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Functional Ecology of Floral Traits and Plant Pollinator Interactions in Two Endemic *Scrophularia* L. Species from Erzincan, Türkiye

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Abstract: Plant–pollinator interactions are fundamental to reproductive success, yet remain understudied in the Turkish ecological context, particularly for endemic species. This study investigates pollinator diversity, behavior, and environmental influences in two rare *Scrophularia* L. species endemic to Erzincan, Türkiye: *S. fatmae* and *S. erzincanica*. Field observations conducted between 2019 and 2020 documented floral visitors, visitation frequency, and the role of floral morphology in guiding pollinator behavior. Climatic variables such as temperature, humidity, and wind were also analyzed in relation to pollinator activity. The high-altitude *S. fatmae* was visited exclusively by *Bombus niveatus,* which proved effective even under cold and windy conditions, whereas *S. erzincanica* attracted a more diverse community, including *Halictus quadricinctus*, *Halictus* sp., and *Lasioglossum pauxillum,* the efficiency of pollination was strongly linked to floral architecture; clustered flowers and staminodes enhanced pollinator guidance and cross-pollination. Statistical comparisons further highlighted differences in body size and foraging strategies between pollinator groups. Environmental conditions were shown to significantly limit pollinator activity, with high humidity and low temperatures reducing visitation. Additionally, unexpected warming events accelerated phenology in *S. fatmae*, indicating potential risks from climate change. Overall, this research provides novel insights into the functional ecology of endemic *Scrophularia* species, demonstrating how floral traits, pollinator behavior, and environmental variables interact to shape reproductive strategies. These findings contribute to biodiversity conservation efforts and underscore the importance of long-term monitoring under changing climatic conditions.

Key words: Endemic plants, floral traits, pollination biology, *Scrophularia fatmae, Scrophularia erzincanica.*

Erzincan Türkiye'den, İki Endemik *Scrophularia* L. Türünde Çiçek Özelliklerinin ve Bitki Polinatör Etkileşimlerinin İşlevsel Ekolojisi

Öz: Bitki-tozlayıcı etkileşimleri üreme başarısı için temel öneme sahiptir, ancak özellikle endemik türler için Türkiye ekolojik bağlamında yeterince araştırılmamıştır. Bu çalışma, Türkiye, Erzincan'a endemik iki nadir *Scrophularia* (*S. fatmae* ve *S. erzincanica*) türündeki tozlayıcı çeşitliliğini, davranışını ve çevresel etkileri araştırmaktadır. 2019 ve 2020 yılları arasında gerçekleştirilen saha gözlemleri, çiçek ziyaretçilerini, ziyaret sıklığını ve çiçek morfolojisinin tozlayıcı davranışını yönlendirmedeki rolünü belgelemiştir. Sıcaklık, nem ve rüzgar gibi iklim değişkenleri de tozlayıcı aktivitesiyle ilişkili olarak analiz edilmiştir. Yüksek rakımlı *S. fatmae*'yi yalnızca *Bombus niveatus* ziyaret etmiştir ve bu tür soğuk ve rüzgarlı koşullarda bile etkili olmuştur; buna karşın *S. erzincanica*, *Halictus quadricinctus*, *Halictus* sp., ve *Lasioglossum pauxillum* dahil olmak üzere daha çeşitli bir topluluğu çekmiştir. Tozlaşmanın verimliliği, çiçek mimarisiyle güçlü bir şekilde bağlantılı olup; kümelenmiş çiçekler ve staminodlar, tozlayıcı rehberliğini ve çapraz tozlaşmayı artırmıştır. İstatistiksel karşılaştırmalar, tozlayıcı grupları arasındaki vücut büyüklüğü ve beslenme stratejilerindeki farklılıkları daha da vurgulamıştır. Çevresel koşulların tozlayıcı aktivitesini önemli ölçüde sınırladığı, yüksek nem ve düşük sıcaklıkların ziyaretleri azalttığı gösterilmiştir. Ayrıca, beklenmedik ısınma olayları *S. fatmae*'de fenolojiyi hızlandırmış ve bu da iklim değişikliğinden kaynaklanan potansiyel riskleri göstermiştir. Genel olarak, bu araştırma, endemik *Scrophularia* türlerinin işlevsel ekolojisine yeni bakış açıları sunarak, çiçek özelliklerinin, tozlayıcı davranışının ve çevresel değişkenlerin üreme stratejilerini şekillendirmek için nasıl etkileşime girdiğini göstermektedir. Bu bulgular, biyolojik çeşitliliğin korunması çalışmalarına katkıda bulunmakta ve değişen iklim koşullarında uzun vadeli izleme çalışmalarının önemini vurgulamaktadır.

