundance of the recorded species were determined on the basis of the flora of Algeria and desert regions (Quézel & Santa 1962-1963).

Origin 2022 software was employed to carry out statistical analyses. Using the calculated data based on the number of species present in each survey for each site, descriptive statistics were displayed as box plots for the study sites. The variation in mean recovery between sites was tested using linear regression.

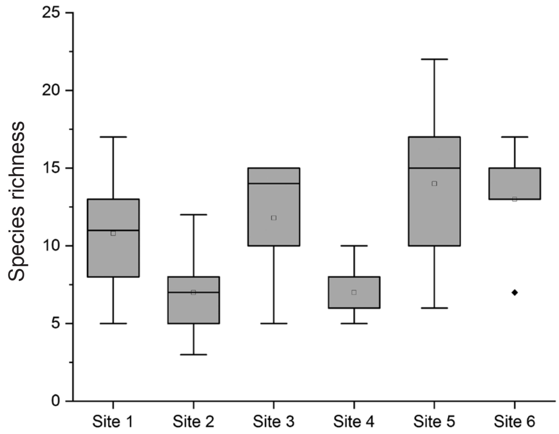

Fig. 2. Distribution of species richness at the study sites in the Algerian Sahara

3. Results

3.1 Richness and structure

The results obtained show that the study area contains 43 species of 39 genera and 22 families (Table 2). The most represented families are the Poaceae (18.6%), Asteraceae (14.0%), Amaranthaceae (9.3%), Apocynaceae (7.0%), Fabaceae, Caryophyllaceae, Solanaceae, and Tamaricaceae (4.7% each). The other 14 families, represented by only one species (2.3%), are the Arecaceae, Brassicaceae, Cucurbitaceae, Euphorbiaceae, Frankeniaceae, Gentianaceae, Heliotropiaceae, Liliaceae, Malvaceae, Orobanchaceae, Primulaceae, Polygonaceae, Resedaceae, and Zygophyllaceae.

The species with the highest overall vegetation cover are: *Imperata cylindrica* (150, including 77.5 at site 2), *Zygophyllum album* (133.5, including 65 at site 6), and *Senecio massaicus* (116, including 42.7 at site 5). The species with the lowest vegetation cover (0.1) are: *Cynanchum acutum*, *Leucaena leucocephala*, *Frankenia pulverulenta*, *Launaea nudicaulis*, *Prosopis juliflora*, *Tamarix aphylla*, *Rumex* spinosus, and *Euphorbia granulata*.

The box plot shows that floristic richness varies between sites, from 16 to 26 species. Site 5 is the richest, including 26 species, with a maximum of 22 species in survey 5 and a minimum of 6 species in survey 1. Site 4 has the lowest richness, including 16 species, with a maximum of 10 species in survey 3 and a minimum of 5 species in survey 1 (Fig. 2).

Linear regression between the different variables (number of genera, number of species, and vegetation cover) was investigated to define the relationships that exist between them. The values of *R* indicate a good correspondence between the number of genera and vegetation cover, with *R*=0.55 (Fig. 3), and between the number of species and vegetation cover, with *R*=0.51 (Fig. 4).

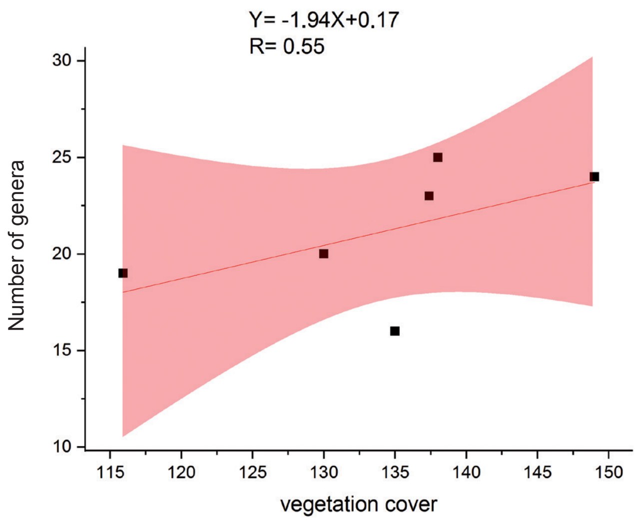

Fig. 3. Relationship between the number of plant genera and vegetation cover at the study sites in the Algerian Sahara

