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Structural Adaptation of *Deverra tortuosa* (Desf.) DC. to Its Natural Habitats in Egypt

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DEVERRA tortuosa (Desf.) DC. is a common medicinal, grazing, and salt-tolerant desert plant that can grow in a variety of habitats. The current study aims to detect anatomical adaptation to stress factors in different organs of the D.tortuosa plant (salinity, and drought). The plant was collected in Egypt from 17 different locations representing seven different habitats (sand dunes, sand flats, salt marshes, wadi bed & slope, roadsides and cultivated lands). The effect of soil factors (soil texture, pH, EC, and organic matter) on the anatomical features of various plant organs (root, stem, and leaf) was investigated. Variations in plant anatomical features were observed in response to significant differences in soil parameters (EC, organic carbon, and ionic content) between desert habitats. According to CCA analysis, periderm thickness is correlated with changes in ion concentrations (Ca^{+2}, K^{+}, and Na^{+}), whereas cortex width is correlated with changes in pH and organic matter content in roots. Meanwhile, the degree of salinity in the habitats is correlated with sclerification in the stem and the widest chlorenchyma cells. Thick epidermis and a large xylem area are required for salt excretion in leaf development, and water conservation is related to changes in moisture content. Reducing plant water loss in the studied desert habitats could explain D. tortuosa's successful growth and survival under such harsh conditions.

Keywords: Anatomical adaptation, *Deverra tortuosa,* Drought, Edaphic factors, Natural habitats, Salinity.

Introduction

Egypt is located in arid and semi-arid regions, so its natural plant cover is patchy and sparse. Climate change is constant in arid and semi-arid regions, causing desertification processes that have severe consequences for wild plants (El-Morsy & Ahmed, 2010). Egypt has a semi-arid climate with hot, dry summers and mild winters with little rainfall. Annual precipitation in Egypt ranges from about 200mm in the northern coastal region to about 50-100mm in the Nile Delta region, and nearly zero in the south (Agrawala et al., 2004).

Plants in their natural habitats can be subjected to a variety of environmental stresses, such as drought, low or high temperature, and salinity. These environmental factors cause secondary physiological adaptation, such as osmotic and oxidative changes, which are harmful to plants and cause changes in their proper growth, development, and metabolism (Bohnert et al., 1995). These mechanisms and features enable plants to withstand adverse conditions and are frequently visible in plant morpho-anatomical features (Ashraf & Harris, 2013). Ecological factors such as water relations and soil parameters (physical and chemical properties) have a significant impact on plant morphology and anatomy. When exposed to environmental stresses, plants' physiology and/or anatomy may change (Muniz et al., 2018).

According to Abd Elhalim et al. (2016), the leaves and stems of *Zygophyllum album* and

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Nitraria retusa are covered by a thick cuticle layer to avoid adverse moisture limited conditions. According to Huang et al. (1997), the presence of Sclerenchyma tissue in the stem phloem of *Ceratoides lateens* and *Peganum harmala* helps them avoid damage caused by high temperature, intense radiation, and drought. As a result of increasing salinity in its habitats, Naz et al. (2013) concluded that roots of *Aeluropus lagopoides* (L.) Trin. ex Thw. have an increase in aerenchyma tissue formation, sclerenchyma tissues in cortical layers, and an increase in the density of the trichmes formed on both surfaces of its leaves.

The presence of sclerenchyma tissue with thick-walled cells, which increases mechanical strength, distinguishes the genus *Deverra* (Batanouny, 2001). *Deverra* roots can reach a depth of 5 metres in wadis, which are characterised by wet soil layers (Walter & Breckle, 2013). *D. tortuosa* (Apiaceae) is also known as “Shabat El-Gabal.” It is found in almost all of Egypt’s phytogeographical regions, particularly desert wadis and sandy and stony plains (Täckholm, 1974; Boulos, 2002). It is a fragrant glabrous shrub with dichotomously branched stems and striate caducus leaves (Bolous, 2009). In addition to its uses as fuelwood, food, and medicinal and aromatic properties, the plant is highly palatable to livestock, particularly camels (Bedair et al., 2020). During the summer, it is considered an important range plant. Its shoots are used as a condiment and to treat asthma and intestinal cramps (El-Seedi et al., 2013). The plant’s essential oil is also an important source of antibiotics against some pathogenic microorganisms (Azzazi et al., 2015). The current study aims to detect anatomical adaptation in different organs of the *D. tortuosa* plant to multiple stress factors (high temperature, salinity, and drought) in various Egyptian habitats.

Material and Methods

Plant collection and preparation for anatomy

D. tortuosa aerial parts and roots were collected from seventeen different locations in Egypt (along the North-Western Coast, Western and Eastern deserts) to represent the most variations of the seven habitats: (sand dunes, sand flats, salt marshes, wadi, roadsides and cultivated lands). Wadis include slops and beds, as well as cultivated lands such as fig, olive, and barely fields. (Fig..1 and Table1) in the springs of 2015 and 2016.