Anahtar kelimeler: Çiçek özellikleri, endemik bitkiler, *Scrophularia fatmae, Scrophularia erzincanica*, tozlaşma biyolojisi.

1. Introduction

Turkey stands out as a unique global entity harboring three distinct floristic regions and their associated climates, making it one of the countries with the richest flora in the temperate climate zone [1]. It boasts an

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impressive inventory of 11,707 plant species, of which 171 are exotic, 70 are agricultural, and 11,466 are native species, with 3,649 of the native plant species being endemic to Turkey [2]. Turkey's high plant diversity is directly linked to the interrelationships with pollinator communities for the sustainability of ecosystems. The reproductive success of plant species depends largely on pollinator diversity and the continuity of interaction networks, and this relationship is a key element supporting the continuity of ecosystem services [3-5]. This makes plant-pollinator relationships critical for biodiversity conservation. Although it possesses various pollinator insect species, current knowledge is limited, and focused research is needed to identify and analyze these crucial components of ecosystems. The complex interaction between flowering plant species and their pollinators is widely recognized as a fundamental factor affecting reproductive success and distribution. Variations in reproductive success, floral phenology, and gender distribution in plants are observed depending on functional pollinator groups [6]. Pollination is a vital mechanism for seed development in flowering plants, facilitating gene flow between plant populations [7,8]. Insects, particularly bees, flies, butterflies, moths, and beetles, are the primary pollinators of herbaceous plants with showy flowers.

Concerns have arisen regarding the disruption of plant-pollinator relationships due to global climate changes, habitat destruction, environmental pollution, and intensive use of pesticides and insecticides, leading to the endangerment of insect biodiversity [9]. Recent analyses have revealed a global pollination crisis, highlighting the precarious state of endemic and rare plant associations [4, 7-8]. Consequently, prioritizing the identification of pollinators within comprehensive conservation measures has become an urgent necessity [12]. Preserving relationships between plants and their pollinators contributes significantly to ecosystem continuity [13]. Investigating plant-pollinator relationships is critical for understanding the effects of global warming, the causes of pollinator decline, the structure of communication networks between pollinators and plants, and the efficiency of food production dependent on pollinators. Although the number of pollinator insect species in Turkey exceeds 25,000, limited information is available about the biodiversity of these species [14]. Moreover, while studies have been conducted to identify pollinator species in orchards, the characteristics affecting plant-pollinator relationships have not been comprehensively analyzed [14-16]. Recent species-specific pollination studies have revealed that approximately 80% of global pollination services are performed by about 2% of pollinator species [17]. Recognition of the critical roles played by non-visitor pollinator species in natural ecosystems demonstrates that these species contribute to wild plant seed and fruit formation, sustaining broader biodiversity across trophic networks [18].

