Research Article

The new locally endemic genus Yazdana (Caryophyllaceae) and patterns of endemism highlight the high conservation priority of the poorly studied Shirkuh Mountains (central Iran)

Jalil Noroozi1*, Atefeh Pirani2,3, Hamid Moazzeni3, Mohammad Mahmoodi4, Golshan Zare5, Alireza Noormohammadi6, Michael H.J. Barfuss1, Michael Suen1, and Gerald M. Schneeweiss1

1Department of Botany and Biodiversity Research, University of Vienna, Vienna 1030, Austria
2Department of Biology, Faculty of Sciences, Ferdowsi University of Mashhad, Mashhad 91779-48974, Iran
3Department of Botany, Research Center for Plant Sciences, Ferdowsi University of Mashhad, Mashhad 91779-48974, Iran
4Botany Research Division, Research Institute of Forests and Rangelands, Agricultural Research, Education and Extension Organization (AREEO), Tehran 13185-116, Iran
5Department of Pharmaceutical Botany, Faculty of Pharmacy, Hacettepe University, Ankara 06100, Turkey
6Cologne Excellence Cluster for Cellular Stress Responses in Aging-Associated Diseases (CECAD), University of Cologne, Cologne 50931, Germany
*Author for Correspondence. E-mail: jalil.noroozi@univie.ac.at
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Abstract

Although mountain ranges are often recognized as global biodiversity hotspots with a high level of endemism, diversity and biogeographic connections of isolated and weakly explored mountains remain poorly understood. This is also the case for Shirkuh Mts. in central Iran. Here, Yazdana shirkuhensis gen. & spec. nov. (Caryophylineae, Caryophyllaceae) is described and illustrated from the high alpine zone of this mountain. Molecular phylogenetic analyses of nuclear and plastid DNA sequence data show that Y. shirkuhensis is related to Cyathophylla and Heterochroa (tribe Caryophyllaceae). The newly described genus and species accentuate Shirkuh Mts. as a center of endemism, which harbors a high number of narrowly distributed species, mostly in high elevations reaching alpine habitats. As this area is currently not protected, a conservation priority is highlighted for high elevations of Shirkuh Mts.

Key words: biogeography, endemism, genus novum, phylogeny, species nova, taxonomy.

1 Introduction

Mountains are biodiversity hotspots (Spehn et al., 2011), which harbor a considerable number of endemic species (Barthlott et al., 1996; Körner, 2003), mostly in the alpine zone (Nagy & Grabherr, 2009; Hobohm et al., 2014). Iran is a mountainous country (Fig. 1), and a high proportion of the Iranian flora (74%) is concentrated or even restricted to mountain ranges (Noroozi et al., 2019b). With increasing elevation, the rate of endemism increases, and in spite of the small area size of the alpine zone relative to lower elevations, a considerable number of Iranian endemic species are restricted to this habitat (Noroozi et al., 2018, 2019a, 2019b). Although larger areas of alpine zone can be found in Alborz and Zagros, there are numerous smaller and isolated high mountains in different parts of the country. One of these isolated mountain systems is Shirkuh in central Iran (4050 m a.s.l. at the highest peak; Fig. 1), west of the city of Yazd. Together with the Kerman massif, Shirkuh Mts. have recently been identified as an area of endemism (Noroozi et al., 2019b). However, the high elevations of the Yazd-Kerman Massifs have been poorly investigated, and in remote regions, it is still possible to find taxa new to the regional flora or even new to science (e.g., Ajani et al., 2010; Noroozi et al., 2010; Rajaei et al., 2011; Mahmoodi et al., 2013; Moazzeni et al., 2014, 2016; Doostmohammadi & Kilian, 2017). Indeed, during a field trip to the highest summit of Shirkuh Mts. in summer 2012, an annual species of Caryophyllaceae was collected close to the summit. It could neither be determined with available floras nor could it be unambiguously assigned to any of the Iranian genera of the family, suggesting that it belongs to a new taxon.

Caryophyllaceae is a large mainly Holarctic family of approximately 3000 species of herbs and subshrubs, with its diversity center in the Mediterranean and the adjacent Irano-Turanian region (Bittrich, 1993; Chaffari, 2004; Hernández-Ledesma et al., 2015). Recent molecular investigations of the
family have shown that many of the traditionally defined genera are not monophyletic (Dillenberger & Kadereit, 2014; Pirani et al., 2014; Sadeghian et al., 2015; Madhani et al., 2018). This is also the case for the tribe Caryophylleae, where, based on morphology (connate sepals, stipitate ovary, and presence of two styles), the plant from the Shirkuh Mts. was suspected to belong to. Madhani et al. (2018), revising tribe Caryophylleae, described three new genera and resurrected one genus. Thus, currently the tribe contains 14 genera (Acanthophyllum C.A.Mey., Balkana Madhani & Zarre, Bolanthus (Ser.) Rchb., Cyathophylla Bocquet & Strid, Dianthus L., Diaphanoptera Rech.f., Graecobolanthus Madhani & Rabeler, Gypsophila L., Heterochroa Bunge, Petroana Madhani & Zarre, Petrorhagia (Ser.) Link, Psammophiliella Ikonn., Psammosilene W. C. Wu & C. Y. Wu, Saponaria L.), of which seven are found in Iran (Acanthophyllum, Cyathophylla, Dianthus, Diaphanoptera, Gypsophila, Petrorhagia, Saponaria; Madhani et al., 2018).

As morphological data did not permit assignment of the plants from Shirkuh Mts. to any of the currently recognized genera, we used molecular phylogenetic data to place this taxon within the phylogenetic framework of the tribe Caryophylleae established by Pirani et al. (2014) and Madhani et al. (2018). Hence, by determining the phylogenetic position of the new taxon based on molecular data, we wanted to clarify its taxonomic position. In light of the obtained taxonomic results (i.e., description of a new genus and species: see Section 3) and a lack of a phytochorlogic study of endemics in the Shirkuh Mts., we subsequently addressed the floristic relationships of these mountains to other mountain ranges of the Iranian Plateau on the basis of distribution patterns of Iranian endemics.