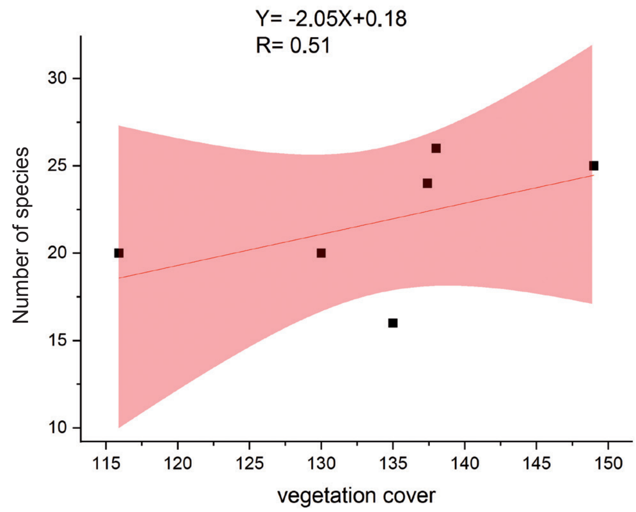

Fig. 4. Relationship between the number of plant species and their vegetation cover at the study sites in the Algerian Sahara

Table 2. List of species recorded at the study sites in the Algerian Sahara

Species	Family	L-f	M t	D t	Ch t	A c	Sites	Overall VC
Anagallis arvensis L.	Primulaceae	Th	a	Anemo	Cos	R	2, 3, 5, 6	10.6
Asphodelus tenuifolius Cavan.	Asphodelaceae	Th	a	Anemo	Mac-M	C	1, 6	47.6
Bassia muricata (L.) Asch.	Amaranthaceae	Th	a	Zoo	M-SA	C	1, 3, 4-6	0.7
Brassica tournefortii Gouan.	Brassicaceae	Th	a	Baro	M	R	5, 6	5.1
Calotropis procera Act.	Apocynaceae	Ph	p	Anemo	Tr-SA	R	1, 3, 4-6	1.2
Centaurium pulchellum (Sw.) Hayek ex Hand.-Mazz. et al.	Gentianaceae	Th	a	Anemo	PTm	R	4	5.0
Cistanche phelypaea (L.) P. Cout.	Orobanchaceae	Th	a	Anemo	M-SA	C	1-6	16.1
Citrullus colocynthis (L.) Schrad.	Cucurbitaceae	Th	a	Anemo	M-SA	CC	1, 5	0.5
Cornulaca monacantha Del.	Amaranthaceae	Ch	p	Baro	SA	AC	3, 4,	0.4
Cutandia dichotoma (Forssk.) Trab.	Poaceae	Th	a	Anemo	M	C	3, 5	10.2
Cynanchum acutum L.	Apocynaceae	H	p	Anemo	M-As	RR	3	0.1
Cynodon dactylon (L.) Pers.	Poaceae	H	p	Baro	Cosm	CCC	5, 6	15.2
Euphorbia granulata Forssk.	Euphorbiaceae	Th	a	Baro	SA	C	6	0.1
Frankenia pulverulenta L.	Frankeniaceae	Th	a	Baro	M	AC	3	0.1
Heliotropium bacciferum Forssk.	Heliotropiaceae	Ch	p	Baro	SA	CC	1	5.4
Hordeum murinum L.	Poaceae	Th	a	Zoo	Circ-bor	CC	5	0.2
Hyoscyamus muticus L.	Solanaceae	H	p	Zoo	SA	R	5, 6	0.4
Imperata cylindrica (L.) P.Beauv..	Poaceae	H	p	Anemo	Tr-M-SA	AC	2-4	150.0
Launaea glomerata (Cass.) Hook. F.	Asteraceae	Th	a	Anemo	M-SA	RR	1-3, 5, 6	38.6
Launaea nudicaulis (L.) Hook. f.	Asteraceae	Th	a	Anemo	SA	CC	4	0.1
Launaea resedifolia (L.) Kuntze	Asteraceae	Th	a	Anemo	M-SA	CC	1, 3, 5, 6	16.3
Leucaena leucocephala (Lam.) de Witt	Fabaceae	Ph	p	Anthro	CA	-	1	0.1
Lolium multiflorum Lam.	Poaceae	Th	a	Baro	Med	CC	1, 2, 5, 6	0.9
Malva parviflora L.	Malvaceae	Th	a	Baro	M	CC	2, 5, 6	5.6
Pergularia tomentosa L.	Apocynaceae	Ch	p	Anemo	SA	CC	1, 3, 5, 6	26.1
Phalaris minor Retz.	Poaceae	Th	a	Zoo	PSTr	AR	1, 3, 5, 6	10.6
Phoenix dactylifera L.	Arecaceae	Ph	p	Anthro	N Afr	CCC	2-6	0.8
Phragmites australis (Cav.) Trin. ex Steud.	Poaceae	H	p	Anemo	Cosm	C	1-6	73.0
Polypogon monspeliensis (L.) Desf.	Poaceae	Th	a	Zoo	PSTr	CC	2-6	33.3
Prosopis juliflora (Sw.) DC.	Fabaceae	Ph	p	Zoo	Tr-STr	-	4	0.1
Pulicaria arabica (L.) Cass.	Asteraceae	H	p	Anemo	SA	AC	1-5	40.7
Randonia africana Coss.	Resedaceae	Ch	p	Baro	SA	R	3, 4	0.2
Rumex spinosus L.	Polygonaceae	Th	a	Anemo	M	RR	5	0.1
Salsola foetida Delile ex Spreng.	Amaranthaceae	Ch	p	Anemo	SA	R	1-6	1.4
Senecio massaicus (Maire) Maire	Asteraceae	Th	a	Anemo	SA	R	1-6	116.0
Silene setacea Otth	Caryophyllaceae	Th	a	Anemo	SA	C	1, 3	10.1
Silene villosa Forssk.	Caryophyllaceae	Th	a	Anemo	Sah	R	6	0.2
Solanum nigrum L.	Solanaceae	Th	p	Zoo	Cosm	R	3,	5.0
Sonchus oleraceus L.	Asteraceae	Th	a	Anemo	Cosm	CCC	1-6	1.7
Tamarix aphylla (L.) Karst.	Tamaricaceae	Ph	p	Baro	SA	C	4,	0.1
Tamarix gallica L.	Tamaricaceae	Ph	p	Baro	M-SA	C	1, 2, 4-6	16.2
Traganum nudatum Delile	Amaranthaceae	Ch	p	Baro	SA	C	2-4	0.8
Zygophyllum album L.f.	Zygophyllaceae	Ch	p	Baro	SA	C	1-6	133.5

