Taxonomic implications of micro-morphological features for taxon delimitation within the *Quercus libani* complex (*Fagaceae*) in Iran

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Abstract. *Quercus libani* is the main oak species in the northern Zagros Forests of Iran. The morphological characters of this species show high variation, which is the reason why it has previously been split into up to 12 different species, which commonly are very difficult to determine because of the lack of morphological characters clearly distinguishing them. This paper examines the micro-morphological characteristics of leaves and pollen grains of the *Q. libani* complex using scanning electron microscopy (SEM). A Multivariate Discriminant Analysis was applied to micro-morphological quantitative and qualitative features. Five entities were recognized corresponding to various earlier described species.

Key words: Intraspecific variability, micro-morphological characteristics, Multivariate Discriminant Analysis, pollen, *Quercus libani*, SEM, taxonomy

Introduction

Members of the genus *Quercus* L. (*Fagaceae*) have a wide geographical range, which occupies vast territories of the Northern Hemisphere in North America, Europe and Asia (Camus 1936-54; Schwarz 1936-39; Manos & al. 2001; Borazan & Babaç 2003; Naryshkina & Evstigneeva 2009; Denk & Grimm 2010). Several taxonomic groups within the genus *Quercus* are noted for their complex patterns of variation, which causes difficulties for identification of taxa at the species level (Bacilieri & al. 1996). Thus the infrageneric classification of *Quercus* has been subject to considerable changes (Ørsted 1871; Camus 1936–1954; Schwarz 1936, 1936–1939; Menitsky 1984).

Quercus is the most diverse genus of *Fagaceae* in the forests of Iran (Sabeti 1976). Several oak species grow abundantly in the Zagros, Arasbaran and Hyrcanian Forests displaying remarkable morphological variation. All oak species of Iran belong to the subgenus *Quercus* and two sections: sect. *Quercus* and sect. *Cerris* (Menitsky 1971). During the study of *Quercus* species of the Zagros Mountain we have been confronted with the complex taxonomic situation within *Q. libani* Oliv. s.l. The populations that belong to *Q. libani* are restricted to the northern Zagros Forests in western Iran. The taxonomy of taxa within the *Q. libani* complex has been dealt with by many authors (Parsa 1949; Bobek 1951; Djavanchir Khoie 1967; Menit-

sky 1971; Sabeti 1976). These authors have focused on leaf and acorn morphology in the recognition of taxa. The morphological characters of these taxa show high variation. According to Parsa in *Flore de l`Iran* (1949), two taxa, including *Q. libani* and *Q. libani* Oliv. var. *vesca* (Kotschy) Boiss., were recognized for the Zagros Mountain. Two years later Bobek (1951) reported only *Q. libani* from these forests. The most comprehensive study of *Quercus* in Iran was carried out by Djavanchir Khoie in *Les Chênes de l`Iran* (1967). He considered 12 taxa within the *Q. libani* complex, of which ten species are endemic to Iran (*Q. apiculata* Djav.-Khoie, *Q. carduchorum* K.Koch, *Q. hedjazii* Djav.-Khoie, *Q. irregularis* Djav.-Khoie, *Q. libani*, *Q. magnosquamata* Djav.-Khoie, *Q. ophiosquamata* Djav.-Khoie, *Q. ovicarpa* Djav.-Khoie, *Q. polynervata* Djav.-Khoie, *Q. scalaridentata* Djav.-Khoie, *Q. subcordata* Djav.-Khoie, *Q. tregubovii* Djav.-Khoie). Despite this account, most of the taxa recognized by Djavanchir Khoie (1967) are still enigmatic to taxonomists, because the characters of leaf and acorn morphology that were used so far as distinguishing features are highly variable and cannot be applied easily to determine the species within this complex. Other taxonomic treatments of *Q. libani* s. l. are carried out by Menitsky in *Flora Iranica* (1971), who recognized only *Q. libani* in this group, and Sabeti (1976), who recognized five taxa within the complex, including *Q. carduchorum*, *Q. libani*, *Q. magnosquamata*, *Q. ovicarpa,* and *Q. polynervata*. Since 1976, there has been no comprehensive taxonomic study of this complex. Since new collections from the distribution area of *Q. libani* in Iran are available and new reports about the conservation status of oak species in the Zagros Mountain are currently being compiled, a comprehensive taxonomic study is urgently needed for evaluation of the intraspecific entities.

Among the numerous taxonomic studies of *Quercus* of special importance are those that have used the characteristic features of leaves (e.g. trichomes, epicuticular waxes and stomata) (Dyal 1936; Saenz de Rivas 1968, 1969; Saenz de Rivas & Rivas Matínez 1971; Hardin 1976, 1979a, b; Kissling 1977, 1980a, b; Bačić 1981; Uzunova & Palamarev 1985, 1992a, b, 1993; Llamas & al. 1995; Bussotti & Grossoni 1997; Uzunova & al. 1997; Fortini & al. 2009; Tschan & Denk, 2012). Furthermore, the analysis of pollen morphology has proved to be of some help in this respect, both with the light and the scanning electron microscopy (Van Campo & Elhai 1956; Monoszon 1962; Smit 1973; Colombo & al. 1983; Solomon, 1983a, b; Médus & Gonzalez Flores 1984; Scareli-Santos & al. 2007; Denk & Grimm 2009; Naryshkina & Evstigneeva 2009).

In the present research project, we have thoroughly surveyed the habitats of genus *Quercus* in the forests of Iran, investigating the distribution patterns, population structure and ecological conditions. Furthermore, we reviewed this genus with emphasis on the leaf and pollen grain micro-morphological characteristics (Panahi & al. 2011, 2012a, b). Here we are reporting the results of our work on the *Q. libani* complex. In the course of this research we carried out a detailed comparative characterization of foliar and pollen grain micro-morphological characters in the Iranian populations of the *Q. libani* complex, in order to evaluate the taxonomic significance of these characters and to define a binary key that can be used for identification of the intraspecific taxa within this complex. A Multivariate Discriminant Analysis was also performed on 12 entities in the complex to define the morphological groups.

Material and methods

Mature leaves and male inflorescences were collected fresh from locations throughout the geographical range of the *Q. libani* complex in the northern Zagros Forests. Each taxon was sampled from ten individuals. Specimens were selected to ensure the broadest possible representation of the known extent of range and habitats of the taxa. The collected samples were dried under room temperature and preserved as herbarium sheets. Vouchers are deposited in the herbarium of the Research Institute of Forests and Rangelands of Iran (TARI). Additional herbarium materials were examined at TARI and the herbarium of the Natural Resources Faculty, University of Tehran. Some of the voucher specimens of this study are listed in Table 1.