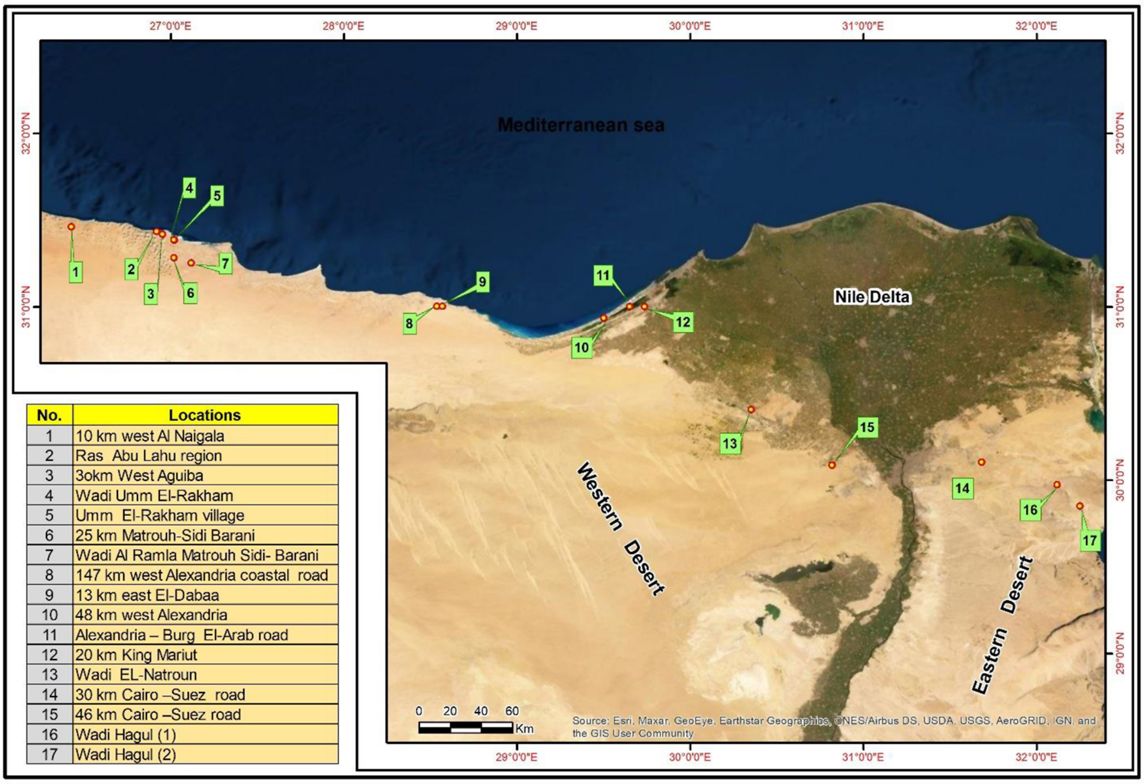

Fig. 1. Locations recorded for *Deverra tortousa* (Desf.) DC. in Egypt (Google Earth)

TABLE 1. Localities, habitats and GPS data of collected *Deverra tortuosa*(Desf.) DC. in Egypt

No.	Locality	Habitat	Coordinates
1	10 km west Al NaigalaMatrouh –Sallum road	Fig field	N 31 27 449, E 26 25 323, Alt: 86m
2	Ras AbuLahu region	Sand flat	N 31 26 346, E 26 55 649, Alt: 18m
3	Ras Abu Lahu, 3okm West Aguiba	Fig field	N 31 25755, E 2657 839, Alt: 37m
4	Wadi Umm El-Rakham	Wadi slope	N 31 23 919, E 27 01 102, Alt:18m
5	Umm El-Rakham village	Olive field	N 31 23 969, E 27 01910, Alt: 3m
6	25 km Matrouh-Sidi Barani	Barley field	N 31 17 300, E 27 01 571, Alt: 151m
7	Wadi Al RamlaMatrouh Sidi-Barani	Roadside	N 31 15 972, E 27 07 893, Alt: 120m
8	147 km west Alexandria coastal road	Fig field	N 31 00 905, E 28 33 573, Alt: 12m
9	Alexandria-Matrouh coastal–road, 13 km east El-Dabaa	Fig field	N 31 00 895, E 28 34 707, Alt: 22m
10	48 km west Alexandria	Sand dune	N 30 56 543, E 29 30 113, Alt: 20m
11	Alexandria – Burg El-Arab road	Salt marshe	N 31 00 631, E 29 39 200, Alt: 2m
12	20 km King Mariut - Burg Al-Arab road	Salt marshe	N 31 00 725, E 29 44 947, Alt: 34m
13	Wadi EL-Natroun- Cairo-Alexandria desert road	Sand flat	N 30 24 231, E 30 21 872, Alt: 49m
14	30 km Cairo –Suez road	Sand flat	N 30 06 538, E 31 41 118, Alt: 237m
15	46 km Cairo –Suez road	Sand flat	N 30 05 773, E 31 49 896, Alt: 230m
16	Wadi Hagul (1)	Wadi bed	N 29 58 261, E 32 07 991, Alt: 85m
17	Wadi Hagul (2)	Wadi bed	N 29 51 285, E 32 15 379, Alt: 97m

The plant was harvested during the flowering-fruiting stage and packed in polyethylene bags before being transported to the lab. The samples were washed with distilled water before being separated into root, stem (taken at 10-15cm from the base), and leaf. Formalin, glacial acetic acid, and ethyl alcohol were used to fix the separated parts (F.A.A.; 5: 5: 90). Specimens were embedded in paraffin wax after fixation, sectioned at 10-15 m, and stained with safranin and light green according to (Sass, 1961). The sections were examined and photographed under a light microscope by Olympus. According to Abd El-Gawad et al. (1989), a planimeter was used to estimate each tissue in the section area.

Soil analysis

From each studied location, three soil samples were collected from the root rhizosphere at 0–30 cm. The particle size of soil samples was determined mechanically using sieves (Jackson, 1967; Piper, 1950). According to Roweel (1994), soil salinity (mscm-1) was determined using an electrical conductivity metre (60 Sensor Operating Instruction Corning) and soil reaction was determined using a pH metre (Model 9107 BNORION type) according to Brower & Zar (1984). Roweel-style soil moisture determination (Roweel, 1994). The total nitrogen was calculated using the Kjeldahl method (James, 1995). Using ferrous ammonium sulphate, the organic carbon percentage was calculated (Tinsley, 1950). According to Rowell, the cations Na+ and K+ were determined using a flame photometer (PFP7, Genway) (1994). According to Xiandeng & Bradley (2000), Mg^{+2} and Ca^{+2} were determined using Inductivity Coupled Spectrometry Plasma (ICP) (Ultima2-Jobin Yvon), while P^{+3} was estimated using a spectrophotometer (Metertek sP-850) as in Allen (1989). According to Jackson, chloride (Cl^-) and total carbonates (CO_3^{-2}) were determined (Jackson, 1967). Roweel's law was used to determine soluble bicarbonates (HCO_3^-) (Rowell, 1994). Sulfate content was precipitated as barium sulfate according to the turbidimetric method using a spectrophotometer (MeterteksP-850) (Johnson &Nishita, 1952).

Data analysis

According to SPSS software, a one-way analysis of variance (ANOVA-1) was used to determine the significance variation in soil properties and different anatomical structure of different studied organs of D.tortuosa recorded in different habitats (mean multiple comparisons were performed according to Duncan's tests), and then testing the data for normality and homogeneity of variance (SPSS, 2006). Furthermore, the effects of various habitats on both roots and stems were evaluated using repeated measurement ANOVAs and SPSS 21.0 software (SPSS, 2006) and the relationship between the habitats, soil characteristics and root/ shoot/ leaf anatomical data was determined by Canonical Correspondence Analysis (CCA) according to terBraak (1987).