2 Material and Methods

2.1 Study area
Shirkuh Mts. (31°380′ to 31°880′ N; 53°700′ to 54°430′ E) are located in the southern part of the Irano-Turanian region, with a dry and continental climate (Zohary, 1973; Ebrahimi et al., 2010; Djamali et al., 2012), and annual rainfall of 350–400 mm mainly from October to May (Grunert et al., 1978). However, during the Pleistocene ice ages, these mountains were locally glaciated (Haars et al., 1974). Based on the Global Bioclimatic Classification System developed by Rivas-Martínez et al. (1997, 1999), Shirkuh Mts. belong to the Mediterranean Xeric continental, which is surrounded by Mediterranean Desertic continental (Djamali et al., 2011). Shirkuh Mts. are a part of the Yazd-Kerman area of endemism within the Irano-Anatolian biodiversity hotspot (Noroozi et al., 2019b), and they have recently been identified as a priority conservation gap (i.e., a center of endemism that is not or only marginally covered by protected areas; Noroozi et al., 2019a). Steppe vegetation dominates across all elevation zones. The alpine zone is above ca. 3500 m a.s.l. and, similar to other alpine habitats of the region (Noroozi et al., 2008), is covered by thorn-cushion grasslands (Figs. 2A–2D), rock habitats (Figs. 2E, 2F), screes (Figs. 2G, 2H), and snowbeds (Fig. 2I).

2.2 Plant material
Plant material of the new taxon was collected in early July 2012 and, in the course of a trip dedicated to re-collect this species, in mid July 2019. For the molecular investigation, leaves of six individuals (one collected in 2012, taken as a herbarium voucher, and five collected in 2019, stored in silica-gel) were used. For detailed morphological...
investigation, 18 individuals (3 from 2012 and 15 from 2019) were collected as vouchers.

2.3 Molecular phylogenetic analysis
Total genomic DNA was extracted using the DNeasy Plant Mini Kit (QIAGEN, Hilden, Germany) according to the manufacturer’s protocol. The plastid rps16 intron and the nuclear ribosomal ITS (internal transcribed spacer) regions were amplified and sequenced using the primers rpsF and rpsR2 (Oxelman et al., 1997), and ITS18Sfa (ITS18Scf, 5’-GAA TGG TCC GGT GAA GTG TTC G-3’) and ITS26Sra (ITS26Scsr, 5’-GGA CGC TTC TCC AGA CTA CAA TTC G-3’; Barfuss, 2012), respectively. For ITS, two additional sequencing reactions were performed using the internal primers ITS5-8Sfa (ITS5-8Scf, 5’-GAC TCT CGG CAA CGG ATA TCT CG-3’) and ITS5-8Sra (ITS5-8Scsr, 5’-GAT GCG TGA CGC

Fig. 2. Some of the characteristic species of the dominant vegetation types in the alpine zone (above 3500 m a.s.l.) of Shirkuh Mts. A, Astragalus microphysa Boiss., Fabaceae (3600–4050 m a.s.l.). B, Cousinia lasiolepis Boiss., Asteraceae (3600–4050 m a.s.l.). C, Eremurus persicus Boiss., Asphodelaceae (3600–3900 m a.s.l.). D, Onobrychis cornuta (L.) Desv., Fabaceae (3600–4050 m a.s.l.). E, Silene nurensis Boiss. & Hausskn., Caryophyllaceae (3600–4050 m a.s.l.). F, Scorzonera intricata Boiss., Asteraceae (3500–4050 m a.s.l.). G, Arenaria persica Boiss., Caryophyllaceae (3700–4050 m a.s.l.). H, Scorzonera paradoxa Fisch. & C.A.Mey. (3600–4050 m a.s.l.). I, Ranunculus eriorrhizus Boiss. & Buhse, Ranunculaceae (3700–4050 m a.s.l.). Photos by J. Noroozi.
CCA GGC AG-3'), which are located in the 5.8S region (Barfuss, 2012). Wet lab procedures principally follow the protocol by Ehrendorfer et al. (2018), but amplification was done with 2x Phusion Green Hot Start II High-Fidelity PCR Master Mix (Thermo Scientific, Vienna, Austria) using a standard protocol with optimized annealing temperatures (rps16: 68 °C; ITS: 70 °C) and the addition of 3% DMSO (Sigma-Aldrich) for ITS.

Sequences were trimmed and assembled in Geneious 6.1.2 (https://www.geneious.com). The 12 newly obtained sequences (six for each marker) were added to the Caryophyllaceae data set of Madhani et al. (2018) and aligned using the MUSCLE plug-in in Geneious 6.1.2. Thus, the ITS data set contained 132 accessions representing 113 species and the rps16 data set contained 119 accessions representing 86 species (Doc. S1). Following Madhani et al. (2018), the genus Silene (five species sampled) was selected as outgroup. Nuclear and plastid DNA sequence data were analyzed separately and jointly. Combinability of the markers was assessed with the incongruence length difference (ILD) test (Farris et al., 1995) implemented as the partition homogeneity test in PAUP* 4.0b164 (Swofford, 2002) at the CIPRES portal using a full heuristic search, 10 random taxon addition replicates, tree bisection and reconnection (TBR) branch swapping, and with MaxTrees set to 100. Moreover, visual inspection of nodes in the separate analyses did not show any mutually strongly contradicted nodes (i.e., with bootstrap support values of at least 70 and posterior probabilities of at least 0.95).