Leaf samples measuring about 10 mm^2 were removed from the surface midway between the base and apex, midvein and margin and were mounted directly on aluminum stubs using double-side adhesive tape. Pollen obtained from herbarium specimens was acetolysed after a standard method described by Erdtman (1969) and modified by Harley (1992), and prepared for light (LM) and scanning electron microscopy (SEM). Slides for LM were studied with an Olympus microscope under a ×100 lens. Measurements were tak-

en from 50 grains, systematically scanning the slide for each examined taxon. The mean, range and standard deviation (SD) were calculated for polar axis (P) and equatorial diameter (E). The ratio of polar axis to equatorial diameter (P/E) was provided as an index of pollen shape (Faegri & Iversen 1964). For SEM, pollen and leaf specimens were sputter-coated with gold palladium for 5 minutes in a Humer II Sputtering Device and observations were performed using a Hitachi (S-4160) SEM and Leo SEM-440I at an accelerating voltage of 10–15 kv. SEM micrographs were used mainly for studying the overall shape, type of sculpturing, and to get more detailed information on the structural, sculptural and suprasculptural patterns of pollen grains. In the case of leaves, epidermal structures such as trichome types, number of trichome rays, length of trichome rays, dimension and location of stomata and type of epicuticular wax were studied by SEM.

Quantitative micro-morphological variables of leaves and pollen grains were scored and analyzed by the discriminant analysis method to differentiate the examined taxa by multivariate measurements. Trichome nomenclature follows the one proposed by Hardin (1976, 1979a). Epicuticular waxes and stomata were classified following Safou & Saint-Martin (1989) and Barthlott & al. (1998). Terminology used for pollen shapes and features followed Erdtman (1952), Halbritter & al. (2006) and Hesse & al. (2009).

Table 1. List of species and the collection data.

Taxon	Collection data
Q. apiculata Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, 2030a (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2030b (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2030c (NRF) Kurdistan: Baneh, Armardeh road, Neyzehroud village, 1606 m, Panahi and Pourhashemi, 91416 (TARI) Kurdistan: Baneh, Belakeh village, Djavanchir, no number (NRF)
Q. carduchorum K.Koch	Kurdistan: Marivan, Owraman road, Djavanchir, 2032 (NRF) Kurdistan: 9 km from Baneh to Armardeh, 1630 m, Panahi and Pourhashemi, 91439 (TARI) Kurdistan: 9 km from Baneh to Armardeh, 1640 m, Panahi and Pourhashemi, 91441 (TARI) Kurdistan: 9 km from Baneh to Armardeh, 1630 m, Panahi and Pourhashemi, 91442 (TARI) Kurdistan: 11 km from Baneh to Armardeh, 1730 m, Panahi and Pourhashemi, 95032 (TARI)
Q. hedjazii Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, 2040b (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2040k (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2040l (NRF) Kurdistan: 11 km from Baneh to Armardeh, 1727 m, Panahi and Pourhashemi, 95033 (TARI) West Azerbaijan: Sardasht, Mirabad, Molla Allah Cemetery, 1425 m, Panahi and Pourhashemi, 95054 (TARI)
Q. irregularis Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, no number (NRF) Kurdistan: Baneh, Belakeh village, Djavanchir, no number (NRF) Kurdistan: Baneh-Saqqez road, Pass of Khan, 1856 m, Panahi and Pourhashemi, 95064 (TARI) Kurdistan: 11 km from Baneh to Armardeh, 1732 m, Panahi and Pourhashemi, 95029 (TARI) West Azerbaijan: Sardasht, Mirabad, 1410 m, Panahi and Pourhashemi, 95056 (TARI)
Q. libani Oliv.	Kurdistan: Baneh, Belakeh road, Djavanchir, 2053p (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2053t (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2053r (NRF) Kurdistan: Baneh-Marivan road, Haji Abdol village, Haji Abdol Cemetery, 1878 m, Panahi and Pourhashemi, 95106 (TARI) West Azerbaijan: Sardasht, Mirabad, Molla Allah Cemetery, 1425 m, Panahi and Pourhashemi, 95053 (TARI)
Q. magnosquamata Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, 2048 (NRF) Kurdistan: Baneh, Belakeh-Kandehsoureh road, Djavanchir, 2047c (NRF) Kurdistan: Marivan, Bayeveh, Djavanchir, 2046a (NRF) Kurdistan: Marivan, Chenareh, Djavanchir, 2057g (NRF) Kurdistan: 9 km from Baneh to Armardeh, 1630 m, Panahi and Pourhashemi, 91440 (TARI)
Q. ophiosquamata Djav.-Khoie	Kurdistan: Baneh, Armardeh road, Djavanchir, 2059 (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, no number (NRF) Kurdistan: Baneh, Armardeh road, Neyzehroud village, 1590 m, Panahi and Pourhashemi, 91443 (TARI) Kurdistan: Baneh-Sardasht road, Zervar village, 1509 m, Panahi and Pourhashemi, 91406 (TARI) Kurdistan: 11 km from Baneh to Armardeh, 1732 m, Panahi and Pourhashemi, 95030 (TARI)
Q. ovicarpa Djav.-Khoie	Kurdistan: Baneh, Mojassah village, 1647 m, Panahi and Pourhashemi, 95071 (TARI) Kurdistan: Baneh-Saqqez road, Pass of Khan, 1856 m, Panahi and Pourhashemi, 95063 (TARI) Kurdistan: Baneh-Sardasht road, Djavanchir, no number (NRF) West Azerbaijan: Piranshahr, Perdaneh, 1298 m, Panahi and Pourhashemi, 95041 (TARI) West Azerbaijan: Sardasht, Mirabad, 1410 m, Panahi and Pourhashemi, 95058 (TARI)

Table 1. Continuation.

Q. polynervata Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, no number (NRF) Kurdistan: Baneh, Belakeh road, 1700 m, Djavanchir, 2071 (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2071c (NRF) Kurdistan: Baneh, Belakeh, Djavanchir, 2071d (NRF) Kurdistan: Baneh, Belakeh, 1420 m, Panahi and Pourhashemi, 91410 (TARI)
Q. scalaridentata Djav.-Khoie	Kurdistan: Marivan, Chenareh, Djavanchir, 2075b (NRF) Kurdistan: Marivan, Chenareh, Djavanchir, 2075c (NRF) Kurdistan: Marivan, Chenareh, Djavanchir, 2075d (NRF) Kurdistan: Baneh, Armardeh road, Neyzehroud village, 1707 m, Panahi and Pourhashemi, 91418 (TARI) Kurdistan: 22 km from Baneh to Belakeh, 1739 m, Panahi and Pourhashemi, 91413 (TARI)
Q. subcordata Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, no number (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, no number (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, no number (NRF) Kurdistan: Baneh, Armardeh road, Neyzehroud village, 1606 m, Panahi and Pourhashemi, 91446 (TARI) West Azerbaijan: Sardasht, Mirabad, 1410 m, Panahi and Pourhashemi, 95059 (TARI)
Q. tregubovii Djav.-Khoie	Kurdistan: Baneh, Belakeh road, Djavanchir, 2076p (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2076q (NRF) Kurdistan: Baneh, Belakeh road, Djavanchir, 2076l (NRF) Kurdistan: Baneh, Belakeh road, 1620 m, Djavanchir, 2076s (NRF) Kurdistan: Baneh, Armardeh road, Kocher Cemetery, 1707 m, Panahi and Pourhashemi, 95024 (TARI)

Results

Epidermal characteristics

Trichomes

In the studied taxa, trichomes were present on the abaxial surface or on both surfaces of leaves, but trichome density and variability were more abundant on the abaxial leaf surface. The differences of trichome types on the abaxial and adaxial surfaces of different entities are summarized in Table 2. We have identified four different trichome types as follows:

Simple-uniseriate type, that is thin-walled, multicellular and uniseriate, with different length diameter. This type was observed on the abaxial surface in all studied taxa and only on the adaxial surface of *Q. carduchorum*.