Results

Sampling and soil analysis

All soil characteristics studied (except K) differ significantly (at P 0.0001) between the seven habitats studied (Table 2). Sands predominate in all habitats, with the highest concentration found in sand dunes (98.9 %) and the lowest in wadi bed (69.64 %). Except for wadi slopes, roadsides, and cultivated lands, gravel was the second most common component; the sum of silt and clay was the third most common. The highest percentage of gravel was found in a wadi bed (24.27%), while the lowest was found in sand dunes (0.86%). Furthermore, the highest value of the sum of silt and clay was found in cultivated lands (9.11%), while the lowest was found in sand dunes (0.72%).

Sand dunes have the highest values of bicarbonates (8.6mg $100g^{-1}$) and the lowest values of pH (7.5), EC (0.2ms/cm), K (0.01mg $100g^{-1}$), Mg (2.5mg 100 g^{-1}), SO_4 (0.014mg $100g^{-1}$) and Cl^- (0.3mg 100 g^{-1}), while sand flats have highest contents of P^{+3} (0.22mg 100 g^{-1}) and SO_4^{-2} (0.05mg $100g^{-1}$) and lower total content in carbonate (4.5mg $100g^{-1}$). Salt marshes have highest EC (0.54 ms/cm) and Mg^{+2} (5.5mg 100 g^{-1}), but lower pH (7.5) and moisture content (0.58%). Wadi slopes have highest contents in organic carbon (0.6 %) and total CO_3^{-2} (5.65mg $100g^{-1}$), but lower Ca^{+2} (1.8mg $100g^{-1}$) and SO_4^{-2} (0.014mg $100g^{-1}$), while wadi beds have highest values in moisture (6.23 %) and Ca^{+2} (3.3mg $100g^{-1}$), but lower N^{+2} (0.02%), Na^+ (0.035mg $100g^{-1}$), P^{+3} (0.03mg $100g^{-1}$) and SO_4^{-2} (0.014mg $100g^{-1}$). Road sides have highest records in N^{+2} (0.23%) and Cl^- (1.0mg $100g^{-1}$), but lower O.C (0.16%) and HCO_3^- (3.5mg $100g^{-1}$), while cultivated lands have highest pH (7.8), Na^+ (4.2mg $100g^{-1}$) and K^+ (0.21mg $100g^{-1}$) outlined in Table 2.

Anatomical results

Root anatomy

Secondary growth is represented in *D. tortuosa* roots collected from different habitats (Fig. 2). The outermost layers formed periderm, the periderm layer width ranged from 125µm and 300µm in wadi slopes and salt marshes habitat, respectively (Table 3, Fig. 2). Tanniniferous ducts randomly distributed in periderm. The periderm is followed by the cortical thin-walled, elliptical or polygonal parenchyma cells. The narrowest cortex width recorded in sand dunes habitat 288µm, while the widest in wadi slope habitat 650µm (Table 3, Fig 2). The vascular tissues are arranged in a compact vascular cylinder interrupted by narrow medullary rays. The thinnest phloem arch thickness found in sand dunes habitat 56µm, while the widest in wadi slopes habitat 125µm (Table 3, Fig 2). Xylem tissue represented mostly by fibers, narrow rows of xylem ray. Xylem arch length ranges from 346µm to 1016µm in the habitat of wadi beds and sand flats, respectively. The narrowest width of vessels found in sand flats specimens 28µm and the widest in roadsides 82µm (Table 3, Fig. 2). Pith is mostly absent in all sectors of different habitats and only represented as parenchymatous cells in sand flats and roadsides. All measured anatomical characters are highly significantly different (at P ≤0.0001) between habitats (Table 3).

TABLE 2. Soil characters supporting growth of *Deverra tortuosa* (Desf.) DC. collected from different habitats in Egypt (Mean±SE)

Soil characters		Habitat							*F*- value
		Sand dunes	Sand flats	Salt marshes	Wadi slope	Wadi bed	Road sides	Cultivated lands	
Gravel	(%)	0.86 ± 0.10e	5.44 ± 0.57c	11.7 ± 0.81b	4.11 ± 0.24d	24.27 ± 0.69a	5.93 ± 0.31c	5.22±0.56c	123.5*
Sand	(%)	98.9 ± 0.75a	90.1± 0.86b	80.19 ± 0.5d	89.92 ± 0.69c	69.64 ± 0.56e	90.63 ± 0.45b	85.67 ±0.8c	243.1*
Silt+clay	(%)	0.72 ± 0.01f	4.34 ± 0.37e	8.1 ± 0.56c	7.14 ± 0.28d	7.59 ± 0.24c	8.44 ± 0.69b	9.11±0.44a	12.3*
Moisture	(%)	0.7 ± 0.012d	2.6 ± 0.12b	0.58 ± 0.06f	0.9 ± 0.01c	6.23 ± 0.07a	0.63 ± 0.017e	0.61 ± 0.05e	898.3*
N	(%)	0.12 ± 0.035c	0.22 ± 0.02a	0.2 ± 0.0034b	0.03 ± 0.00028d	0.02 ± 0.0023d	0.23 ± 0.0086a	0.11 ± 0.0057c	209.1*
O.C	(%)	0.31 ± 0.023d	0.23 ± 0.0058e	0.44 ± 0.01b	0.6 ± 0.01a	0.37 ± 0.02c	0.16 ± 0.0080f	0.33 ± 0.01d	219.4*
pH		7.5 ± 0.0028c	7.64 ± 0.0092b	7.5 ± 0.01c	7.75 ± 0.0086a	7.8 ± 0.0098a	7.54 ± 0.02c	7.8 ± 0.017a	32.3*
EC (mS/cm)		0.2 ± 0.00115f	0.42 ± 0.0012b	0.54 ± 0.00057a	0.26 ± 0.000057e	0.2 ± 0.00028f	0.39 ± 0.000057c	0.34 ± 0.00057d	456.2*
Na	mg/100g	0.21 ± 0.05c	0.18 ± 0.0029cd	0.39 ± 0.02b	0.15 ± 0.0028d	0.035 ± 0.0034e	0.37 ± 0.0028b	4.2 ± 0.0034a	417.1*
K	mg/100g	0.01 ± 0.028a	0.1 ± 0.0029ab	0.06 ± 0.0041ab	0.08 ± 0.004b	0.02±0.0023ab	0.2 ± 0.0028ab	0.21 ± 0.0034ab	1.4 ns
Mg	mg/100g	2.5 ± 0.028g	5.4 ± 0.28b	5.5 ± 0.34a	3.8 ± 0.17d	4.4±0.75c	3.2 ± 0.43f	3.4 ± 0.46e	168.8*
Ca	mg/100g	2.3 ± 0.17e	2.8 ± 0.23c	3.2 ± 0.28b	1.8± 0.16 f	3.3±0.28a	3.0 ± 0.28b	2.5 ± 0.34d	138.2*
P	mg/100g	0.04 ±0.00046e	0.22 ± 0.00029a	0.09 ± 0.0023d	0.07 ± 0.00057d	0.03±0.0051e	0.2 ± 0.004b	0.13 ± 0.04c	159.4*
Cl	mg/100g	0.3 ± 0.04f	0.7 ± 0.02c	0.9 ± 0.017b	0.6 ± 0.017d	0.4±0.01e	1.0 ± 0.023a	0.7 ± 0.02c	141.6*
HCO_3	mg/100g	8.6 ± 0.051a	7.6 ± 0.1b	3.8 ± 0.046f	5.6 ± 0.051d	4.6±0.046e	3.5 ± 0.05g	7.5 ± 0.04c	681.2*
CO_3	mg/100g	5.6 ± 0.02b	4.5 ± 0.51f	5.1 ± 0.46e	5.65 ± 0.023a	5.5±0.23c	5.46 ± 0.86d	5.5 ± 0.04c	289.1*
SO_4	mg/100g	0.014 ± 0.00012e	0.05 ± 0.000057a	0.031± 0.00057b	0.014 ± 0.00011e	0.014±0.00057e	0.023 ± 0.0011c	0.016±0.00057d	935.7*