The three datasets (ITS, rps16, and combined datasets) were analyzed using maximum likelihood (ML) and Bayesian methods. The best-fit substitution models for the ITS and the rps16 data, determined using the Akaike Information Criterion (AIC) as implemented in jModelTest 2.1.4 (Darriba et al., 2012), were the GTR + I + G and the GTR + G model, respectively. Maximum likelihood analysis was carried out on the RAxML web server (RAxML- HPC2 on XSEDE; available at the CIPRES portal: http://www.phylo.org/index.php/portal/) using 1000 bootstrap replicates, obtained by the rapid bootstrap algorithm (Stamatakis et al., 2008). Bayesian inference (BI) analyses were performed using MrBayes 3.1.2 (Huelsenbeck & Ronquist, 2001) using default prior settings and a random starting tree. The analysis consisted of four parallel runs, each with three heated chains and one cold chain that were run for 10 million generations, with each sampling every 1000 generations. The quality of the analysis was checked by comparing likelihood values and parameter estimates from different runs in Tracer 1.6 (Rambaut et al., 2014) and by average standard deviations of split frequencies (less than 0.01), and the first 25% of the trees were discarded as burn-in. The remaining trees were summarized in a 50% majority-rule consensus tree.

2.4 Morphological analysis
Morphological characteristics such as plant habit and the color of the flowers were investigated in the natural habitat; measurements and the study of micromorphological characteristics were conducted on the 18 collected individuals (see Section 2.2). Morphological data for Cyathophylla and Heterochroa, the closest relatives of the new taxon, were extracted from literature (Schischkin, 1936; Barkoudah, 1962; Davis, 1966; Strid, 1986; Rechinger & Schiman-Czeika, 1988; Madhani et al., 2018).

2.5 Biogeography of Shirkuh Mts.
All endemic species of the Iranian Plateau present (also) in Shirkuh Mts. at elevations above 1400 m a.s.l were recorded, and their distribution patterns in different mountain ranges of Iran (which are well associated with the identified areas of endemism of this region according to Noroozi et al., 2018, 2019b) were analyzed. These data were extracted from the database of endemic vascular plant species of Iran (Noroozi et al., 2019b). The distribution patterns were illustrated by ArcGIS 10 (Esri, Redlands, CA, USA; Jenness, 2013).

3 Results and Discussion
3.1 Phylogenetic analyses and taxonomic treatment
The newly obtained sequences are available in GenBank under accession numbers MK627517 and MN381230–MN381234 for ITS and MK651077 and MN417289–MN417292 for rps16. The newly generated ITS sequences did not contain any polymorphic sites. All accessions of the new taxon form a clade (bootstrap support [BS]/posterior probability [PP] of 84/1.00 from ITS; BS/PP of 91/1.00 from rps16; BS/PP of 92/1.00 from the combined dataset; Doc. S2). The new taxon is placed in tribe Caryophyllaeae with strong support as closely related to Cyathophylla and Heterochroa (BS/PP of 84/0.98 from ITS; BS/PP of 91/1.00 from rps16; BS/PP of 92/1.00 from the combined dataset; Fig. 3). Whether the new taxon is sister to Heterochroa, as inferred by ITS, or to Cyathophylla, as inferred by rps16 and the combined data, remained unclear due to low support values (Fig. 3). Both genera belong to subtribe Caryophyllinae, whose internal relationships were barely known until the recent molecular study of Madhani et al. (2018). This is also the case for Heterochroa and Cyathophylla, which were previously classified under Gypsophila and Saponaria, respectively (see Madhani et al., 2018, for details on their taxonomic history). Heterochroa includes six perennial species distributed in Kazakhstan, Mongolia, N China, and Russia, whereas Cyathophylla comprises two annual species distributed from Greece to Turkmenistan (Madhani et al., 2018). However, several of these species are only poorly known. The new species from Shirkuh Mts. has dark purple stems and calyces covered with long-stemmed glandular hairs, only slightly clawed bicolored and emarginate petals. As it differs morphologically from both Heterochroa and Cyathophylla in habit, coloration, leaf shape and petal shape, and color, and as the phylogenetic position of the new taxon relative to these two genera remains unclear (contradicting, yet insufficiently supported relationships inferred from the two markers: Fig. 3), the plant from Shirkuh Mts. is described here as a new species and placed in a new genus.

Yazdana A.Pirani & Noroozi, gen. nov. (Figs. 4, 5)
Type: Yazdana shirkuhensis A.Pirani & Noroozi, sp. nov.
Iran, Yazd, Baft, Dehbal village, near the highest summit of Shirkuh Mts., 31.610° N, 54.068° E, 3950–4050 m a.s.l., on limestone scree, 14 July 2019, J. Noroozi 4003 (holotype, TARI; isotypes, FUMH, IRAN, HUM, W, WU). Additional specimens: Iran, Yazd, Shirkuh Mt., 31.610° N, 54.068° E, 4000 m a.s.l., on scree grounds, 5 July 2012, J. Noroozi 2827 (WU).
Diagnosis: This monotypic genus is similar to *Cyathophylla* and *Heterochroa*, but differs from *Cyathophylla* by non-perfoliate leaves, bicolored petals, and capsules enclosed in the calyx, and from *Heterochroa* in being annual, possessing dark purple stems, having basal spatulate leaves and capsules ± enclosed in the calyx. A comparison among the three genera is provided in Table 1.

Note: The generic and the specific names are published here simultaneously via a single diagnosis (descriptio generico-specifica; see Art. 38.5 of the Shenzhen Code: Turland et al., 2018).

Description: Annual herb, up to 17 cm high, densely branched from the base, covered with ± dense long glandular hairs, glabrescent with age. Stems prostrate, dark purple. Leaves opposite, basal leaves in rosette, spatulate, ca. 5–10 × 1–2 mm, cauline leaves oblong-lanceolate, ca. 3–5.5 × 1.5–2 mm. Flowers in lax monochasial inflorescences; pedicellate, pedicels 3–15 mm long; sepals five, 3–3.5 mm long, connate at lower 2/3; calyx 10-nerved, cylindrical, dark purple to dark green, covered with glandular hairs; petals 5, bicolored (white to white tinged with purple at the upper 2/3 and greenish at the lower third), emarginate, 4–4.5 mm long, only slightly clawed; stamens 10, enclosed, 3.5–4 mm, developing non-simultaneously (episepalous stamens reach full length distinctly before the epipetalous stamens); styles 2, 1.5–2 mm; ovary with a short gynophore; ovules 6–10; capsules oblong, slightly shorter than or subequal to the calyx, opening with 4 valves; seeds 1–8, reniform to reniform-roundish, black, 1 × 0.8 mm.