Solitary type, that is single, long, usually straight and unicellular, often thin-walled. This trichome type was commonly observed on the midrib of all studied taxa.

Fasciculate type, that is erect, with thick-walled cells, clustered and fused at the base. We have found this trichome type on the edge of the midrib in all studied taxa.

Stellate type, usually thick-walled, with a single set of radiating, slender rays, projecting horizontally from a common center, sessile or stipitate. This trichome is the most abundant type in all examined taxa. We found both sessile (e.g. *Q. libani*) and stipitate (e.g. *Q. apiculata*) trichomes among the examined specimens.

Table 2. Trichome types of the studied entities.

Entity	Trichome types			
	Simple-uniseriate	Solitary	Fasciculate	Stellate
Q. apiculata	–/+	–/+	–/+	–/+
Q. carduchorum	+/+	–/+	–/+	+/+
Q. libani	–/+	–/+	–/+	–/+
Q. magnosquamata	–/+	–/+	–/+	+/+
Q. ophiosquamata	–/+	–/+	–/+	–/+

Adaxial surface/Abaxial surface. – = absent, + = present.

Epicuticular wax

Only one type of epicuticular wax, of smooth layer, was recognized on the abaxial and adaxial surfaces in the *Q. libani* complex. Epicuticular wax forms an amorphous layer.

Stomata

Stomata were elliptical in outline in all examined taxa. They were raised above the epidermal surface in all examined taxa, except in *Q. magnosquamata* in which the guard cells were at the same level with the surrounding epidermal cells. The rims of stomata were entirely covered by epicuticular wax of the smooth-layer type, but the pore was visible in all taxa.

Pollen characteristics

Details of the quantitative features of polar axis, equatorial diameter and P/E of pollen grains are presented in Table 3. The morphology of pollen grains is similar among the studied taxa and is characterized as follows: type single, isopolar, apertures tricolporate, colpi of medium length, oblate-spheroidal in shape. The main surface features of the investigated pollen grains are subdivided into structural patterns (assumed expressions of exine structure exposed at the tectum surface) that may be scabrate, rugulate, rugulate-striate, and rugulate-verrucate; sculptural patterns (projections superimposed upon the tectum surface) which include verrucae of different sizes; and suprasculptural patterns (superimposed upon sculptural features) which include microstriate and microverrucate ornamentation.

Table 3. Details of pollen grains of the studied entities.

Entity	Shape	Polar axis		Equatorial diameter		P/E
		Mean (μm) ± SD	Range (μm)	Mean (μm) ± SD	Range (μm)	
Q. apiculata	Oblate-spheroidal	31.4±2.3	28–36.8	32.6±2.4	27.2–38.6	0.96
Q. carduchorum	Oblate-spheroidal	28.9±1.3	26.4–31.2	31.6±1.6	28–34.4	0.92
Q. libani	Oblate-spheroidal	29.7±2.3	24–34.4	31.5±1.9	28–36	0.94
Q. magnosquamata	Oblate-spheroidal	27.6±1.1	24–32	30.8±1.8	27.2–34.8	0.90
Q. ophiosquamata	Oblate-spheroidal	26.6±1.4	32.2–28.8	29.8±1.5	27.2–32.8	0.90

Discriminant analysis of the studied taxa

Descriptive statistics of micro-morphological variables is shown in Table 4. Scatter plots of the discriminant function results are presented in Fig. 1. Altogether, nine canonical functions have been separated, the first two functions describing 85.7 % of the total variance (Tab. 5). The structure matrix of canonical functions indicates that the length and number of stellate rays on the adaxial surface contribute most to discriminant function 1. This function includes 59.3 % of the total variance. The length and number of stellate rays on the abaxial surface are the greatest contributors to segregation along function 2 (Tab. 6). This function represents another 26.4 % of the total variance.

As it can be seen from the canonical graph (Fig. 1), some taxa form clusters owing to high similarity among them. On the basis of the results of discriminant analysis, leaf and acorn morphological characters and qualitative characters of the pollen grains, the studied taxa are classified into five distinct groups (entities), as follows:

– Group 1: *Quercus libani*, *Q. hedjazii*, *Q. polynervata*, *Q. ovicarpa*, *Q. subcordata*, *Q. tregubovii* and *Q. irregularis*
– Group 2: *Quercus apiculata*
– Group 3: *Quercus carduchorum*
– Group 4: *Quercus magnosquamata*, *Q. scalaridentata*
– Group 5: *Quercus ophiosquamata*

The new grouping shows 88.6 % correct identification. Discriminant function 1 most effectively separates *Q. libani* from *Q. carduchorum* and *Q. magnosquamata*. Also, discriminant function 1 separates *Q. apiculata* and *Q. ophiosquamata* from *Q. libani*, but isolation is incomplete.

Table 4. Descriptive statistics of trichomes and stomata of the studied entities.

Entity	NStR-AbS	NStR-AdS	LStR-AbS (μm)	LStR-AdS (μm)	LFaR-AbS (μm)
Q. apiculata	4–8	---	(74–) 111.1±8.9 (–168)	---	(120–) 211.6±15.1 (–337)
Q. carduchorum	4–8	4–8	(74–) 101±7.1 (–155)	(95–) 144±8.3 (–171)	(70–) 99.2±6.8 (–149)
Q. libani	4–8	---	(51–) 86.4±6.9 (–152)	---	(120–) 204.2±20.3 (–311)
Q. magnosquamata	4–11	4–8	(63–) 95±11.2 (–121)	(67–) 99.5±4.6 (–147)	(111–) 147.4±12.6 (–200)
*Q. ophiosquam*ata	4–8	---	(82–) 127.3±15 (–210)	---	(153–) 200.8±18.5 (–251)

Note. NStR-AbS: number of stellate rays on abaxial surface; **NStR-AdS**: number of stellate rays on adaxial surface; **LStR-AbS**: length of stellate rays on abaxial surface; **LStR-AdS**: length of stellate rays on adaxial surface; **LFaR-AbS**: length of fasciculate rays on abaxial surface; **LSoR-AbS**: length of solitary rays on abaxial surface; **LSt**: Length of stomata; **WSt**: width of stomata; **L/W-R-St**: length/width ratio of stomata.

Table 4. Continuation .