Maximum and minimum values are underlined.

E.C: Electrical conductivity, and O.C: Organic carbon.

* P ≤0.0001, ns: Not significant

Means in the same line followed by different letters are significantly different at P<0.05 according to Duncan's multiple range test.

TABLE 3. Root anatomical measurements (μm) of *Deverra tortuosa* (Desf.) DC. collected from different habitats in Egypt (Mean±SE)

Root character	Habitat						
	Sand dunes	Sand flats	Salt marshes	Wadi slope	Wadi bed	Road sides	Cultivated lands
Periderm width	223 ± 11.5f	299 ± 8.9b	300 ± 3.2a	125 ± 1.8g	231.5 ± 8.1e	295 ± 9.0c	273 ± 22.3d
Cortex width	288 ± 13.1g	385 ± 18.6f	648 ± 6.9b	650 ± 19.8a	488 ± 12.8e	505 ± 19.2c	442 ± 12.0c
Phloem width	56 ± 0.5f	102 ± 9.9d	119 ± 2.5b	125 ± 1.7a	104 ± 4.4d	98 ± 8.4e	109 ± 7.4c
Xylem arch length	548 ± 18.5c	1016 ± 29.1a	522 ± 12.7d	372 ± 7.2f	346 ± 2.5g	660 ± 20.3b	435 ± 19.6e
Vessel diameter	44 ± 3.1d	28 ± 0.2f	51 ± 1.9c	59 ± 2.5b	42 ± 2.8e	82 ± 7.3a	55 ± 3.3c

n= 3. Maximum and minimum values are underlined.
All anatomical characters are highly significantly different at P ≤0.0001between habitats.
Means in the same line followed by different letters are significantly different at P<0.05 according to Duncan's multiple range test.

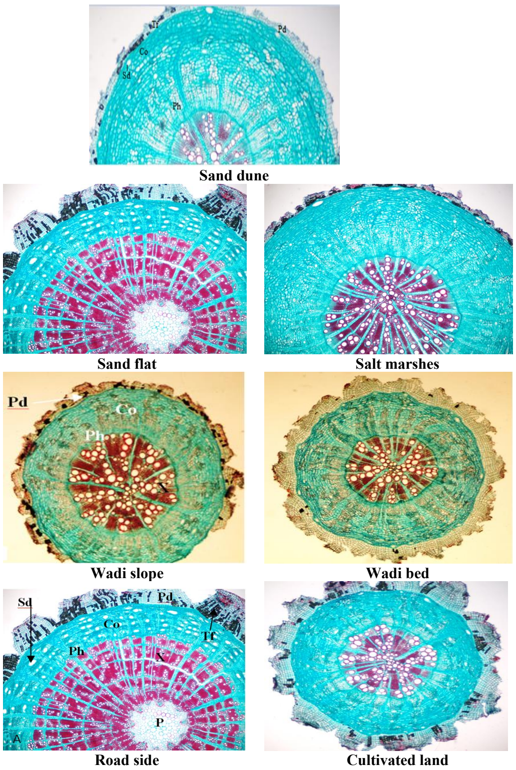

Fig. 2. Rootscross-section of *Deverra tortuosa* (Desf.) DC. collected from different habitats in Egypt [Pd (Periderm), Co (Cortex), Sd (Secretory ducts), Ph (Phloem), X (Xylem), P (Pith) and Tf (tanniniferous cells). Magnification= 10X]

Stem anatomy

The stem outline of *D. tortuosa* in all studied habitats is cylindrical, wavy, and glabrous; the epidermis is uni-layered, with cells covered by a thin layer of cuticle (Fig. 3). In wadi slopes and sand dunes, the cuticle thickness ranges from 11µm to 18µm, respectively (Table 4, Fig 3). Epidermal cells are tangentially arranged and tetragonal in shape, with thicknesses ranging from (16.6–22.9µm). The cortex is divided into three tissues: Collenchyma, chlorenchyma, and sclerenchyma. Collenchyma consists of two rows of oval or rounded cells. The cultivated lands habitat has the narrowest collenchyma width records at 14µm, while the sand dunes habitat has the widest at 26µm (Table 4, Fig. 3). Chlorenchyma cells are palisade in shape and consist of 3-4 rows; the narrowest chlorenchyma measures in roadside 129µm and the widest measures in wadi bed 160µm. Scelerenchyma alternates with chlorenchyma and the narrowest scelerenchyma width found in wadi bed 142µm and the widest in road sides 170µm. Secretory ducts represented in cortex facing the phloem; the diameter of secretory ducts is variable and ranges from 38µm -55µm in sand dunes and wadi bed habitats, respectively (Table 4, Fig. 3).