Etymology: The generic name refers to the city of Yazd in central Iran, whereas the specific name refers to Shirkuh Mts. in the vicinity of Yazd.

Distribution: It is found only in Shirkuh Mts., immediately below the highest summit (4050 m a.s.l.) on the northern slope.

**Fig. 3.** Majority-rule consensus trees inferred from Bayesian analysis of A, ITS (left) and rps16 data (right) and B, of the combined data from tribe Caryophyllaeae; both the clade of six accessions of *Yazdana shirkuhensis* (black triangles) and the clades not pertinent for the position of *Yazdana* (white triangles) are collapsed (see Madhani et al., 2018, for details on these latter lineages). Numbers above branches indicate posterior probabilities and those below indicate maximum likelihood bootstrap values.
Habitat: This species grows on limestone screes in the high alpine zone. The accompanying species of Yazdana, based on six vegetation plots (each of $5 \times 5$ m), are presented in Table 2. Although the number of annual species is usually very low in the high alpine zone of Iranian mountains (Noroozi et al., 2008), there are several annual and geographically restricted species in these small scree patches. A similar situation can be found near the summit of Hezar Mt. in Kerman, where recently a new annual Senecio has been discovered (Noroozi et al., 2010).

Conservation status: The new species is known only from the type locality. In the year 2012, only a few specimens were collected from a small plot ($5 \times 5$ m) without particular attention to the population size. In 2019, the location was well explored to find more individuals of the species and to make more detailed observations on its ecology and accompanying species. The species grows only in the northern slope and in a few scree patches from 3950 up to 4050 m a.s.l. The size of the population was estimated to have been between 100 to 200 individuals in this year. Its conservation status is, thus, given as Critically Endangered (CE, i.e., facing an extremely high risk of extinction in the wild) according to IUCN criterion B (geographic range; IUCN, 2012). Generally, alpine and subnival species are under high pressure due to ongoing global warming (Dullinger et al., 2012; Pauli et al., 2012). In the absence of higher elevations or alternative habitats for this species to shift up, with ongoing global warming, it is possibly even more strongly threatened.

Identification key: To allow Yazdana to be distinguished from other genera of tribe Caryophyllaeae, we present a generic key modified from the one provided by Madhani et al. (2018; modifications are indicated in bold):

1a. Seeds peltate, with central (facial) hilum; embryo straight..........................................................2
1b. Seeds reniform, reniform-oblong, reniform-roundish or comma-shaped, with lateral hilum; embryo curved or hook-shaped........................................................................................................5
2a. Leaves with short petiole, ovate; stamens 5; capsules membranous, nearly indehiscent..............Psammosilene

Fig. 4. Yazdana shirkuhensis. A, Habit. B, Leaf attachment. C, Inflorescence. D, Flower. E, Longitudinal sections of early (left) and late (right) flower. F, Calyx. G, Petal. H, Pistil. I, Seed. J, multicellular glandular hairs. Drawings by G. Zare.
2b. Leaves sessile, linear, subulate, grass-like; stamens (5) to 10; capsules papery, dehiscent
3a. Calyx without membranous commissures, with 35 or more veins, rarely 5–15-nerved (cf. Velezia); calyx tube long tubular, teeth straight..............................................................3
3b. Calyx with membranous commissures, with 5–15 veins; calyx tube variously shaped, if tubular the teeth recurved to deflexed.........................................................4
4a. Seeds >1.5 mm, with thin margin, smooth on surface..............................................................Dianthus (incl. Velezia)
4b. Seeds <1.5 mm, with thickened margin, reticulate on surface.........................................................Petrorhagia
5a. Seeds comma-shaped (or oblong), with hook-shaped embryo..........................................................6
5b. Seeds reniform, reniform-roundish, or reniform-oblong, embryo curved........................................7
6a. Petals turning abruptly downward and becoming clearly deflexed (Greece).................................Graecobolanthus
6b. Petals recurved gradually (Turkey to the coastal mountains of Syria, Lebanon and Palestine)..........................................................Bolanthus (incl. Phrynella)
7a. Calyx bladdery inflated, or turbine, constricted at teeth, commissural region membranous hyaline, sometimes wing-like..............................................................Diaphanoptera
7b. Calyx campanulate, cylindrical, or tubular, if inflated, commissural regions papery or leafy and main veins with leafy wings.................................................................8
8a. Bracteoles present, leafy, papery or rarely membranous; calyx papery in texture or only membranous at intervals..........................................................Acanthophyllum
8b. Bracteoles absent..............................................................9
9a. Calyx bladdery inflated, nerves prominent and thick, costate, or winged, midveins 5; bracteoles membranous hyaline..............................................................Gypsophila (cf. Vaccaria)
9b. Calyx tubular, campanulate, cylindrical, or obconical, not much inflated, lateral nerves obscure, not prominent and thick, midveins 5 or more; bracteoles absent............................10
10a. Calyx obscurely nerved or with 15–25 nerves, commissures absent or present; petals inconspicuous, or clawed, mostly with appendages..................................................11
10b. Calyx 5–10 nerved, with membranous commissures; petals not or only indistinctly clawed, without appendages..............................................................12
11a. Plants annual; inflorescences congested; capsule slightly longer than the calyx; coronal scales absent..............................................................Cyrtophyilla
11b. Plants annual, biennial or perennial; inflorescences usually lax; capsule mostly shorter than the calyx; coronal scales mostly present.............................................Saponaria
12a. Leaves fleshy, spathulate; flowers very small: calyx <4 mm, corolla <5 mm; seed testa with swollen cells tuberculate on pericinal wall, testa cells polygonal-oblong, moderately elongated (Iberian Peninsula, Socotra).......................................................Petroana
12b. Leaves not fleshy or subfleshy, linear, lanceolate, or ovate; flowers small or large; seed testa variously shaped, with or without tubercles............................................13
13a. Petals bicolored..........................................................................................................................14
13b. Petals always concolored, variously colored; leaves slender, in few species triquetrous, then the plants mostly caespitose, paired at nodes........................................15
14a. Plants red on the outer surface, white or pink on the inner surface; leaves triquetrous, mostly 3 or 4 at each node (Albania, Serbia, Bosnia)..................................................Balkan
14b. Petals greenish at base, white to white tinged with purple at apex, leaves slender, paired at each node (Iran)...........................................................................Yazdana
15a. The stigmatic surface terminal; ovules fewer than 24..............................................................................16
15b. The stigmatic surface extending along the inner side of styles; ovules 24–36........................................20
16a. Stem nodes with small lateral shoots in leaf axils giving a verticillate appearance; leaves acerose, spinous, or terminating to a spine.................................Acanthophyllum
16b. Lateral shoots in leaf axils absent; leaves not spiny except in G. acantholoides and G. pinifolia........17
17a. Capsules shorter than the calyx.................................................................................................18
17b. Capsules exceeding the calyx.................................................................................................19
18a. Plants annual, shorter than 10 cm, covered by long glandular hairs...........................................Bolanthus confertifolius
18b. Plants perennial, if annual then taller than 10 cm and glandular hairs absent or short...............................Gypsophila
19a. Plants perennial; capsules ±indehiscent........................................................................................17
19b. Plants annual or perennial; capsules dehiscent........................................................................20
20a. Calyx without membranous commissural intervals or with very narrow ones, calcium oxalate crystals absent; stamens shorter than the petals.............................Heterochroa
20b. Calyx with membranous commissural intervals encompassing calcium oxalate crystals; stamens longer (or sometimes shorter) than petals........................................21
21a. Annual plants with fibrous roots, puberulent below and glabrous in inflorescence (subcosmopolitan, absent in Australia and New Zealand)..............Psammophiliella
21b. Annual or perennial plants with tap root, variously hairy................................................................Gypsophila