Entity	LSoR-AbS (µm)	LSt (µm)	WSt (µm)	L/W-R-St
Q. apiculata	(65–) 118.6±9 (–143)	25.7±1.7	18.5±1.3	1.4
Q. carduchorum	(119–) 231±18.4 (–384)	28.1±2.5	17.5±2.4	1.64
Q. libani	(117–) 273±15.1 (–351)	24.6±1.8	18±1.6	1.38
Q. magnosquamata	(103–) 167.8±12.8 (–235)	20.3±1.5	12.5±1	1.64
Q. ophiosquamata	(141–) 280±22.1 (–394)	25.8±1.8	17±1.8	1.54

Table 5. Summary of canonical discriminant functions.

Discriminat function [a]	Eigen value	% of variance	Cumulative (%)	Canonical correlation
1	23.723	59.3	59.3	0.980
2	10.550	26.4	85.7	0.956

[a] First two canonical discriminant functions were used in the analysis.

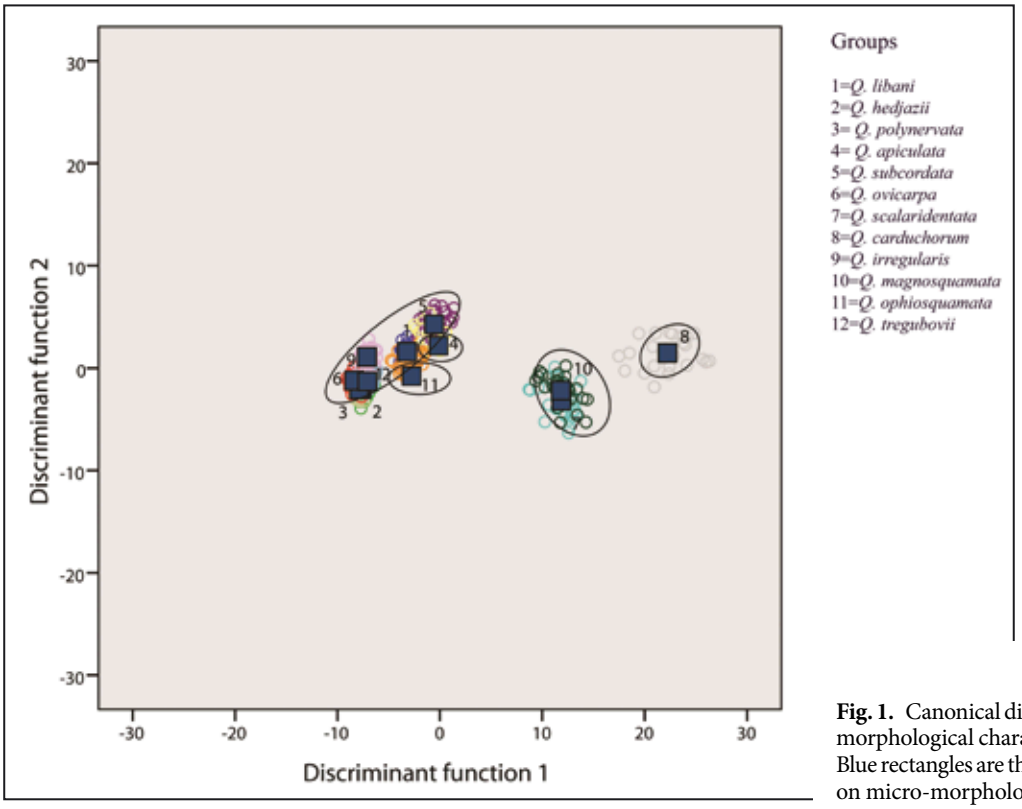

Fig. 1. Canonical discriminant functions of micro-morphological characters of the *Q. libani* complex. Blue rectangles are the centroids of each taxon based on micro-morphological variables analysis.

Table 6. Pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions.

Discriminat function	Variable								
	NStR-AbS	LStR-AbS	NStR-AdS	LStR-AdS	LSoR-AbS	LFaR-AbS	L/W-R-St	Po-L	Eq-D
1	0.162	0.087	0.617*	0.754*	0.142	–0.175	0.068	–0.070	–0.064
2	0.689*	0.693*	–0.141	–0.177	–0.120	0.162	0.005	0.157	0.136

* Largest absolute correlation between each variable and any discriminant function.

Description of taxa

Brief descriptions of the micro-morphological characters of the examined taxa, such as quantitative features of trichomes, stomata, wax and tectum surface of the pollen grains are presented below:

Q. apiculata Djav.-Khoie, Les Chênes de l`Iran, 55 (1967).

On the abaxial surface two forms of sparse stellate trichomes are observed: stipitate-stellate trichomes with 4–8 (commonly 8) rays (70–170 µm long); the rays are fused into an erect stipe and then diverged horizon-

tally. A few appressed sessile-stellate trichomes with 4 rays and lower density are observed on the midrib. Fasciculate trichomes with long rays (120–340 μm long) are found on the midrib edges. There are few solitary trichomes with medium-size rays (65–140 μm long) on the midrib. Simple-uniseriate trichomes are distributed sparsely among the stellate trichomes on the lamina. Density of trichomes on the abaxial surface is very low. No trichomes were observed on the adaxial surface.

The stomata are elliptical and the rim is completely covered with wax, but the pore is visible (Fig. 2A-C).

The shape of pollen grains is oblate-spheroidal. The structural pattern of the tectum surface is scabrate, with sparse micro-perforations that are regularly distributed. These pores are much smaller than 1 μm in diameter and correspond to the microchannels through the tectum, according to Rowley & Gabarayeva (2004). The sculptural elements are verrucae, with a diameter of 0.1–0.5 μm, regularly scattered on the tectum surface (Fig. 3A-D).

Q. carduchorum K.Koch, in Linnaea, 22: 320 (1849).

This entity is characterized by its dense indumentum consisting of different types of trichomes on both sides of the leaves. The density of trichomes is higher on the abaxial surface. Four types of trichomes are observed on the abaxial surface, including appressed stellate trichomes with 4–8 (commonly 6–8) rays measuring 70–155 μm, and fasciculate with 70–150 μm long rays that are fused together at the base near the midrib edges. Stellate trichomes are numerous, whereas fasciculate types are less abundant. A few simple-uniseriate trichomes are found on the lamina. Furthermore, solitary trichomes with medium to long-size rays (120–390 μm long) are observed on the midrib. On the midrib, solitary and stellate trichomes are frequently found. The most frequent trichome on the adaxial surface is of stellate type, with 4–8 rays (95–170 μm long). In *Q. carduchorum*, trichome density on the abaxial and adaxial surfaces is higher than in the other entities of this complex.

The stomata are elliptical and the rim is completely covered by wax (Fig. 2D-F).

The structural pattern of pollen is rugulate, with dense micro-perforations in the mesocolpium, which usually occur in grooves between the verrucae; the grooves are about 0.5 μm long. The sculptural protuberances, which occur on the tectum are verrucate, of different sizes. The suprasculpture is microverrucate to microstriate (Fig. 3E-H).