Explanations: L-f (Life-form), Ch – chamaephytes, H – hemicryptophyte, Ph – phanerophyte, Th – therophyte; M t (Morphological types), a – annual, p – perennial; D t (Dispersal types), Zoo –zoochore, Baro – barochore, Anemo – anemochore, Anthro – anthropochore; Ch t (Chorological types), M-SA – Mediterranean Saharo-Arabian, SA – Saharo-Arabian, Tr-SA – Tropical-Saharo-Arabian, M-As – Mediterranean Asian, NAfr – endemic to North Africa; Cosm – cosmopolitan, M – Mediterranean, Sah – Saharan, CA – Central American, Tr-STr –Tropico-subtropical, PTm – Palaeo-temperate, Mac-M – Macaro-Mediterranean, Circ-bor – circumboreal, Tr-M-SA – Tropical-Mediterranean-Saharo-Arabian, PSTr – Palaeo-subtropical; Ac (Abundance classes), AC – fairly common, C – common, CC – very common, CCC – particularly common, AR – fairly rare, R – rare, RR – very rare; VC – vegetation cover (see Chapter 2.3)

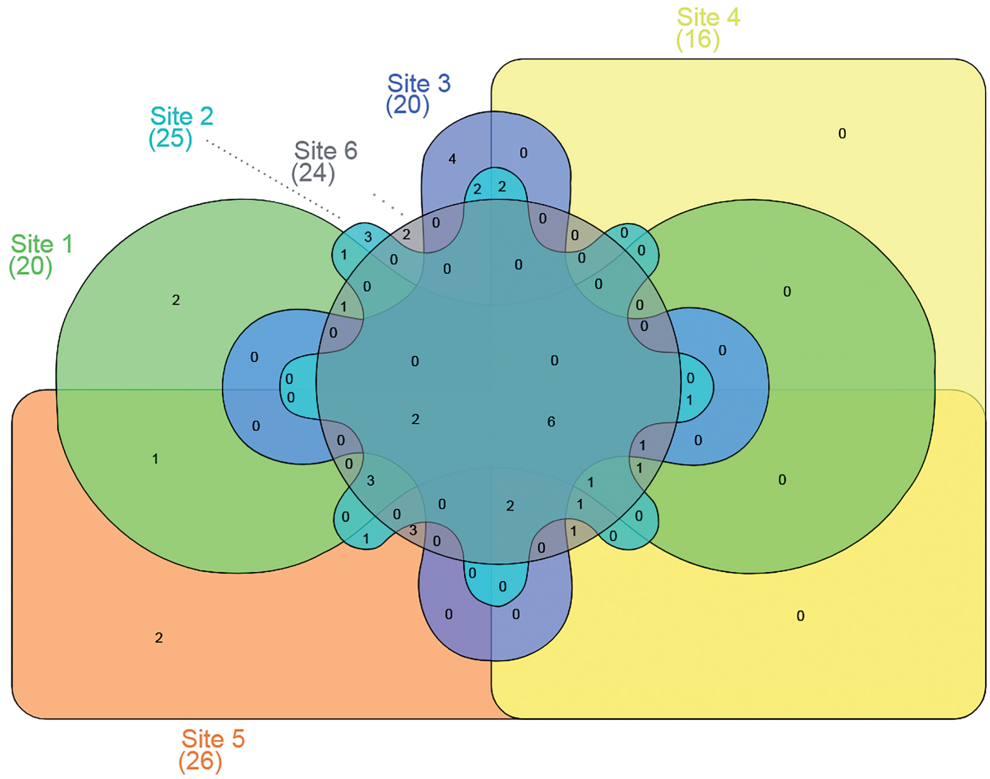