3.2 Plant biogeography of Shirkuh Mts.
A total of 125 plant species endemic to the Iranian Plateau are recorded from Shirkuh Mts. above 1400 m a.s.l. (Fig. 6A), with 13 of those being local endemics (Fig. 6B). The full species list and their distributions in different mountain ranges are presented in Table 3. Of the 125 species, 95 species are also recorded from Zagros, 70 species from the Kerman massif, 31 species from Alborz, 20 species from the Azerbaijan Plateau, and 14 species from Kopet Dagh-Khorassan (Fig. 6A). Of these 125 endemic species, 9 species are restricted to the Yazd-Kerman area (Fig. 6C), 27 species are distributed in the Shirkuh Mts. and in Zagros (Fig. 6D), 30 species are found in the Yazd-Kerman and Zagros (Fig. 6E), and 11 species are widely distributed in the Iranian Plateau (Fig. 6F). These data show that Shirkuh Mts. are not only a biodiversity hotspot with a rich local endemism, but they are also floristically well connected to the mountain ranges of the Iranian Plateau. This connection is stronger with the
geographically close ranges of Zagros and the Kerman massif (Fig. 6A).

Of the 13 species endemic to Shirkuh Mts., two species are distributed mainly between 1400 and 2000 m a.s.l. (*Acantholimon horridum* Bunge, Plumbaginaceae; *Echinops cervicornis* Bornm., Asteraceae), three species between 2000 and 2500 m a.s.l. (*Astragalus darrehbidensis* Podlech & Zarre and *Astragalus mehrizianus* Podlech & Maassoumi, both Fabaceae; *Dionysia khatamii* Mozaff., Primulaceae), three species between 2500 and 3000 m a.s.l. (*Dionysia curviflora* Bunge, Primulaceae; *Gypsophila yazdiana* Falat., F. Ghahrem. & Assadi, Caryophyllaceae; *Nepeta asterotricha* Rech.f., Lamiaceae), one species between 3000 and 346

**Fig. 5.** A, B, Habitat and C, D, E, habit of *Yazdana shirkuhensis*. The plants are found only on the northern slope of the highest summit of Shirkuh Mts. (3950–4050 m a.s.l.), where they grow on limestone scree. Photos by J. Noroozi.
Table 1 Comparison of morphological characteristics of *Yazdana* and allied genera (Rechinger & Schiman-Czeika, 1988; Madhani et al., 2018)

| Cyathophylla | Heterochroa | Yazdana |
|-------------|-------------|---------|
| Habit       | Annual      | Perennial cespitose | Annual |
|             | Indumentum  | Glabrous or covered with long glandular multicellular and sessile glandular hairs | Covered with long multicellular glandular hairs |
| Basal leaves | In a rosette, ovate or broadly spatulate, obtuse | Lacking | In a rosette, spatulate |
| Cauline leaves | Linear-lanceolate, ovate to rounded | Linear, linear-subulate, linear-lanceolate, lanceolate, or ovate | Oblong-lanceolate |
| Cauline leaf size | 4–10 × 1–5 mm | 3–10 × 0.5–4 mm | 3–5.5 × 1.5–2 mm |
| Calyx       | 5 or 15-nerved | 5-nerved | 10-nerved |
| Petal color | Concolorous (rose or pink) | Concolorous (white to purple) | Bicolorous (greenish at base, white to white tinged with purple at upper part) |
| Capsule length | Exceeding the calyx | Equaling or exceeding the calyx shorter or subequal to the calyx |
| Seed shape  | Roundish | Reniform-oblong | Reniform to reniform-roundish |

3500 m (*Helichrysum davisianum* Rech.f., Asteraceae), and four species between 3500 and 4050 m a.s.l. (*Astragalus issatissensis* Maassoumi & Mahmoodi, *Oxytropis shirkuhi* Vassilcz., and *Oxytropis yazdi* Vassilcz., all three Fabaceae; *Y. shirkuhensis* A. Pirani & Noroozi, Caryophyllaceae). *A. issatissensis* was described as a new species (Mahmoodi et al., 2013) from material collected during the same field trip in 2012 when *Y. shirkuhensis* was collected for the first time.