Q. libani Oliv., Voy. Emp. Ottoman, 2:290, Atlas: tab. 32 (1801).

Syn.: *Q. hedjazii* Djav.-Khoie, Les Chênes de l`Iran, 82 (1967); *Q. irregularis* Djav.-Khoie, Les Chênes de l`Iran, 85 (1967); *Q. ovicarpa* Djav.-Khoie, Les Chênes de l`Iran, 101 (1967); *Q. polynervata* Djav.-Khoie, Les Chênes de l`Iran, 105 (1967); *Q. subcordata* Djav.-Khoie, Les Chênes de l`Iran, 113 (1967); *Q. tregubovii* Djav.-Khoie, Les Chênes de l`Iran, 117 (1967).

In this entity no trichomes were observed on the adaxial surface, but a few sparsely distributed multicellular simple-uniseriate, solitary, fasciculate, and stellate trichomes were observed on the abaxial surface. The main trichomes are sessile-stellate, with 4–8 (commonly 6) rays (50–150 μm long), symmetric, completely flat on the lamina, and fasciculate with commonly four long rays (120–310 μm long). There are a few solitary hairs (115–350 μm long) on the midrib.

Both stomata and rim are clearly elliptical in shape. The stomata are easily visible because of the light tomentum. The stomatal rim is covered by a smooth layer of wax on the abaxial surface (Fig. 2G-I).

The sculptural protuberances of pollen grains, which occur on the tectum, are verrucate, with a diameter of about 0.5 μm, regularly distributed on the tectum surface. The tectum surface between sculptural features is rugulate. Some sparse micro-perforations are observed in the tectum. Geniculus is occasionally present in the pollen of this entity (Fig. 3I-L).

Q. magnosquamata Djav.-Khoie, Les Chênes de l`Iran, 93 (1967).

Syn.: *Q. scalaridentata* Djav.-Khoie, Les Chênes de l`Iran, 109 (1967).

The abaxial surface is covered with appressed stellate trichomes, with 4–11 (often 8) rays measuring 60–120 μm, and fasciculate trichomes with erect long (110–200 μm) rays, fused together at the base. The number of rays in the stellate trichomes in this entity is higher than elsewhere in the *Q. libani* complex. The midrib is covered with medium-sized solitary (100–235 μm) and stellate trichomes, commonly with 4–7 rays. On the adaxial surface, trichomes are restricted to 4–8 rayed stellate ones (65–145 μm long), scattered irregularly and sparsely on the epidermal surface. Stomata are elliptical and at the lev-

el of lamina. They are not raised, so that the boundary between guard cells and the lamina is difficult to see. The rim is covered by wax, but the stomatal pore is visible (Fig. 2J-L).

The structural pattern of pollen is rugulate to striate, irregularly distributed on the tectum surface. Sparse micro-perforations in the tectum are observed. The sculptural pattern is verrucate, with diameters lower than 0.5 µm, regularly scattered on the tectum surface. Secondary ornamentations of the microstriate type are seen on the sculptural patterns (Fig. 4A-D).

Q. ophiosquamata Djav.-Khoie, Les Chênes de l`Iran, 97 (1967).

The most abundant trichome on the abaxial surface is of the stellate type, with 4–8 (commonly 8) rays, 80–210 µm long and completely appressed to the lamina. The length of rays in the stellate trichomes is longer than in other entities in *Q. libani*. A few fasciculate trichomes, with 150–250 µm long rays are seen along the midrib. On the midrib, a few solitary hairs (140–390 µm long) are observed. No trichomes were observed on the adaxial surface.

The wax is of the smooth-layer type. The stomata are raised; both the stomata and the rim are clearly elliptical in shape (Fig. 2M-O).

The structural pattern of the tectum surface is rugulate-verrucate, with sparse micro-perforations. The sculptural elements are of the verrucate type, with diameters of 0.5 µm. Some of these elements are connected into verrucae, with diameters of about 1 µm. The suprasculpture is microverrucate (Fig. 4E-I).

The LM micrographs of some studied taxa are presented in Fig. 5.

Discussion

Our research has shown that the exine ornamentations of pollen grains in the entities of the *Q. libani* complex have differences in structural patterns. Denk & Grimm (2010) reported a general pattern of oaks forming a monophyletic Group Cerris among all living oaks. Variability within species in this group is higher than between the species (Denk & Grimm 2009). We have studied mature leaf samples of all examined entities collected at approximately the same time during the year and at the same stage of growth, in order to avoid biased conclusions related to the age and growth rate of leaves (Llamas & al. 1995; Tschan & Denk 2012), which may be misleading. Hence, the presence or absence of trichomes on the adaxial leaf surface can be used to delimit the studied entities. Furthermore, the length and number of rays in the stellate trichomes provides valuable data for discrimination of the examined entities.

The canonical graph obtained from discriminant analysis of quantitative variables of leaves and pollen grains (Fig. 1) has clearly separated *Q. carduchorum*, *Q. magnosquamata* and *Q. scalaridentata* from the remainder in this complex, because of the presence of trichomes on their adaxial leaf surface. In addition, exine ornamentation of the pollen grains of these entities helped us to distinguish them.

Koch (1849) described *Q. carduchorum* from the Kurdistan province of Iraq and Turkey. Subsequently, Djavanchir Khoie (1967) reported this taxon from forests in the northern part of the Zagros Range in Iran (Baneh and Sardasht Forests). This entity is a small deciduous tree, up to 10 m high, with tomentose leaves, buds and annual branches densely yellowish-brown; leaves with irregular and deep cuts, branches reddish-brown; cup spirals 9–10, which are the best morphological discriminative characters of this species. In our study, we have identified some clear and obvious differences in leaf trichomes and pollen grain ornamentation, too. *Quercus carduchorum* is characterized by the presence of stellate trichomes, with 4–8 rays measuring 95–170 µm on the adaxial leaf surfaces, and high density of trichomes on the abaxial leaf surface. The pollen structural pattern is of the rugulate type, with dense micro-perforations that occasionally are connected together in grooves between the verrucae. The suprasculpture of microverrucate to microstriate type distinguishes this entity from the remainder in the *Q. libani* complex, thus in our opinion it should be recognized as a well-defined entity in this complex.