Fig. 5. Six-set Venn diagram showing the distribution of plant species at the study sites. The numbers in brackets represent the total number of species at each site, while the numbers within the diagram are species shared with the corresponding sites

3.2. Similarity analysis between sites

The Venn diagram shows the distribution of species between study sites (Fig. 5). There are 6 species common to all sites, i.e. omnipresent: *Sonchus oleraceus*, *Phragmites australis*, *Zygophyllum album*, *Salsola foetida*, *Cistanche phelypaea*, and *Senecio massaicus*. There are 3 species common to sites 1, 3, and 6 (*Phalaris minor*, *Launaea resedifolia*, and *Pergularia tomentosa*), another 3 common to sites 5 and 6 (*Hyoscyamus mu-*

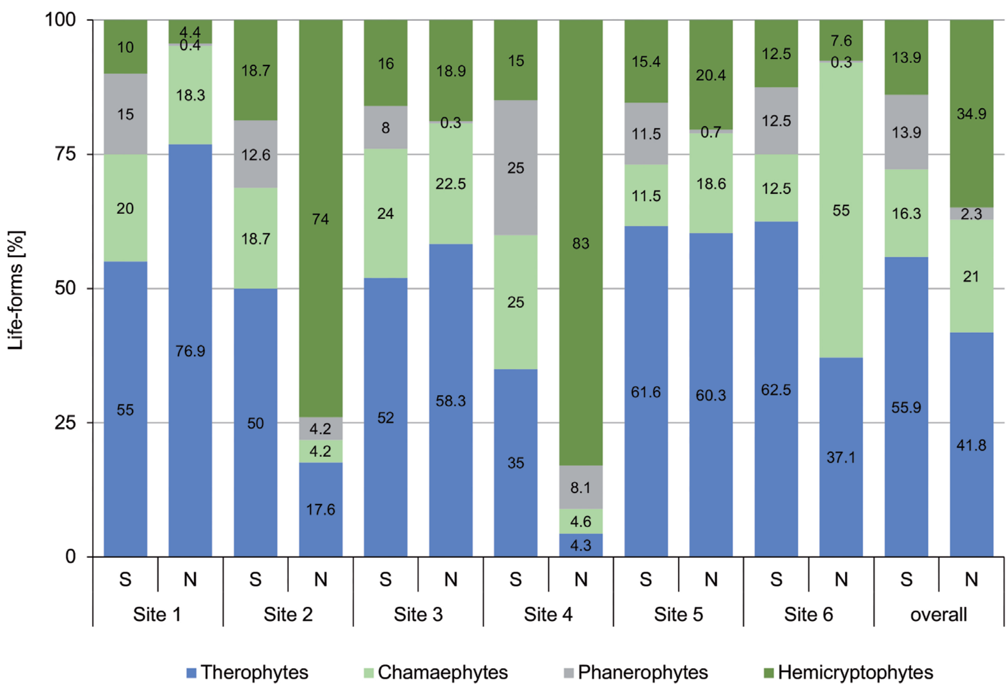

Fig. 6. Raw spectra (based on species richness, *S*) and real spectra (based on abundance, *N*) of plant life-forms at the study sites