Vascular bundles are represented by discrete medullary rays; the main vascular bundles alternate with small secondary vascular bundles formed by interfascicular cambium. The main vascular bundle in cultivated land ranges from 28 to 34 in salt marsh habitats (Table 4, Fig. 3). The width of the phloem varies from 37µm in sand dunes to 60µm on a wadi slope. The cambium is distinguished by 2-6 layers and varies in width from 22µm in sand dunes to 40µm in sand flats. The shortest main xylem arch is 58µm long and the longest is 123µm long in a wadi slope. The narrowest xylem vessel width is 22µm in sand dunes and the widest is 31µm in sand flats and cultivated land habitats. Pith is parenchyma with its cells containing some solitary and druses crystals. The narrowest pith diameter find in salt marshes 825µm and the widest measure in cultivated land habitats 1700µm and its cells are polygonal in shape. There are tanniniferous elements distributed randomly in the epidermis, cortex, and pith (Fig. 3). Cystolith crystals are represented only in specimens collected from wadis and roadsides. All anatomical characters measured were highly significantly different (at P≤ 0.0001) between habitats (Table 4).

Leaf anatomy

Plants with leaves collected only from 5 habitats (sand dunes, sand flats, saltmarshes, wadi beds and cultivated lands) and all anatomical characters measured were highly significantly different (at P≤ 0.0001) between habitats (Table 5). The leaves are crescent-shape and dorsiventral in the cross-section. Both upper and lower epidermis uni-layered with glabrous compact thin-walled cells, the upper epidermis thickness found in wadi beds 12µm, while the widest ones recorded in salt marshes 20µm (Fig. 4). The lower epidermis cells vary from 16-22µm in thickness, cover with thick cuticles and interrupted with sunken stomata. The cutin layer ranges from 8µm -19µm in sand dunes and sandflats; respectively. Both upper and lower epidermis followed by one or two layers of oval collenchyma cells; the collenchyma measured in wadi beds 42µm and sandflats 75µm, while width of collenchyma arch ranged from 42µm (wadi beds) to 52µm (salt marshes). Mesophyll tissue is represented by parenchyma and palisade tissue. Parenchyma cells are hexagonal and its width was from 116µm (salt marshes) to 216µm (sand dunes and sand flats) (Table 5, Fig. 4).

The lower epidermis is followed by two layers of chlorophyllous palisade tissue, its width was from 58 µm (wadi beds) to 87µm (sand dunes). The number of vascular bundle ranges from 10 in wadi beds to 16 in sandflats; the smallest length of xylem arch found in sand dunes habitat 21µm and the maximum length found in wadi beds habitat 35µm. The phloem width was from 25 m (saltmarshes) to 40µm (sandflats) habitat. The secretary ducts are distributed with the vascular bundles, the diameter of secretary ducts measures 26 µm in salt marshes to 39µm in sanddunes habitats. Solitary crystals and tanniniferous cells are distributed randomly in the lower epidermis and mesophyll tissue.

TABLE 4. Stem anatomical measurements (µm) of *Deverra tortuosa* (Desf.) DC. collected from different habitats in Egypt (Mean±SE)

Stem characters (µm)		Habitat						
		Sand dunes	Sand flats	Salt marshes	Wadi slope	Wadi bed	Road sides	Cultivated lands
Cuticle width		18±0.66a	16±0.07c	17±0.74b	11±0.37e	13±0.055d	14±2.2c	13±0.7d
Epidermis width		22.9± 1.2a	18 ±.3d	18±0.53d	17±0.77e	19±0.75.5c	20±2.5b	16.6±0.4e
Collenchyma width	Cortex	26±0.44a	22±12.3b	21±1.3c	20±0.5d	21±1.7c	20±1.5d	14±0.5e
Palisade width	Cortex	147±12.3b	149±2.4b	134±0.98e	144±3.4c	160±11a	129±3.2f	141±5.4d
Fiber width	Cortex	160±11.1c	159±3.4	145±2.4	148±3.7	142±0.33	170±3.3	148±3.7
No. secretory ducts		33±2.6b	33±12b	34±0.8a	29±1.4d	30±1.7c	33±1.5b	28±1.2d
Diameter of secretory ducts		38±2.2e	47±15.15d	39±0.89	54±1.4b	55±1.9a	50±2.2c	41±0.8e
No. Vascular bundles		33±0.98b	33±2.5b	34±0.77a	29±0.32d	30±1.8c	33±1.4b	28±1.2e
Phloem width		37±1.5f	44±6.5d	43±2.6d	60±2.5a	57±2.2b	40±2.2e	46±4.4c
Cambium width		22±0.66f	40±2.6a	27±0.75e	38±0.098b	32±3.2d	33±1.6c	32±3.2d
Xylem arch length		86±2.5e	107±14.5c	82±2.8f	123±1.11a	114±2.7b	58±1.5g	108±2.3d
Vessel diameter		22±0.44e	31±2.7a	26±0.87d	26±0.98d	30±0.97b	28±1.3c	31±1.2a
Pith diameter		1300±55.8c	1475±55.7b	825±33.6f	1200±66.4d	1150±44.8e	1190±12.2e	1700 ±6.8a

n= 3. Maximum and minimum values are underlined.

All anatomical characters are highly significantly different at P ≤0.0001between habitats.

Means in the same line followed by different letters are significantly different at P<0.05 according to Duncan's multiple range test.

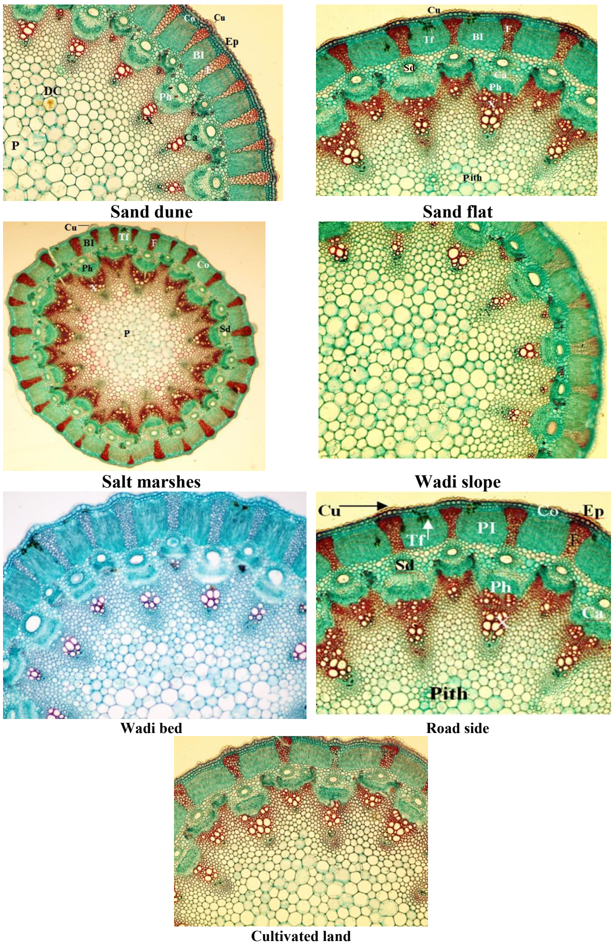

Fig. 3. Stem cross-section in *Deverra tortuosa* (Desf.) DC. collected from different habitats in Egypt [Cu (Cutin), Ep (Epidermis), Co (Collenchyma), PI (Palisade tissue), F (Fibers), Sd (Secretory ducts), Ph (Phloem), Ca (Cambium), X (Xylem), P (Pith), Tf (Tanniniferous cells), DC. Druses crystal. Magnification = 10X]