Pollination not only enhances the reproductive success of plants but also provides unique indirect contributions to ecosystems. The symbiotic relationship between plant species specialized for specific pollinators and pollinator populations is evident, and studies show that plant populations decline with decreasing bee populations. The impact of climate change on pollinator life further emphasizes the increasing importance of plant-pollinator relationships [19]. Gibson et al. [20] emphasize that approximately 12.5% of global plant species are at risk of extinction, underscoring the necessity of strong and healthy plant-pollinator relationships to ensure the long-term survival of plants. Türkiye's extraordinary plant diversity and high levels of endemism, with over 3,600 species [2], make plant-pollinator relationships critical for biodiversity conservation. However, knowledge of its pollinators remains limited, creating an urgent research gap. This study highlights the role of pollinators in maintaining ecological and evolutionary processes within the context of plant diversity [19-20]. In this context, our study aims to examine the pollinator diversity and behavior of two *Scrophularia* L. species endemic to Erzincan province, Turkey. One of these species, *Scrophularia fatmae* Kandemir & İlhan, is an obligate alpine and local plant, while the other, *Scrophularia erzincanica* R.R.Mill, is more widespread in the province but localized in small populations. The objectives and significance of our research can be summarized as follows: I). To address the gap in studies on plant-pollinator relationships in Turkey. II). To determine the pollinator diversity of *Scrophularia fatmae* and *Scrophularia erzincanica* species. III). To analyze the behavior of pollinators of these two endemic species. IV). To provide data for assessing the potential impacts of climate change on plant-pollinator relationships. V). To emphasize the importance of plant-pollinator interactions for biodiversity conservation and sustainable agricultural practices.

2. Materials and Methods

2.1. Study area

The study employed pollinators within the habitats of *S. erzincanica* and *S. fatmae* as the primary research subjects. Field investigations were conducted during the vegetation periods of 2019-2020, encompassing March to October. The identifications of the two endemic species used in this study are as follows. *S. fatmae* was collected by Ali Kandemir on July 4, 2019, from a snow pit behind a mountain house, around melting snow, at an altitude of 2964 m, near the top of Ergan mount and recorded with the herbarium number 11098, EBYU 0000046. *S. erzincanica* was collected by Ali Kandemir on the Erzincan-Sivas highway, 12 km after the university campus, on the flowing slopes, at an altitude of 1468 m, on May 11, 2019, and recorded with the herbarium number 11013, EBYU 0000044 (Table 1). To align with the phenology of the plant species, pollinator observations and behavioral studies focused on *S. erzincanica* from April to June and on *S. fatmae* from June to September. The geographical distribution of *S. erzincanica* was ascertained through a combination of extant literature and preliminary field observations. The species was identified along the Erzincan-Sivas trajectory, extending from the urban center to Sakaltutan Pass, as well as in the vicinity of Beşikli and Sürek villages in the Kemah district. In addition, its observation between the villages of Eriç and Yücebelen in the Kemah district and on Keşiş Mountain in the Üzümlü district indicates that it is present in different localities in Erzincan and has a wide distribution. Our research has concentrated on the roadsides between the 15th and 20th km of the Erzincan-Sivas highway, where the species' distribution is most dense. The species and their distribution areas are shown in Figure 1.