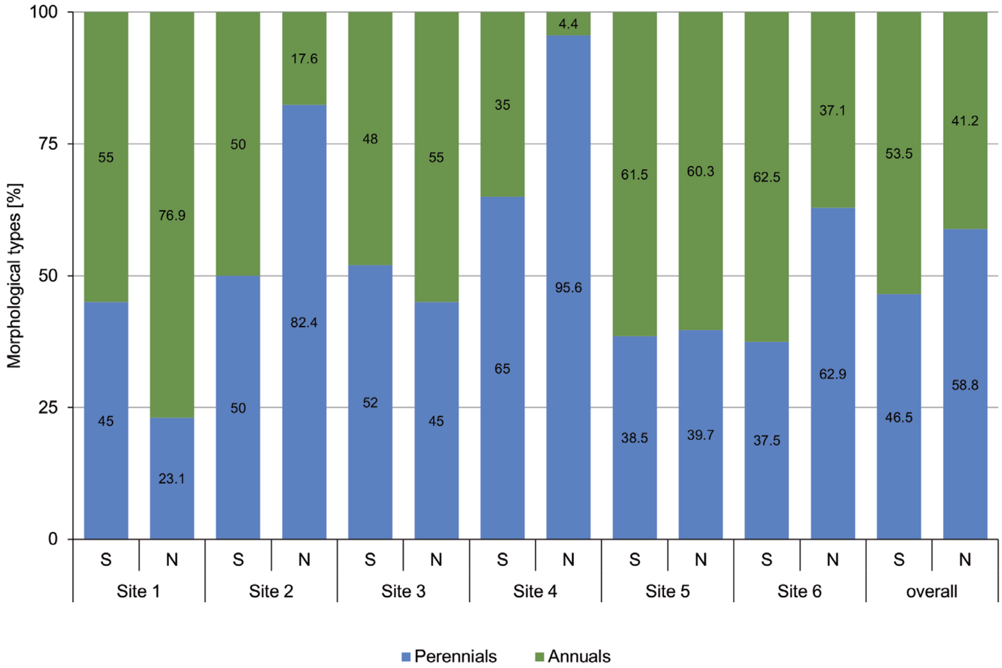

Fig. 7. Raw spectra (based on species richness, *S*) and real spectra (based on abundance, *N*) of morphological types of plants at the study sites

ticus, *Cynodon dactylon*, and *Brassica tournefortii*), while 2 are common to sites 1, 3, 4, 5, and 6 (*Bassia muricata* and *Calotropis procera*) and another 2 are common to sites 2, 3, 4, 5, and 6 (*Phoenix dactylifera* and *Polypogon monspeliensis*). Additionally, 2 species are common to sites 2, 3, and 4 (*Traganum nudatum* and *Imperata cylindrica*), and another 2 are common to sites 3 and 4 (*Cornulaca monacantha* and *Randonia africana*). The species exclusively present at one site are *Launaea nudicaulis*, *Tamarix aphylla*, *Centaurium pulchellum*, and *Prosopis juliflora* at site 4; *Cynanchum acutum*, *Frankenia pulverulenta*, and *Solanum nigrum* at site 3; *Leucaena leucocephala* and *Heliotropium bacciferum* at site 1; *Hordeum murinum* and *Rumex spinosus* at site 5; and *Euphorbia granulata* and *Silene villosa* at site 6.