TABLE 5. Leaf anatomical measurements (µm) of *Deverra tortuosa* (Desf.) DC. leaf collected from different habitats in Egypt (Mean±SE)

Leaf characters (µm)		Habitat				
		Sand dunes	Sand flats	Salt marshes	Wadi bed	Cultivated lands
Upper epidermis width		13±0.07c	15±0.4b	20±0.6a	12±0.5d	15±0.3b
Parenchyma tissue width		216±8.6a	216±11.1a	116±1.6d	157±7.7c	185±7.6b
Xylem	Number	12±0.4b	16±0.4a	11±0.2c	10±0.3d	11±0.8c
	Xylem arch length	21±0.07d	32±0.5b	27±0.4c	35±0.05a	27±0.7c
	Vessel diameter	12±0.3b	9±0.15d	11±0.4c	12±0.33b	13±0.4a
Phloem width		34±0.4c	40±0.08a	25±0.4e	32±0.5d	38±0.6b
Secretory ducts	Number	11±0.8c	12±0.22b	11±0.9c	10±1.1d	16±0.3a
	Diameter	39±0.4a	32±0.4c	26±0.67d	34±0.7b	39±0.5a
Collenchyma arch		45±0.5d	51±1.6b	52±0.53a	42±0.43e	48±1.2c
Palisade tissue width		87±0.8a	80±2.5b	62±1.6c	58±0.9d	64±3.3c
Lower collenchyma width		67±1.4b	75±2.2a	61±2.5c	42±1.8e	53±3.1d
Epidermis lower width		16±0.9d	22±1.4a	19±1.4b	19±0.66b	17±1.3c
Lower cuticle width		8±0.5e	19±0.06a	9±0.09d	14±0.6b	13±0.6c

n= 3. Maximum and minimum values are underlined.

All anatomical characters are highly significantly different at P ≤0.0001between habitats.

Means in the same line followed by different letters are significantly different at P<0.05 according to Duncan's multiple range test.

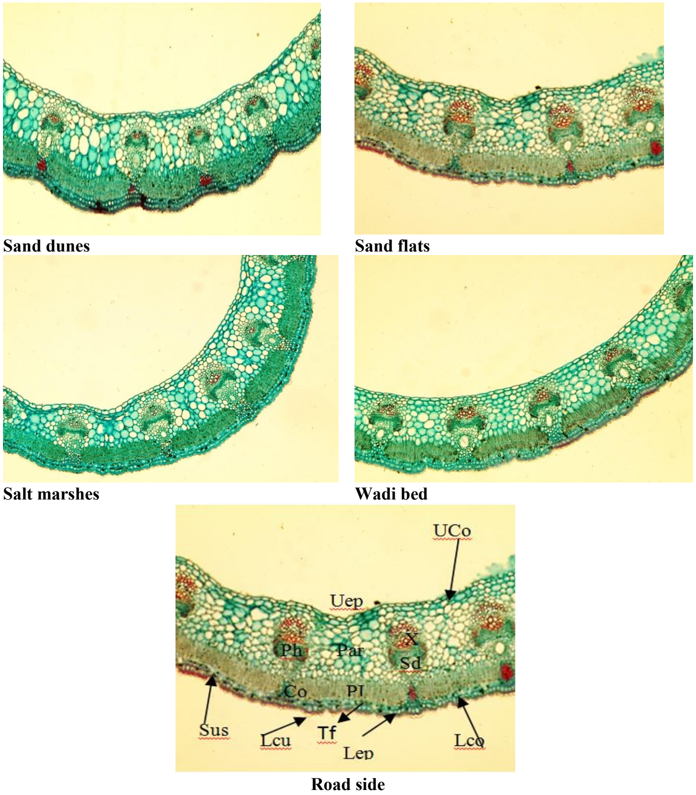

Fig. 4. Leaf cross-section in *Deverra tortuosa* (Desf.) DC. collected from different habitats in Egypt [Uep (Upper epidermis), UCo (Upper Collenchyma), Par (Parenchyma), X (Xylem), Ph (Phloem), Sd (Secretory ducts), PI (Palisade tissue), Co (Collenchyma arch), Lco (Lower collenchyma), Lep (Lower epidermis), Lcu (Lower cuticle), Sus (Sunken stomata) and Tf (Tanniniferous cells). Magnification = 10X]

In the present study epidermis and cortex width are highly significantly different ($P< 0.05$) between plant organs (root, stem and leaf) and is highly significantly different ($P< 0.001$) as result of the interaction between two factors (plant organs and habitats). Xylem (xylem arch length and Vessel diameter) is highly significantly different ($P<0.001$) between habitats but is significantly different ($P< 0.05$) between plant organs. At the same time,the phloem width is significantly different ($P< 0.05$) between plant organs (Table 6).

Soil-anatomical relationship

The soil characters and root/shoot/leaf anatomical characters resulted from the application of CCA indicated that root; cortex and phloem widthes are the most affected with pH and organic carbon content, while xylem arch length is the most affected with salinity, sand percentage, SO_4^{2}, P^{+3} and HCO_3^- concentrations, while xylem vessel diameter is affected by the sum of silt and clay content and carbonate concentration. The periderm width is affected by the mineral concentration (Ca^{+2} and K^+) (Fig. 5). In stem, cortex width is affected by salinity and sand percentage, xylem arch length is affected by changes in pH and organic carbon concentration, xylem vessel diameter and phloem width are affected by the percentage of gravel and amount of silt and clay (Fig. 6). In leaf; epidermis width, xylem vessel diameter and xylem arch length are affected by soil texture and moisture content (Fig. 7).