The presence of trichomes on the adaxial leaf surface of *Q. magnosquamata* and *Q. scalaridentata* clearly separates them from *Q. libani* in the canonical graph. The most important discriminative micro-morphological character of *Q. magnosquamata* and *Q. scalaridentata* is the number of stellate rays on the abaxial leaf surface, which is observed in both these entities and is much denser than in other entities within the *Q. libani* complex. *Quercus magnosquamata* forms small stands mixed with *Q. libani* in forests of Sardasht, Baneh and Marivan, while individuals of

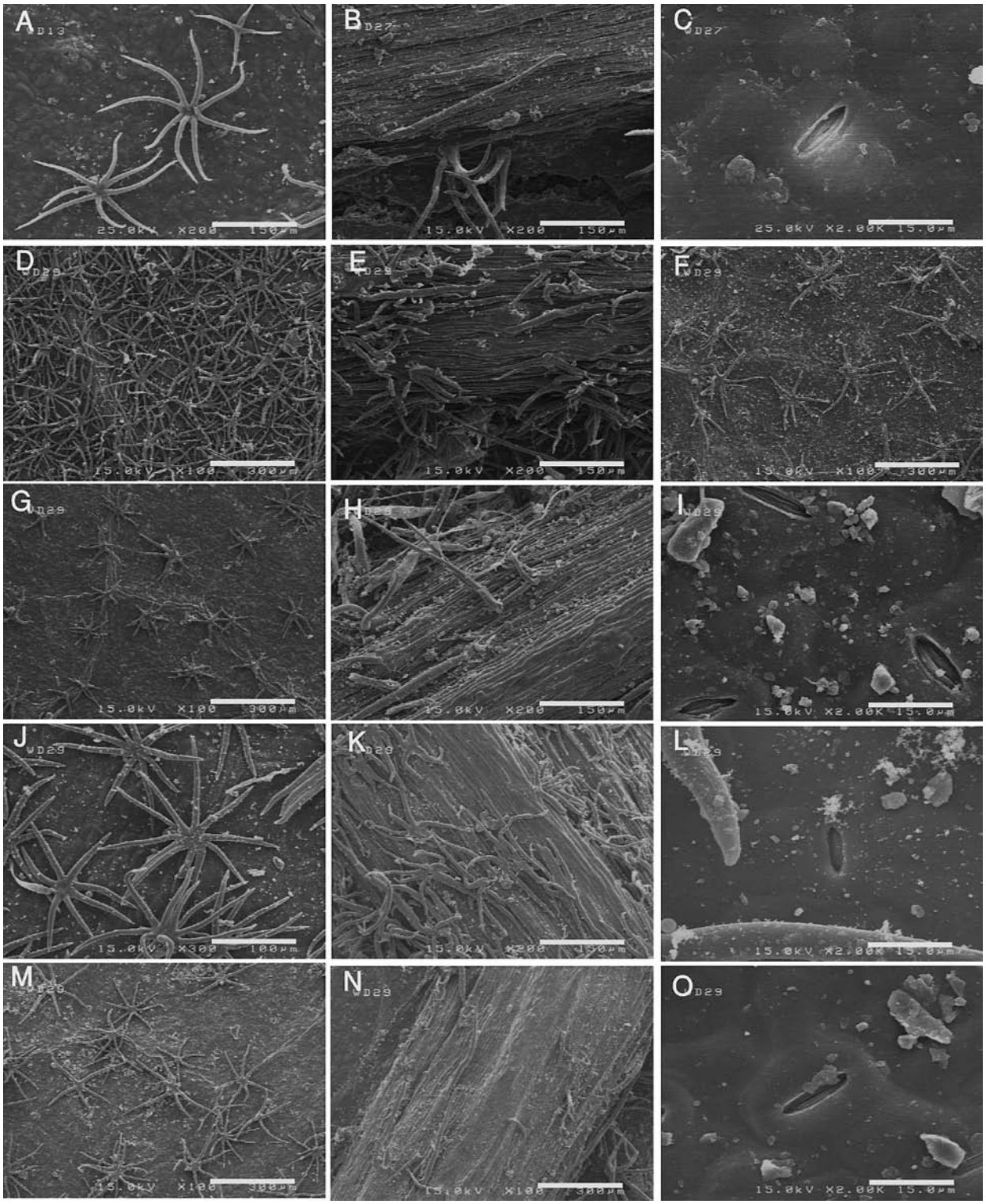

Fig. 2. SEM micrographs of trichomes, midribs and stomata in the *Q. libani* complex: (A-C) *Q. apiculata*, (D-F) *Q. carduchorum*, (G-I) *Q. libani*, (J-L) *Q. magnosquamata*, (M-O) *Q. ophiosquamata*, (A-E,G-O) abaxial surface, (F) adaxial surface, scale bar: (C,I,L,O)= 15 μm; (c,f,i)= 15 μm; (J)= 100 μm; (A,B,E,H,K)= 150 μm; (D,F,G,M,N)=300 μm.