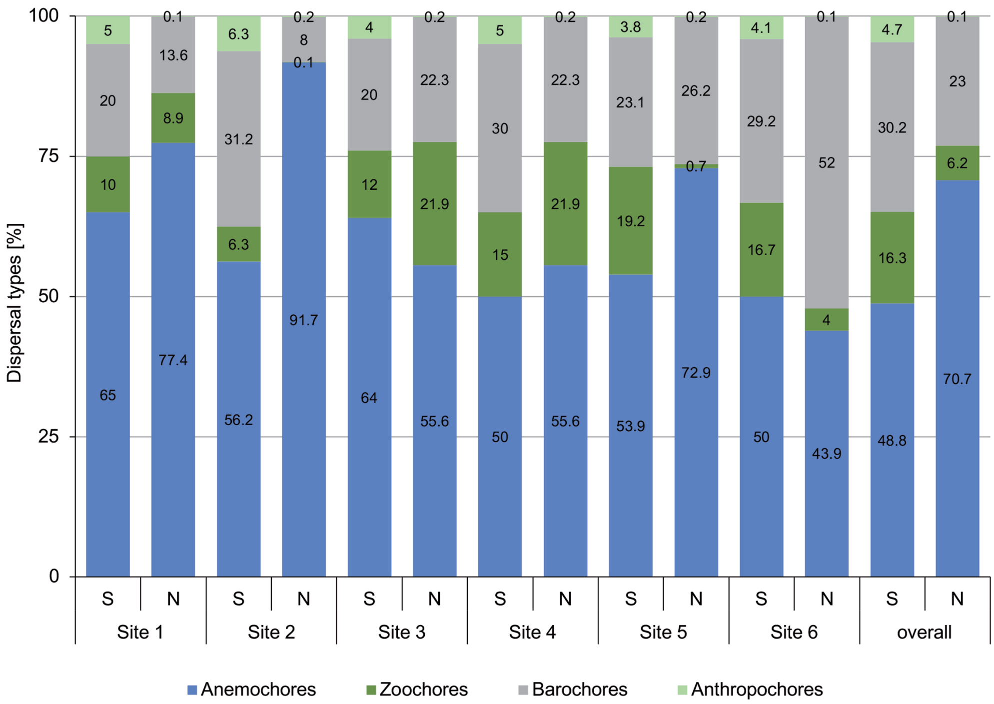

Fig. 8. Raw spectra (based on species richness, *S*) and real spectra (based on abundance, *N*) of plant dispersal types at the study sites

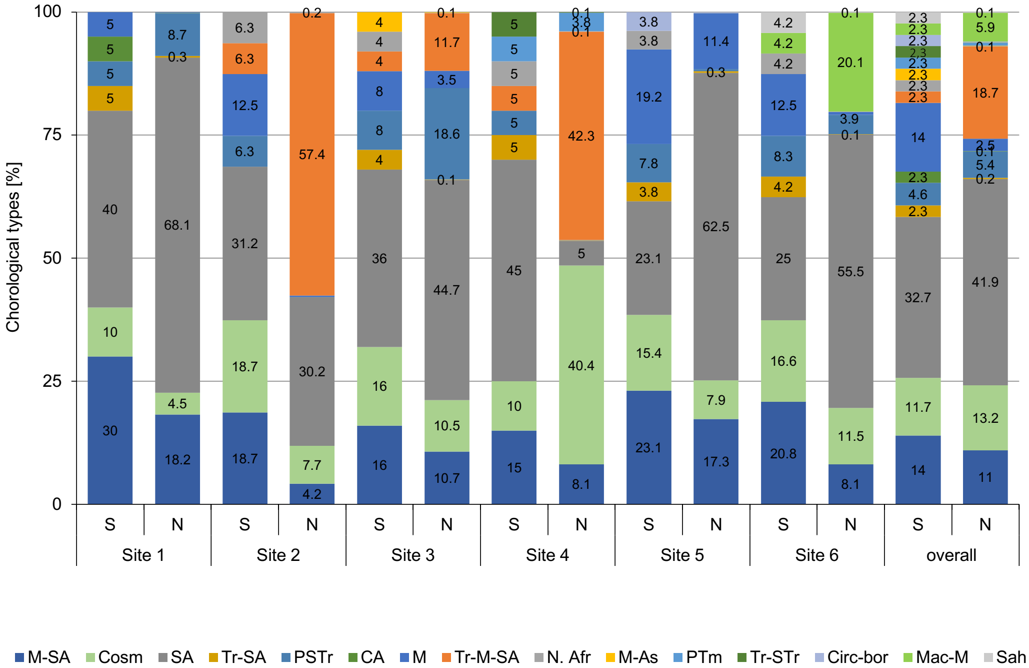

Fig. 9. Raw spectra (based on species richness, *S*) and real spectra (based on abundance, *N*) of chorological types of plants at the study sites

3.3. Functional traits

Except for the real spectrum of sites 2 and 4, dominated by hemicryptophytes (74% and 83% of species, respectively), as well as site 6, dominated by chamaephytes (55%) compared to other biological types (Fig. 6), at the other sites and at the level of the study area, the raw and real spectra show high values of therophytes, with percentages over 35%. Phanerophytes are poorly represented at all the study sites.