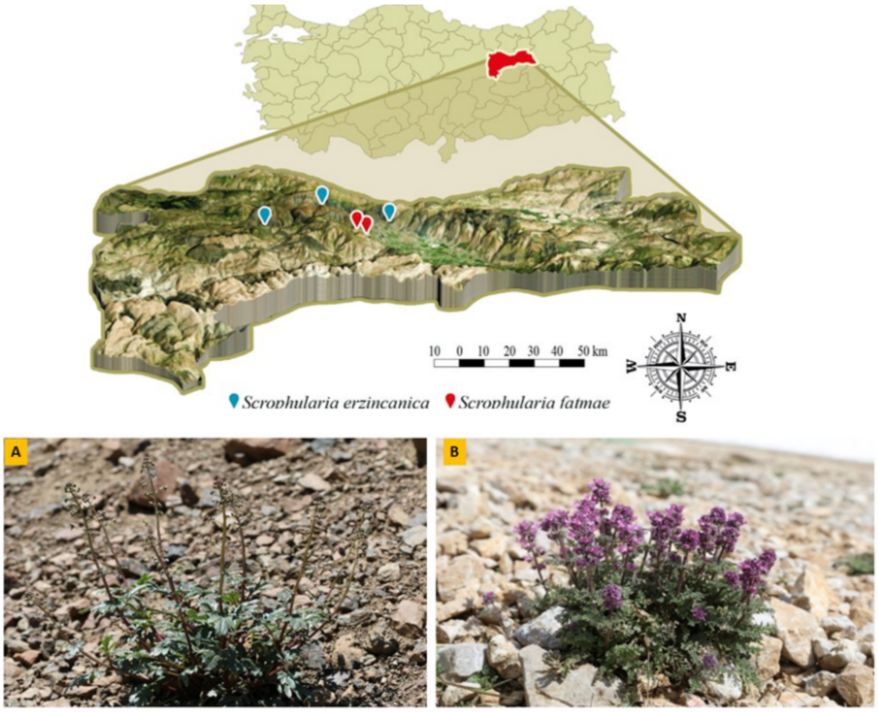

Figure 1. *Scrophularia erzincanica* (A) and *Scrophularia fatmae* (B) species and distribution areas.

Detailed examination of all localities revealed a population of 10 individuals near Sürek Village and fewer than 20 individuals on Keşiş Mount. Monitoring areas were established in 2019 along the Erzincan-Sakaltutan Pass route, selected for its relatively robust population density. *S. erzincanica* predominantly inhabits active slopes composed of serpentine bedrock, within well-ventilated young soils. Notably, it was observed on slopes consisting of clayey young soils surrounding Sürek Village. In contrast, *S. fatmae* is an alpine species endemic to Mount Ergan, located south of the Erzincan Plain (Figure 1). The species was identified in snow beds formed by depressions composed of limestone fragments with about 80 individuals. Observations were continued in both habitats to elucidate the pollination dynamics of the species in greater detail. Images from the habitats of populations of 3 different localities where observation studies are concentrated (Figure 2).

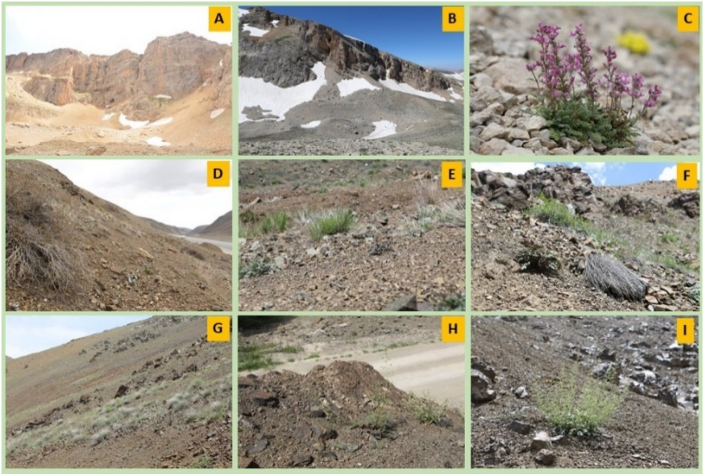

Figure 2. Images from the habitats of the populations (A-B-C = Ergam Mountain; D-E-F= Sakaltutan road; G-H-I= Eriç Yücebelen village).

In addition, location information regarding the distribution areas of species' populations is given in Table 1.

Table 1. Geographic location information regarding the distribution areas of species' populations.