Discussion

In Egypt, *D. tortuosa* has been observed in a variety of habitats (Shaltout et al., 2015). It was collected from seven habitats in Egypt (sand dunes, sand flats, salt marshes, wadis (bed and slope), roadside, and cultivated lands) in three phytogeographical regions (North-Western Mediterranean Coast, Western and Eastern desert). Desert plant species are able to withstand extreme environmental conditions such as water scarcity, stress, and salinity, resulting in changes in their anatomy and morphology. These changes are examples of plant adaptations that increase a plant's ability to withstand various environmental stresses (Poljakoff et al., 1975)

TABLE 6. Results of repeated measurement ANOVA (F values) of anatomical measurements of different plant organ recorded in different habitats in Egypt

Effect	*df*	Epidermis width	Cortex width	Xylem		Phloem width
				Xylem arch length	Vessel diameter	
Habitat	6	818.5^{ns}	10392.6^{ns}	20364.0^{***}	122.3^{***}	355.1^{ns}
Plant organ	2	123.4^{*}	68067.9^{*}	599855.9^{*}	2071.9^{*}	8624.2^{*}
Habitat x plant organ	9	34457.4^{***}	18127.1^{***}	24244.6^{ns}	111.9^{ns}	186.9^{ns}

* P <0.05, ** P<0.01, *** P<0.001, ns not significant (i.e., P> 0.05 insignificant)

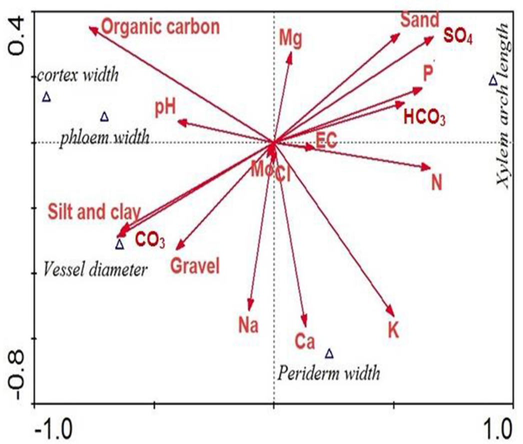

Fig. 5. Canonical correspondence analysis (CCA) biplot of the root anatomical characters in different habitats (represented by triangles) and habitats soil characters (represented by arrows) of *Deverra tortuosa* (Desf.) DC. [Mo: moisture percentage]

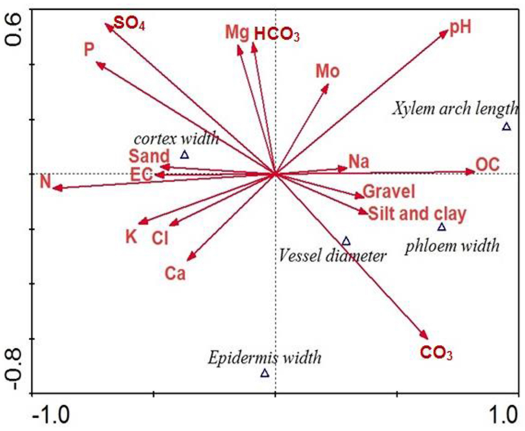

Fig. 6. Canonical correspondence analysis (CCA) biplot of the stem anatomical characters in different habitats (represented by triangles) and habitats soil characters (represented by arrows) of *Deverra tortuosa* (Desf.) DC. [Mo: moisture percentage and OC: organic carbon]

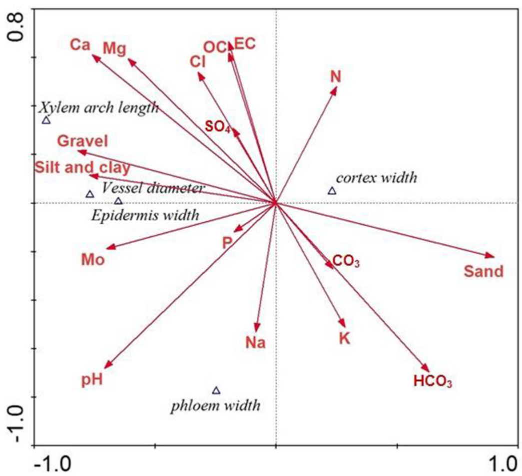

Fig. 7 Canonical correspondence analysis (CCA) biplot of the leaf anatomical characters in different habitats (represented by triangles) and habitats soil characters (represented by arrows) of *Deverra tortuosa* (Desf.) DC. [Mo: moisture percentage and OC: organic carbon]

In present study, sand dunes and sand flats have the highest values of bicarbonates and phosphore and sulphate respectively. This may be a result of urbanization and building of new summer resorts along the Mediterranean coast and quarrying of the stony ridges to make granite bricks (Shaltout & Ahmed, 2012). Also, the agricultural habitats in the wadis have the highest organic carbon, moisture, Ca^{+2} and CO_3^{-2} contents. While roadsides have the comparatively high concentrations of Mg^{+2}, P^{+3}, Ca^{+2}, CO_3^{-2}, HCO_3^{-}, SO_4^{-2}, N^{+2} and Cl^{-}. Ali (2018) reported that soil of urban habitats as roadsides was characterized by a high concentration of calcium carbonate, Nitrogen and sulfate.

Deverra tortuosa is a desert plant exhibits anatomical adaptation, at the root level, the specimens inhabiting salt marshes are characterized by thick periderm and wide cortex. From CCA analysis, it was clear that the thickness of periderm is correlated with the change in the concentration of salts (Ca^{+2}, K^{+} and Na^{+}), while cortex width is correlated with the change in pH and organic matter content. According to Grigore & Toma (2007), the presence of phellem tissue in the old root may delay water absorption, and salts hardly penetrate through the root and spread within the enlarged surface. The increased root surface area provides a larger dispersion area for salts, where they are diluted and become less harmful to the plant.

Under low moisture conditions, Abdel & Al-Rawi (2011) found that increasing root area, particularly cortical thickness, increased root area. This discovery coincides with the salt marsh soil having the lowest moisture percentage (0.58 percent) (Table 2). Reduced xylem area, especially under high salinity and drought stress, was a critical adaptation, as it was characterised by narrower and longer vessels, reducing damage caused by an embolism (Kondoh et al., 2006). This finding is coincide with the result (Table 3) that specimens collected from sand flats and sand dunes are characterized by narrower xylem vessels and long xylem arch length embedded in lignified cells, and may be as a result of increasing in soil salt contents of (P^{+3}, HCO_3^{-}, CO_3^{-2} and SO_4^{-2}) beside the drought conditions (low moisture percentage). According to Abd Elhalim et al. (2016), the xylem vessels of the old roots of Zygophyllum and Nitraria are embedding in fibre tissues, which is a mechanism that aids in the protection of water columns from embolism. According to Jacobsen et al. (2005), the presence of fibres around vessels contributes to cavitation resistance. Specimens collected from Wadis, roadside, and cultivated lands, on the other hand, have thin periderm, narrow cortex, and large xylem vessel diameter.