The raw spectrum of sites 1, 5, 6, and the study area indicates a good representation of annual species, but sites 3 and 4 are dominated by perennials, with values over 50%. As for the real spectrum, sites 1, 3, and 5

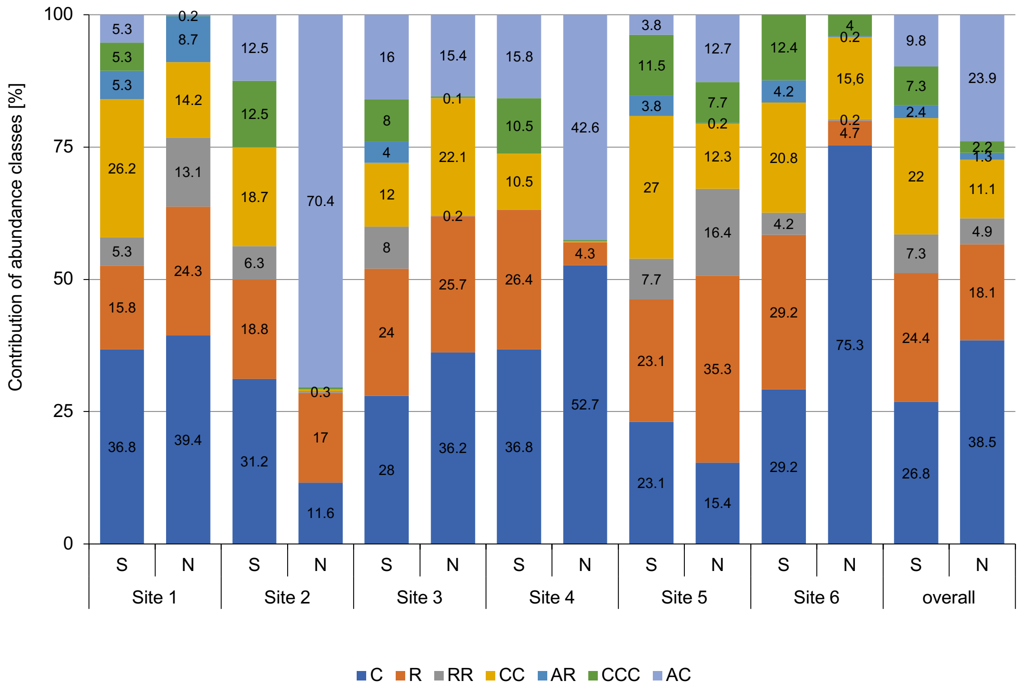

Fig. 10. Raw spectra (based on species richness, *S*) and real spectra (based on abundance, *N*) of plant abundance classes at the study sites

are dominated by annuals, while perennials prevail at sites 2, 4, 6, and the study area, with values over 40% (Fig. 7).

The results of raw spectra for individual sites and the whole study area show a dominance of anemochorous species, with values over 48% (Fig. 8). Concerning the real spectra, anemochore species dominate at all sites and in the study area (with values of 55-91%), except for site 6, where barochores rank first (52%). Anthropochore species are poorly represented at all sites.

A high contribution of the Saharo-Arabian element was recorded at nearly all the study sites and on average in the study area, in both the raw and real spectrum (Fig. 9). It is represented with values over 23%, except for the real spectra of sites 2 and 4, which are dominated by the Tropical-Mediterranean-Saharo-Arabian element (found only at sites 2, 3, and 4).

The plant species of the study sites are distributed among 7 classes of abundance (AC – fairly common; C – common; CC – very common; CCC – particularly common; AR – fairly rare; R – rare, RR – very rare), while class RRR (extremely rare)is not represented (Fig. 10). Classes C, CC, CCC, and R were recorded at all sites; AC at sites 1, 2, 3, 4, and 5; AR at sites 3, 5, and 6 (represented by only one species, *Phalaris minor*), and RR at sites 1, 2, 3, 5, and 6.