Table 2 Accompanying species of *Yazdana shirkuhensis* based on six vegetation plots (5 × 5 m) sorted by life form

| Species | Family | Life form | Distribution |
|---------|--------|-----------|--------------|
| *Acantholimon modestum* Bornm. ex Rech.f. & Schiman-Czeika | Plumbaginaceae | Thorn-cushion | Yazd-Kerman |
| *Acanthophyllum glandulosum* Buhse ex Boiss. | Caryophyllaceae | Thorn-cushion | Iran, Hindu Kush, C Asia |
| *Arenaria persica* Boiss. | Caryophyllaceae | Thorn-cushion | Zagros and Shirkuh Mts. |
| *Alyssum muelleri* Boiss. & Buhse | Brassicaceae | Hemicymopthye | Iran |
| *Asperula glomerata* (M.Bieb.) Griseb. subsp. filiformis (Bornm.) Ehrend. & Schön.-Tem | Rubiaceae | Hemicymopthye | Zagros and Yazd-Kerman |
| *Crepis heterotricha* DC. | Asteraceae | Hemicymopthye | Iran |
| *Cousinia lasioplepis* Boiss. | Asteraceae | Hemicymopthye | Zagros and Shirkuh Mts. |
| *Elymus longearistatus* (Boiss.) Tzvelev | Poaceae | Hemicymopthye | SW Asia |
| *Oxytropis shirkuhi* Vassilcz. | Fabaceae | Hemicymopthye | Shirkuh Mts. |
| *Piptatherum laterale* (Regel) Roshev. | Poaceae | Hemicymopthye | SW and C Asia |
| *Pseudocamelina camelinae* N. Busch | Brassicaceae | Hemicymopthye | Zagros and Yazd-Kerman |
| *Scorzonera paradoxo* Fisch. & C.A.Mey. | Asteraceae | Hemicymopthye | SW Asia |
| *Silene nurensis* Boiss. & Hausskn. | Caryophyllaceae | Hemicymopthye | Zagros and Yazd-Kerman |
| *Stachys obtusircena* Boiss. | Lamiaceae | Hemicymopthye | Zagros and Shirkuh Mts. |
| *Trachydium depressum* (Boiss.) Boiss. | Apiaceae | Hemicymopthye | SW Asia |
| *Zedana anchoniioides* Boiss. (monotypic genus) | Brassicaceae | Hemicymopthye | Zagros and Yazd-Kerman |
| *Allium kotschyi* Boiss. | Alliaceae | Geophyte | Zagros and Shirkuh Mts. |
| *Bromus gracillimus* Bunge | Poaceae | Annual | SW Asia |
| *Chaenorhinum gossecostatum* Speta | Plantaginaceae | Annual | Yazd-Kerman |
| *Polygonum molliaeforme* Boiss. | Polygonaceae | Annual | SW Asia |
| *Sedum kotschyanum* Boiss. | Crassulaceae | Annual | Zagros and Yazd-Kerman |
| *Senecio kotschyanus* Boiss. | Asteraceae | Annual | Yazd-Kerman |
4 Conclusion

In this study, Yazdana, comprising the sole species Y. shirkuhensis from the high alpine zone of the Shirkuh Mts., is introduced as a new genus of Caryophyllaceae. Yazdana is closely related to Cyathophylla and Heterochroa, and thus belongs to a group within Caryophyllinae, whose internal relationships and thus taxonomy have been poorly understood until now (Madhani et al., 2018).

Finding two species new for science (Y. shirkuhensis and Astragalus issatissensis) in a single trip demonstrates that the plant diversity of this area is still poorly explored. Therefore, detailed studies of flora and vegetation of the Shirkuh Mts., especially in high elevations, are highly recommended. Naturally, the area size decreases sharply from lowlands to high elevations. Whereas plant diversity increases until mid elevation (ca. 2000 m a.s.l.), it decreases gradually until the nival zone (Noroozi et al., 2018). In Shirkuh Mts., however, the number of local endemic species does not decrease with increasing elevation, which could be due to the isolation of higher elevations fostering allopatric speciation. Moreover, of the 125 endemic species of the Iranian Plateau present in Shirkuh Mts., nearly half, that is, 59, species are found at elevations above 3500 m a.s.l. (Table 3). Also, of the 22 species recorded to accompany Yazdana (Table 2), 13 species are restricted to Yazd-Kerman area or Zagros plus Yazd-Kerman area. As Shirkuh Mts. constitute a “priority conservation gap”, which means, a center of endemism that
Table 3  Endemic species of the Iranian Plateau found in Shirkuh Mts. (above 1400 m a.s.l.), their distribution in different areas of endemism, and their presence in the alpine zone (i.e., above 3500 m a.s.l.) of Shirkuh Mts.