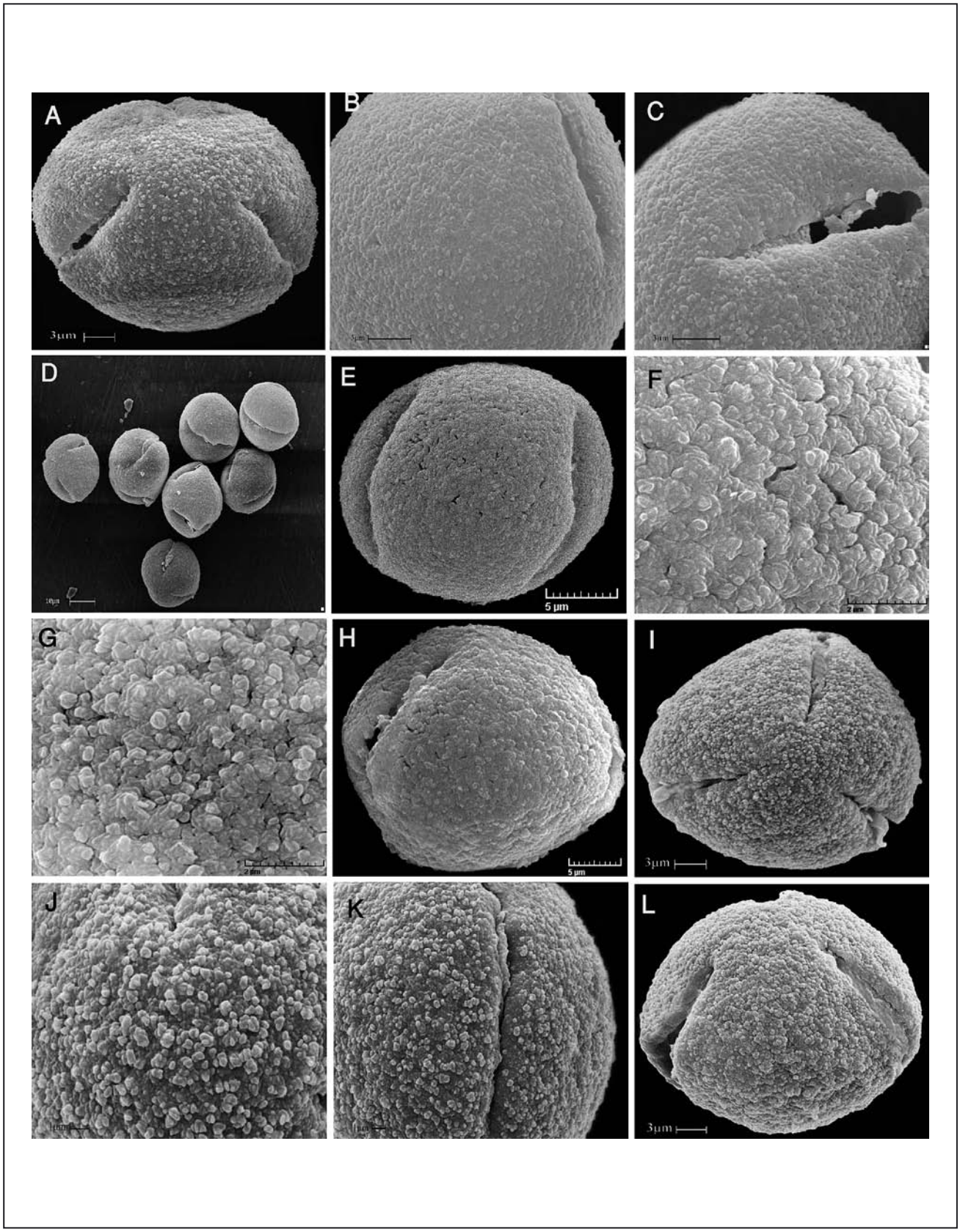

Fig. 3. SEM micrographs of pollen grains of the *Q. libani* complex: (A-D) *Q. apiculata*, (E-H) *Q. carduchorum*, (I-L) *Q. libani*, (A,I) polar view, (E,H,L) equatorial view, (B,C,F,G,J,K) mesocolpium and apocolpium, scale bar: (J,K)= 1 µm; (F,G)= 2 µm; (A,B,C,I,L)= 3 µm; (E,H)= 5 µm; (D)= 10 µm.

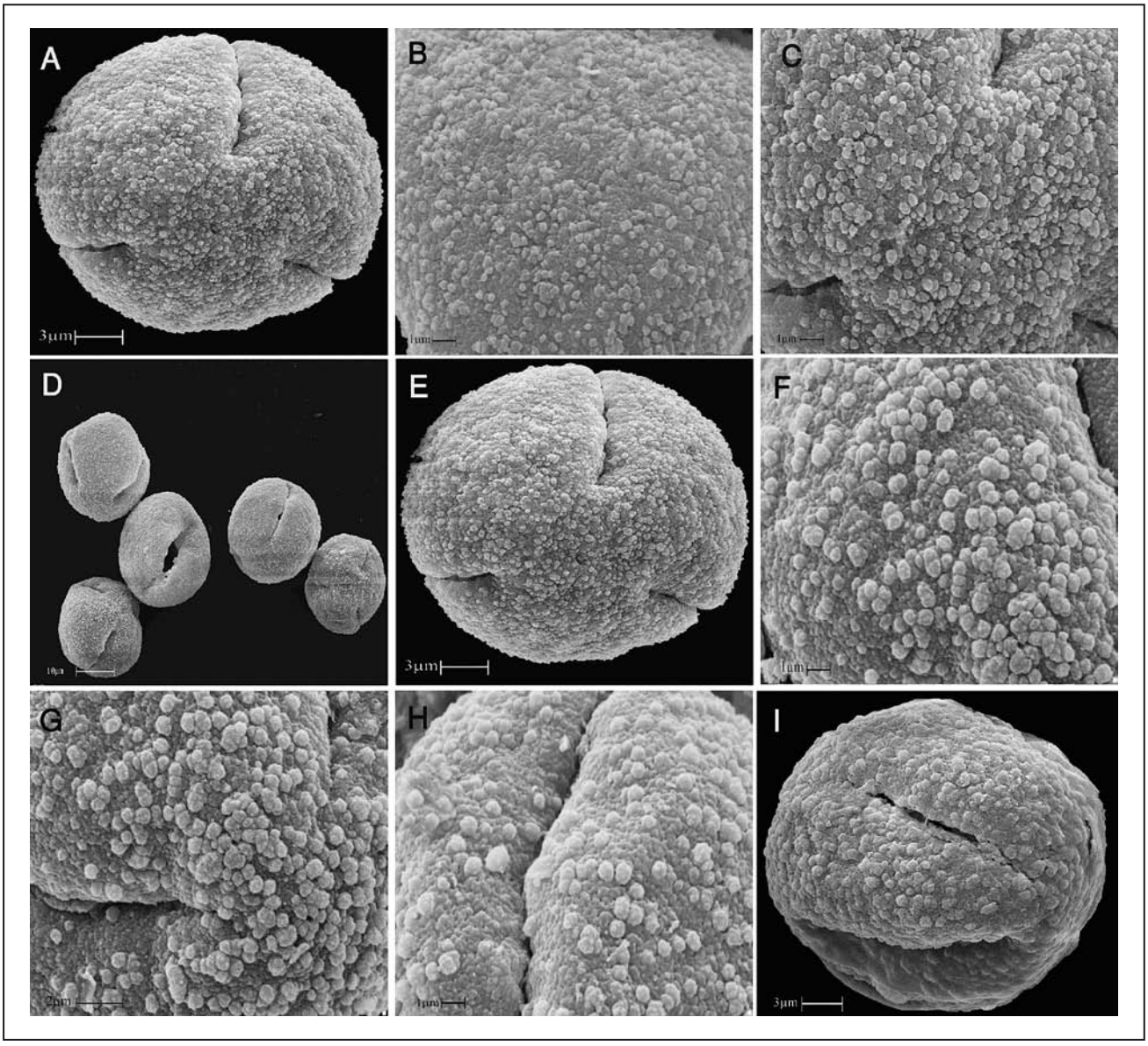

Fig. 4. SEM micrographs of pollen grains of the *Q. libani* complex: (A-D) *Q. magnosquamata*, (E-I) *Q. ophiosquamata*, (A,E) polar view, (I) equatorial view, (B,C,F,G,H) mesocolpium and apocolpium, scale bar: (B,C,F,H)= 1 µm; (G)= 2 µm; (A,E,I)= 3 µm; (D)= 10 µm.

Q. scalaridentata occur only sparsely within *Q. libani* stands in Sardasht and Baneh. With regard to morphological characters, *Q. scalaridentata* is similar to *Q. magnosquamata.* Furthermore, these entities group closely together in the canonical graph and hence they are treated as a single entity. *Quercus magnosquamata* is a deciduous medium-sized tree, up to 15 m high, which has the biggest acorn among the Iranians oaks, with hemispherical cupule, broad inverted scales and a brown tip, the upper cup scales are very long, thick and anfractuous, the cup spirals number 18. The pollen of this entity is characterized by rugulate-striate type of structural pattern, with secondary ornamentation of the microstriate type.