4. Discussion

The composition of the flora is dominated by the family Poaceae, which can be explained by its strategies of resistance to different disturbances (Breman & De Ridder 1991). These results are similar to previous findings on the diversity of flora and vegetation in the Algerian Sahara (Bradai *et al*. 2015; Bouallala *et al.* 2020; Azizi *et al*. 2021; Souddi & Bouallala 2022, 2023).The Asteraceae are the second best-represented family in the Algerian flora (Quézel 1964). These families seem well adapted to the aridity of the environment (Ozenda 2004). Bouallala *et al*. (2020) explain the differences observed in the floristic composition between sites by the micro-environmental conditions of each site (soil properties, micro-climate, sand level, duration of submersion).

The analysis of life-form spectra shows that therophytes are the most represented. The high number of therophytes indicates the high xericity of the study area. This is confirmed by the very high temperatures and low precipitation – accelerating evapotranspiration, which has a negative impact on plants (Fall 2014). Comparable life-form compositions have been recorded in previous studies of arid zones (Bouallala *et al*. 2020; Souddi & Bouallala 2022). Hemicryptophytes are also well represented, demonstrating the opportunistic life strategies necessary to survive in this extreme environment (El-Saied *et al*. 2015). Danin (1996) suggests that the high hemicryptophyte rate in sandy dune ecosystems is associated with their resistance to grazing, sand accumulation, and drought. Hemicryptophytes are characteristic of high-disturbance environments (Bonnet *et al*. 1999; Hamada *et al*. 2004). Therophytes and hemicryptophytes are considered to be favoured by disturbances caused by animals (Vidal 1998). The presence of chamaephytes confirms their good adaptation to the ecological conditions of hyper-arid environments through the development of specific strategies (Azizi *et al*. 2021; Souddi & Bouallala 2022; Merchala *et al*. 2023). Phanerophytes are poorly represented. The low percentage of recorded phanerophytes is consistent with results of studies of plant diversity in Saharan environments (Bouallala *et al*. 2020; Souddi & Bouallala 2023).

The morphological spectra show that annuals are the most represented. This can be attributed to their short life cycle, which allows them to resist the instability of the ecosystem (Gomaa 2012). These results are similar to previous findings in arid regions (Neffar *et al*. 2013; Al-Shehabi & Murphy 2017; Bouallala *et al*. 2020). The presence of perennial species can be explained by morphological and anatomical adaptive strategies, which consist mainly of an increase in the absorbing system and a reduction in the evaporating surface, allowing them to survive for varying periods, depending on the degree of disturbance (Ozenda 2004).

Anemochores and barochores are the dominant groups. The high proportion of anemochorous species can be explained by the characteristics of the diasporas that are easily transported by wind (Bradai *et al*. 2015; Bouallala *et al.* 2020; Souddi & Bouallala 2023). The dispersal of barochorous species is due to gravity and their multiplication capacity (Abdourhamane *et al*. 2017). The presence of many zoochorous species can be explained by the large number of animals involved in the functioning of ecosystems in hot arid zones (Bradai *et al*. 2015). These animals transport and disperse the diaspores during their movements between different sites and during their search for water (Souddi & Bouallala 2023). Finally, the presence of anthropochorous species, with low percentages, is related to a low level of anthropogenic activity.

The dominance of the Saharo-Arabian element in the study area indicates its adaptation to the hyper-arid environment (El-Sheikh *et al*. 2021; Souddi & Bouallala 2022). According to Abd El-Ghani and Amer (2003), the Saharo-Arabian species are good indicators of the quality of desert environmental conditions. The presence of the Tropical-Mediterranean-Saharo-Arabian element is due to the climatic modifications in the Mediterranean region since the Miocene, which caused migrations of tropical and extratropical flora (Quézel 1983).

The analysis of plant abundance classes shows that the common, very common, particularly common, and rare speciesare present at all sites with varying percentages. On the other hand, the fairly common, fairly rare, and very rare species are present at some sites. The co-existence and abundance of plants in the Algerian Sahara can be strongly influenced by environmental factors: climate, soil geomorphology, and anthropogenic action (Ozenda 2004; Bouallala *et al*. 2020; Azizi *et al*. 2021). Human impact causes the degradation of the plant cover and, consequently, the extinction of some species. To preserve this rare and vulnerable flora, specific management measures are necessary (Azizi *et al*. 2021).

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