The widest sclerenchyma tissue in stems is found in salt marsh specimens (with highest EC). Increased soil salinity causes sclerification in the stem cortex, which is referred to as physiological drought (Naz et al., 2013). Abd Elbar et al. (2012) discovered an increase in sclerenchyma tissue in the stems and leaves of *Leptochloa fusca* growing in high salinity conditions, which would provide rigidity to these organs. Sclerenchyma in *Ceratoides lateens* and Paganum harmala stems is useful for phloem to avoid drought damage, according to Huang et al. (1997).

Scholz et al. (2007) discovered that larger chlorenchyma cells can efficiently store water in harsh dry environments. This finding is consistent with our findings for *D. tortuosa* stem, which show that plant specimens collected from dry habitats (road sides, sand dunes, and sand flats) have the widest chlorenchyma cells and have low moisture contents (0.63%, 0.7%, and 0.9%), respectively (Table 2). The presence of palisade shape chlorenchyma in the stem cortex indicated that the stem is the primary photosynthetic organ, which could be another adaptation to arid conditions due to the absence or reduction of leaves under these conditions (El-shourbagy et al., 1991).

Another important adaptation of the stem to the arid and saline environments in which the plant can grow is an increase in the area of the vascular bundle (xylem and phloem) (Awasthi & Pathak, 1999). This finding lends support to the findings (Table 3, Fig. 3) that vascular tissue increased in more stressed habitats (sand flats, salt marshes, wadi beds and roadsides). Abd Elbar et al. (2012) discovered that increasing the salinity levels increased the number of vascular bundles in Leptochloa fusca stem, which compensated for the reduction of xylem and phloem areas in the vascular bundles.

The presence of solitary and drusy crystals in the cortex and pith suggests that calcium ions are involved in increasing salt tolerance in various ways. Plants produce calcium oxalate, which serves as a high-capacity calcium (Ca) regulator and a defence against herbivory (Franceschi & Nakata, 2005). According to Brown et al. (2013), both aridity and soil calcium concentration play important roles in the precipitation of CaOx in Acacia sect. Juliflorae (Benth.), and the distribution and accumulation of CaOx crystals is related to climate.

According to Barhoumi et al. (2007), an increase in epidermis thickness could be caused by high salinity, drought, or physiological drought. The epidermis width and xylem vessel diameter are correlated with a change in moisture in the current study, with specimens collected from salt marshes and sand flats having the widest epidermis in response to high salinity and low moisture, which agrees with Jianjing et al. (2012) who reported that these are features of desert plants as an adaptation to salinity-induced physiological drought. Excess salts are transported to excretory salt structures (secretory ducts) and excreted from the plant body (Cutler et al., 2007).

Conclusion

Deverra tortuosa (Desf.) DC. is a common medicinal plant that can grow in a variety of habitats in Egypt. The plant is subjected to a number of environmental stresses, including drought and high salinity. Salt marsh habitats with low moisture content and high EC value represent the most adaptation characteristics for *D. tortuosa* because the root has a high periderm area and its width is affected by mineral concentration (Ca^{+2} and K^{+}) and cortex and phloem widths are most affected by pH, while xylem arch length is most affected by salinity. Salinity influences the width of the stem's sclerenchyma tissue and the width of the cortex. As a result of the plant's lack or reduction of leaves, palisade-shaped chlorenchyma is considered the primary photosynthetic organ. Soil texture and moisture content influence epidermis width, xylem vessel diameter, and xylem arch length in the leaf.

Conflicts of interest: No conflicts of interest have been declared.

Authors contribution: All authors contribute equally in this work.

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التكيف التركيبي لنبات شبت الجبل في بيئاته الطبيعية في مصر.

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نبات شبت الجبل هو نبات طبي ورعوي شائع الإنتشار وهو من النباتات الصحراوية التي تتحمل الملوحة وله القدرة علي النمو في البيئات المختلفة. تهدف الدراسة الحالية إلى تعيين التكيفات التركيبية في أعضاء نبات شبت الجبل المختلفة للعديد من العوامل البيئية (الملوحة – الجفاف). تم تجميع النبات من سبعة عشر موقعاً مختلفا تمثل سبع بيئات مختلفة في مصرهي: الكثبان الرملية - المسطحات الرملية - المستنقعات الملحية - الوديان - جوانب الطرق -والأراضي الزراعية. تم دراسة تأثير عوامل التربة (قوام التربة - تركيز أيون الهيدروجين - درجة الملوحة -والمادة العضوية) علي التركيب التشريحي لأجزاء النبات المختلفة (الجذر - الساق - الورقة). تم تعيين الاختلافات للسمات التشريحية للنبات وفقاً لللاختلافات الكبيرة لخصائص التربة وخاصة درجة الملوحة والكربون العضوي والمحتوي الأيوني للبيئات الصحراوية المختلفة. باستخدام تحليل الكانوكو بواسطة CCA، وجدأنه في جذر النبات يوجد ارتباط بين سمك طبقة البريدرم وتركيز بعض الأملاح مثل الكالسيوم والبوتاسيوم والصوديوم،وأيضاً بين سمك طبقة القشرة والتغيرفي تركيز أيون الهيدروجين ومحتوى المادة العضوية. بينما في تركيب الساق كان هناك زيادة في نسبة ألياف الاسكلرنشيما بالأضافة إلى زيادة اتساع خلايا كلورنشيما عند زيادة نسبة الملوحة في البيئات المختلفة. أما بالنسبة لتركيب الورقة كان هناك زيادة في سمك طبقة البشرة واتساع مساحة الخشب وذلك للتخلص من الأملاح الزائدة والإحتفاظ بالماء مرتبطاً بالتغير في محتوي الرطوبة. إن اختزال كمية الماء التي يفقدها النبات في البيئات الصحراوية المختلفة التي تتميز بدرجة الملوحة العالية وانخفاض الرطوبة وقلة المواد الغذائية هو ما قد يوضح قدرة نبات شبت الجبل علي تحمل تلك الظروف القاسية في بيئاته الطبيعية.