Among the nine entities *Q. libani*, *Q. hedjazii*, *Q. polynervata*, *Q. apiculata*, *Q. ovicarpa*, *Q. irregularis*, *Q. ophiosquamata,* and *Q. tregubovii* that are placed close together in the canonical graph (Fig. 1), *Q. apiculata* and *Q. ophiosquamata* have distinct features in the exine ornamentation of their pollen grains. The other entities are completely similar to *Q. libani*. Rugulate type of tectum surface with sparse micro-perforations, verrucate type of sculptural protuberances and secondary ornamentation of the microverrucate

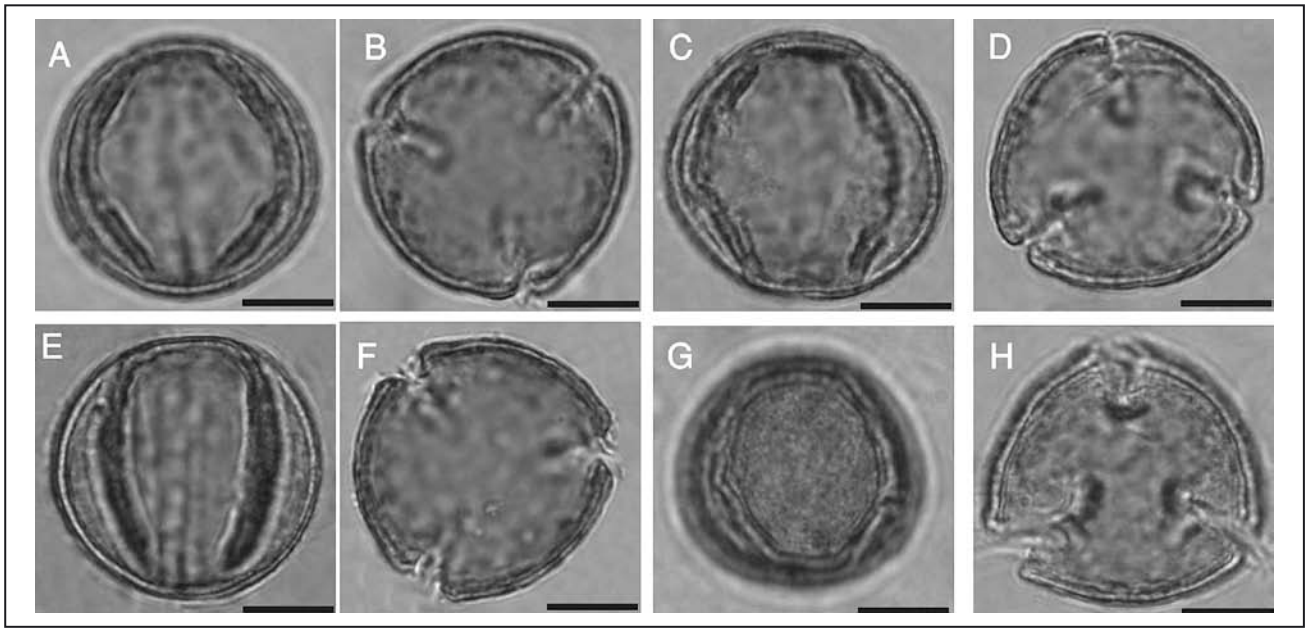

Fig. 5. LM micrographs of pollen grains of the *Q. libani* complex: (A,B) *Q. apiculata*, (C,D) *Q. carduchorum*, (E,F) *Q. libani*, (G,H) *Q. magnosquamata*, scale bar: (A-H)= 10 µm.

type are the micro-morphological characteristics of pollen grains of *Q. libani* s. str. On the basis of micro-morphological characters of the abaxial leaf surface, exine ornamentation of pollen grains and morphological characters of leaf and acorn, we have identified the seven entities mentioned above as closely allied to *Q. libani* s. str. *Quercus libani*, as distinct species of the *Q. libani* complex, has a distribution pattern which covers Iran, the Kurdistan province of Iraq, Syria, Lebanon and Turkey. This species is the widest spread oak species in the northern part of the Zagros Range. It is widely distributed in this region and in some areas forms pure stands.

Quercus libani is a deciduous small tree, up to 10 m high, with dark-grayish bark, cracked in mature trees; expanded crown; leaf base asymmetric cuneate, occasionally round; scales rhomboid, cupule cylindrical, cup spirals 15.

In the canonical graph obtained from the discriminant analysis, *Q. apiculata* has grouped near *Q. libani*, but differred in its pollen grains. The structural pattern of the tectum surface is scabrate, with sparse micro-perforations and the sculptural element is verrucate, with small-size diameter of 0.1–0.5 µm, so that the secondary ornamentation of sculptural patterns is not seen. Furthermore, *Q. apiculata* is characterized by stipitate-stellate trichomes on the abaxial leaf surface that readily distinguish it from *Q. libani*.

Quercus apiculata is a small deciduous tree, up to 6 m high, bark with long and thin scales; cup scales wide, completely appressed, the end of scales recurved, upper scales of the cup long, thick and filiform, cup spirals 10–13. Individuals of this species are distributed in forests of Baneh and Sardasht.

Quercus ophiosquamata is another entity within the *Q. libani* complex described by Djavanchir Khoie (1967). The pollen grains of this species have a structural pattern of rugulate-verrucate type and sculptural pattern of the verrucate type. Some of these elements are connected into verrucae with diameter of 1 µm. Meanwhile, a microverrucate type of suprasculpture is observed in them. Our observations have shown that the micro-morphological difference of epidermal structures between *Q. ophiosquamata* and *Q. libani* is only restricted to the long rays of stellate trichomes (80–210 µm) in *Q. ophiosquamata*. With regard to the morphological characters, the cordate shape of the leaf base in *Q. ophiosquamata* is the best discriminative character to separate this entity. Furthermore, *Q. ophiosquamata* is a medium deciduous tree, 10–13 m high, distributed in the forests of Baneh and Sardasht, with various shape of cup scales: small and similar to scales of snake skin. Our observations suggest that this entity should be treated as a well-defined subspecies in the northern part of the Zagros Range in Iran.

Our results have shown that the leaf indumentum and pollen micro-morphological characters are valuable features for taxon delimitation within the *Q. libani* complex in Iran. On the basis of the currently available micro-morphological characteristics and the results obtained from the discriminant analysis, we have designated five definite species groups. At this stage of our studies, we prefer to refrain from changing the status of taxa within each species group in the belief that such status change would need more investigations, especially molecular studies with suitable markers.

On the basis of our micro-morphological data, we have prepared an identification key to the entities of *Q. libani* complex in Iran which is presented in Table 7.

Table 7. Key to the entities of the *Quercus libani* complex on the basis of micro-morphological characters.

1. Trichomes present on both abaxial and adaxial surfaces 2

– Trichomes present only on abaxial surface 3

2. Abaxial and adaxial surfaces with high density of trichomes, stellate trichomes with 4–8 rays (70–155 µm long) on abaxial leaf surface, stomata are raised . . . . . *Q. carduchorum*

– Abaxial and adaxial surfaces with lower density of trichomes, stellate trichomes with 4–11 rays (60–120 µm long) on abaxial leaf surface, stomata are completely at the level of lamina . . . . . *Q. magnosquamata*

3. Abaxial leaf surface with 4–8 (commonly 8) rays (70–170 µm long) stipitate-stellate trichomes . . . . . *Q. apiculata*

– Abaxial leaf surface with sessile-stellate trichomes, completely appressed on the lamina 4

4. Abaxial leaf surface with 4–8 (commonly 6) medium-size rays (50–150 µm long) stellate trichomes, simple-uniseriate trichomes are abundant . . . . . *Q. libani*

– Abaxial leaf surface with 4–8 (commonly 8) long rays (80–210 µm long) stellate trichomes, a few simple-uniseriate trichomes present . . . . . *Q. ophiosquamata*

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