Species	Population Localities	GPS location	Altitude
S. erzincanica	Sürek-Beşikli Village	39°38'18"N 39°18'12"E	1155 m
S. erzincanica	Keşiş Mountain	39°43'22"N 39°41'07"E	1644 m
S. erzincanica	Sakaltutan geçidi	39°52'12"N 39°04'53"E	1984 m
S. erzincanica	Sivas karayolu	39°52'09"N 39°15'52"E	1580 m
S. erzincanica	Eriç-Yücebelen road	39°31'27"N 38°52'39"E	1141 m
S. fatmae	Ergan Mount	39°35'03"N 39°30'06"E	3016 m
S. fatmae	Ergan Mount 2	39°35'18"N 39°30'22"E	2930 m

2.2. Climatic data collection

Environmental parameters, including temperature, wind conditions, and humidity were meticulously recorded during the monitoring of both species' populations. Supplementary data from Automatic Weather Observation Stations (AWOS) situated in proximity to the monitoring areas of both species were utilized (Table 2). The relation between climatic conditions and pollinator behavior was evaluated based on recorded pollinator visitation times during field studies.

2.3. Observation and identification of floral visitors

Field investigations of *S. erzincanica* were conducted from the second week of April through the first week of June and for *S. fatmae* from June to September. Pollinators and other insect visitors were observed between 09:00-17:00 throughout the flowering period in both species. Insect specimens interacting with the species, particularly those accessing the corolla tube for nectar and pollen collection, were sampled using traps and aspirators. Collected specimens were preserved in polyethylene bags and transported to the laboratory in refrigerated containers. Some samples were preserved in 70% ethanol prior to laboratory analysis. Photographic and video documentation of flowers and pollinators was executed using a Canon 5D Mark IV camera equipped with a 58 mm macro lens. Pollinator identification was confirmed through analysis of photographic and video evidence. Pollinator monitoring schedules were established based on preliminary field studies and referenced pollination studies on the genus *Scrophularia* [21-23]. The phenological stages of *S. erzincanica and S. fatmae* flowers were noted for 30 individuals per species, distinguishing between the 'female phase' (stylus exserted, anthers enclosed) and the 'male phase' (anthers emergent from the corolla) [24]. Insect monitoring was restricted to pollinator visitation hours. Insects consuming plant parts or reducing seed numbers by colonizing fruits were classified as pests. Laboratory specimens were pinned, labeled, and identified by Engin Kılıç using taxonomic references [15, 25-26] and a Leica M165C stereo microscope. Observations aimed to record insect behaviors in relation to the plant's intense odor emission, particularly during windless and rainless conditions coinciding with pollinator visitation hours.

2.4. Pollinator visitation index

The pollinator visitation index (PVI) was calculated following [27] method, where PVI = pollinator activity rate (PAR) × pollinator visitation frequency (F). The index was computed individually for each pollinator. Visitation frequency percentages (number of individuals per flower) were calculated relative to the total number of visits across all observation days. The average time (s) spent in the flower was used as the pollinator activity rate for each species. Visitation intensity was categorized as "no visits," "rare visits" (<10 visits/hour), "intensive visitation" (10-20 visits/hour), and "very intense" (>20 visits/hour). Relevant visitation hours were highlighted in Table 2-3 to illustrate visitation density. A color-graded table was employed to depict the distribution of pollinator visit frequencies across time intervals. While visit frequency encompasses all active pollinator times, recorded visits and total visit duration were derived from occasional records. Due to unequal numbers of recorded visits among pollinators, the average visit time was used as the pollinator activity rate and presented in the tables.

2.5. Statistical analysis

The R statistical analysis program version 3.6.1 [28] was employed for comparing pollinator sizes between species. Tukey's box plots were utilized to illustrate variations in total body sizes of plant pollinators. Additionally, a non-parametric Mann-Whitney U-test was conducted to compare measurements of *Bombus niveatus*, (Hymenoptera: Apidae) a pollinator of *S. fatmae*, with measurements of pollinator insect species associated with *S. erzincanica*.