| Species                                      | Family      | Presence in areas of endemism and beyond<sup>a</sup> | Presence in alpine zone |
|----------------------------------------------|-------------|-------------------------------------------------------|-------------------------|
| Allium austroiranicum R.M.Fritsch           | Alliaceae   | Za, Sh                                                | X                       |
| Allium cathodcarpum Wendelbo                | Alliaceae   | Za, Sh, Ke                                            | X                       |
| Allium jesdianum Boiss. & Buhse              | Alliaceae   | Za, Sh, Ke                                            | X                       |
| Ferula hirtella Boiss.                      | Apiaceae    | Sh, Lo                                                |                         |
| Ferulago contracta Boiss. & Hausskn.         | Apiaceae    | Za, Sh                                                |                         |
| Pimpinella dichotoma (Boiss. et Hausskn.) Wolff | Apiaceae    | Za, Sh                                                |                         |
| Prangos cheilanthifolia Boiss.               | Apiaceae    | Al, Za, Sh, Ke                                        |                         |
| Semenovia frigida (Boiss.) Hausskn.          | Apiaceae    | Za, Sh                                                | X                       |
| Theccocarpus mefolius Boiss.                 | Apiaceae    | Za, Sh                                                |                         |
| Trachydium depressum Boiss.                  | Apiaceae    | Za, Sh                                                | X                       |
| Alrawia bellii (Baker) K.Perss. & Wendelbo   | Asparagaceae| Za, Sh, Ke                                            |                         |
| Centaurea ispanahica Boiss.                  | Asteraceae  | Za, Sh, Ke                                            |                         |
| Cirsium spectabile DC.                       | Asteraceae  | Za, Sh, Ke                                            | X                       |
| Cousinia eriobasis Bunge                     | Asteraceae  | Za, Sh                                                |                         |
| Cousinia lasiolepis Boiss.                   | Asteraceae  | Za, Sh                                                | X                       |
| Cousinia longifolia C.Winkl. & Bornm.        | Asteraceae  | Za, Sh, Ke                                            | X                       |
| Cousinia onopordioides Ledeb.                | Asteraceae  | Al, Sh, Ke, Ko                                        |                         |
| Cousinia sicigera C.Winkl. & Bornm.          | Asteraceae  | Sh, Ke                                                | X                       |
| Crepis heterotricha DC.                      | Asteraceae  | Al, Za, Sh, Ke                                        | X                       |
| Echinops ceratophorus Boiss.                 | Asteraceae  | Za, Sh, Ke                                            |                         |
| Echinops cervicornis Bornm.                  | Asteraceae  | Sh                                                    |                         |
| Echinops jesdianus Boiss.                    | Asteraceae  | Sh, Ke                                                |                         |
| Echinops tenujectus Rech.f.                  | Asteraceae  | Za, Sh, Ke                                            |                         |
| Helichrysum davisanum Rech.f.                | Asteraceae  | Za, Sh                                                | X                       |
| Helichrysum leucocephalum Boiss.             | Asteraceae  | Za, Sh, Ke, Bl, Lo                                   |                         |
| Hertia angustifolia (DC.) O.Kuntze            | Asteraceae  | Al, Za, Sh, Ke                                        |                         |
| Iraneo paucilobus (DC.) B.Nord.              | Asteraceae  | Al, Za, Az, Sh                                       | X                       |
| Jurinea stenocalathia Rech.f.                | Asteraceae  | Sh, Lo                                                |                         |
| Launaea acanthodes (Boiss.) O.Kuntze         | Asteraceae  | Al, Za, Sh, Ke, Ko, Bl, Lo                            |                         |
| Scorzonera intricata Boiss.                  | Asteraceae  | Za, Sh, Ke, Bl                                        | X                       |
| Senecio kotschyansus Boiss.                  | Asteraceae  | Za, Sh                                                | X                       |
| Tanacetum persicum (Boiss.) Mozaff.          | Asteraceae  | Al, Za, Az, Sh, Ko                                   | X                       |
| Taraxacum roseum Bornm.                     | Asteraceae  | Al, Za, Sh, Ko                                        |                         |
| Tragopogon jezdianus Boiss. & Buhse          | Asteraceae  | Al, Za, Sh, Ko                                        |                         |
| Heliotropium aucheri DC.                     | Boraginaceae| Za, Sh, Ke                                            |                         |
| Nonea persica Boiss.                         | Boraginaceae| Al, Za, Az, Sh, Ke                                   | X                       |
| Onosma stenosiphon Boiss.                    | Boraginaceae| Al, Az, Sh, Ke, Ko                                   | X                       |
| Aethionema umbellatum (Boiss.) Bornm.        | Brassicaceae| Za, Sh                                                | X                       |
| Alyssum muelleri Boiss. & Buhse              | Brassicaceae| Az, Za, Sh                                            | X                       |
| Fibigia umbellata (Boiss.) Boiss.            | Brassicaceae| Al, Za, Sh, Ke                                        | X                       |
| Graellsia saxifragolia (DC.) Boiss.          | Brassicaceae| Za, Sh, Ke, Ko                                        | X                       |
| Hesperis leucoclada Boiss.                   | Brassicaceae| Za, Sh                                                |                         |
| Isatis campylocarpa Boiss.                   | Brassicaceae| Za, Sh                                                |                         |
| Matthiola ovatifolia (Boiss.) Boiss.          | Brassicaceae| Al, Za, Az, Sh, Ke                                   |                         |
| Pseudocamelina camelinae N. Busch            | Brassicaceae| Za, Sh, Ke                                            | X                       |
| Pseudofortuynia leucoclada (Boiss.) Khosravi | Brassicaceae| Za, Sh, Ke                                            | X                       |
| Zerdana anchoniioides Boiss.                 | Brassicaceae| Za, Sh, Ke                                            | X                       |
| Arenaria persica Boiss.                      | Caryophyllaceae| Za, Sh                                                | X                       |
| Gypsophila yazdiana Falat., F.Ghahrem. & Assadi | Caryophyllaceae| Sh                                                    |                         |
| Silene daenensis Melzh.                     | Caryophyllaceae| Za, Sh                                                | X                       |
| Silene goniocaula Boiss.                    | Caryophyllaceae| Za, Az, Sh                                            | X                       |
| Silene gynodoica Ghaz.                      | Caryophyllaceae| Al, Za, Az, Sh, Ke                                   | X                       |
| Silene nurensis Boiss. & Hausskn.            | Caryophyllaceae| Za, Sh, Ke                                            | X                       |

Continued
| Species                                           | Family                  | Presence in areas of endemism and beyond<sup>a</sup> | Presence in alpine zone |
|--------------------------------------------------|-------------------------|-------------------------------------------------------|-------------------------|
| Yazdana shirkuhensis A.Pirani & Noroozi          | Caryophyllaceae         | Sh                                                    | X                       |
| Colchicum varians (Freyn & Bornm.) Dyer           | Colchicaceae            | Za, Sh                                                |                         |
| Sedum kotschyanum Boiss.                         | Crassulaceae            | Za, Sh, Ke                                            | X                       |
| Euphorbia connota Boiss.                         | Euphorbiaceae           | Sh, Ke                                                |                         |
| Euphorbia erythraenia Boiss.                     | Euphorbiaceae           | Za, Sh, Ke                                            |                         |
| Euphorbia malleata Boiss.                        | Euphorbiaceae           | Za, Sh                                                | X                       |
| Astragalus albispinus Sirj. & Bornm.              | Fabaceae                | Za, Sh, Bl                                            |                         |
| Astragalus anserinaefolius Boiss.                 | Fabaceae                | Za, Sh, Ke, Bl                                        |                         |
| Astragalus calliphyssa Bunge                     | Fabaceae                | Za, Sh, Ke                                            |                         |
| Astragalus cephalanthus DC.                       | Fabaceae                | Za, Sh                                                |                         |
| Astragalus daenensis Boiss.                      | Fabaceae                | Za, Sh, Ke                                            | X                       |
| Astragalus darrehbidenis Podlech & Zare           | Fabaceae                | Sh                                                    |                         |
| Astragalus glauccanthus Fisch.                    | Fabaceae                | Al, Za, Sh, Ke                                        |                         |
| Astragalus griseus Boiss.                        | Fabaceae                | Za, Sh                                                | X                       |
| Astragalus horridus Boiss.                       | Fabaceae                | Za, Sh                                                |                         |
| Astragalus impexus Podl.                         | Fabaceae                | Za, Sh                                                |                         |
| Astragalus ischredensis Bunge                    | Fabaceae                | Za, Sh                                                |                         |
| Astragalus issatissensis Maassoumi & Mahmoodi    | Fabaceae                | Za, Sh                                                | X                       |
| Astragalus johannis Boiss.                       | Fabaceae                | Za, Sh                                                | X                       |
| Astragalus longistylus Bunge                     | Fabaceae                | Al, Za, Sh, Ke                                        |                         |
| Astragalus lycioides Boiss.                      | Fabaceae                | Al, Sh, Ko, Ke                                        | X                       |
| Astragalus mehrizianus Podlech & Maassoumi       | Fabaceae                | Sh                                                    |                         |
| Astragalus melanocalyx Boiss. & Buhsse            | Fabaceae                | Za, Sh                                                |                         |
| Astragalus melanodon Boiss.                      | Fabaceae                | Za, Sh, Ke                                            | X                       |
| Astragalus microphysa Boiss.                     | Fabaceae                | Za, Sh                                                | X                       |
| Astragalus myriacanthus Boiss.                   | Fabaceae                | Za, Sh, Ke                                            | X                       |
| Astragalus pseudoshebarensis Podlech             | Fabaceae                | Za, Sh, Ke                                            |                         |
| Astragalus rhodosemi Boiss. & Hausskn.            | Fabaceae                | Za, Az, Sh, Ke                                        |                         |
| Astragalus spachianus Boiss. & Buhsse             | Fabaceae                | Za, Sh, Ke                                            | X                       |
| Astragalus tenuiscapus Freyn & Bornm.            | Fabaceae                | Za, Sh, Ke                                            |                         |
| Astragalus trachyacanthos Fischer                | Fabaceae                | Al, Az, Sh, Ke                                        |                         |
| Astragalus yazdii (Vassilcz.) Podlech & Maassoumi| Fabaceae                | Za, Sh, Ke                                            | X                       |
| Cicer spiroceras Jaub. & Spach                   | Fabaceae                | Za, Sh, Ke, Bl                                        |                         |
| Onobrychis plantago Bornm.                       | Fabaceae                | Sh, Ke                                                | X                       |
| Oxytropis shirkhi Vassilcz.                      | Fabaceae                | Sh                                                    | X                       |
| Oxytropis yazdi Vassilcz.                        | Fabaceae                | Sh                                                    | X                       |
| Ajuga chamaeistus Ging. ex Benth.                | Lamiaceae               | Al, Za, Az, Sh, Ke                                    |                         |
| Hymenocrater yazdianus Rech.f.                  | Lamiaceae               | Za, Sh, Ke                                            | X                       |
| Lagochilus macracanthus Fisch. & C.A.Mey.        | Lamiaceae               | Al, Za, Sh, Ko, Lo                                    |                         |
| Nepeta atroritrica Rech.f.                      | Lamiaceae               | Sh                                                    |                         |
| Nepeta bakhtiarica Rech.f.                      | Lamiaceae               | Za, Sh                                                |                         |
| Nepeta crassifolia Boiss. & Buhsse                | Lamiaceae               | Al, Za, Sh, Ko                                        |                         |
| Nepeta glooecepha Rech.f.                       | Lamiaceae               | Za, Sh                                                |                         |
| Phlomis acheri Boiss.                            | Lamiaceae               | Za, Sh                                                |                         |
| Salvia eremophila Boiss.                         | Lamiaceae               | Za, Sh, Ke, Lo                                        |                         |
| Satureja bchartariaca Bunge                      | Lamiaceae               | Za, Sh, Ke                                            | X                       |
| Scutellaria multicaulis Boiss.                   | Lamiaceae               | Za, Az, Sh, Ke                                        |                         |
| Stachys asterocalyx Rech.f.                     | Lamiaceae               | Za, Sh                                                | X                       |
| Stachys obtusicrena Boiss.                      | Lamiaceae               | Za, Sh                                                |                         |
| Thymus carmanicus Jalas                         | Lamiaceae               | Al, Za, Az, Sh                                        | X                       |
| Thymus daenensis Celak.                          | Lamiaceae               | Al, Za, Az, Sh                                        |                         |
| Fritillaria zagrica Stafp                        | Liliaceae               | Za, Az, Sh                                            |                         |
| Telephium eriglaucum Williama                   | Paronychiaceae          | Za, Sh                                                |                         |
| Acantholimon festucaceum (Jaub. & Spach)         | Plumbaginaceae          | Al, Za, Az, Sh, Ke                                    |                         |
is currently not within any protected area (Noroozi et al., 2019a), we suggest protecting the area as efficiently as possible to conserve its unique and vulnerable biodiversity.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary Material

The following supplementary material is available online for this article at http://onlinelibrary.wiley.com/doi/10.1111/jse.12575/suppinfo:

Doc. S1. Voucher information: species name, geographical origin, collector(s), voucher (herbarium), GenBank accession numbers for ITS and rps16, respectively. Species names follow the taxonomic treatment suggested in the present study.

Doc. S2. All phylogenetic trees obtained from three datasets using Maximum likelihood and Bayesian approaches.