3. Results

3.1. Climatic data

The climatic conditions associated with *S. erzincanica* and *S. fatmae* habitats before, during, and after flowering are presented in Table 2, including mean temperature, humidity, and wind conditions from Automatic Weather Observation Stations for 2019 and 2020. The table also delineates the minimum and maximum values of climate data recorded during the pollinator visitation period for both species. Pollinator activity in *S. erzincanica* was not observed when humidity exceeded 50% or at temperatures of 16.0 °C or below. Similarly, *S. fatmae* exhibited no pollinator activity under wind conditions with an intensity of 7.5 m s-1 or greater. Analysis of climatic data when the pollinator activity was noticed indicates that *S. erzincanica* pollinators demonstrate activity across a broader temperature range. While *S. erzincanica* pollinators are active within relative humidity ranges of 10-48%, they exhibit enhanced activity within the 15-30% relative humidity range. The data in Table 2 suggest a higher frequency of days with strong winds and lower average temperature values in the *S. fatmae* habitat.

Table 2. Average climate data for 2019-2020 measured in *Scrophularia fatmae* and *Scrophularia erzincanica* habitats.

Months	**Average temperature (℃)**		**Average humidity (%)**		**Average wind speed (m/s)**	
	S. fatmae	*S. erzincanica*	*S. fatmae*	*S. erzincanica*	*S. fatmae*	*S. erzincanica*
March	-	6.7	-	55.1	-	1.2
April	-	10.4	-	50.9	-	1.3
May	10.4	16.9	54.6	45.3	4.2	1.3
June	14.1	22.2	56.4	40.7	3.2	1.3
July	16.1	24.8	52.9	35.0	3.1	1.4
August	16.4	-	49.4	-	2.7	-
September	14.5	-	45.0	-	3.3	-
min. and max.	14.6-25.6	16.0-31.7	22.0-67.0	10.0-48.0	0.7-7.2	0.4-4.6

The minimum (min.) and maximum (max.) values of environmental parameters at which pollinator activity was recorded during field observations are shown.

A significant increase in average temperature was observed for *S. fatmae* in July 2020 (17.4 °C) compared to July 2019 (14.8 °C), which accelerated the blooming period and resulted in developmental challenges for 30 individuals. Compared to the previous vegetation period, the high temperatures in July 2020 are thought to have resulted in shorter flowering periods, reduced synchrony between individuals, and premature senescence of floral organs in S. fatmae. These developmental challenges are also likely to have reduced opportunities for effective cross-pollination. Detailed analysis of all these factors is needed in separate studies. This unexpected temperature elevation is considered a potential threat to *S. fatmae*, an alpine-adapted species facing new challenges due to climate change. Fruit damage by harmful insects was observed in the *S. erzincanica* population, while *S. fatmae* individuals in 2020 showed evidence of consumption by herbivorous animals, potentially birds, rabbits, or mountain goats. Furthermore, flowering times in *S. erzincanica* demonstrate synchronicity among individuals within the population, whereas *S. fatmae* exhibits an extended flowering period from the first week of July until the end of October. The asynchronous blooming of *S. fatmae* individuals following snowmelt results in heterogeneous flowering times within the population.

3.2. Pollinators

The pollination periods for *S. erzincanica* and *S. fatmae* were observed to occur from late April to mid-June and late June to late August, respectively. The identified pollinators for *S. erzincanica* included *Halictus quadricinctus* (Fabricius, 1776) (Hymenoptera-Halictidae), *Halictus* sp. (Hymenoptera-Halictidae), *Lasioglossum pauxillum* Schenck. (Hymenoptera-Halictidae), and *Eristalis tenax* L. (Linneaus, 1758) (Diptera-Syrphidae) (Figure 3). Pollinator activity varied between the two vegetation periods, with *Halictus* sp., *L. pauxillum*, and *E. tenax* active in 2019, and *L. pauxillum* and *H. quadricinctus* active in 2020. *B. niveatus* was identified as the sole pollinator for *S. fatmae* (Figure 3).

Figure 3. Pollinators of *Scrophularia* species (Pollinators for *Scrophularia erzincanica*: A-B= *Halictus quadricinctus*, C-D= *Lasioglossum pauxillum*, E=*Halictus* sp., F=*Eristalis tenax*, Pollinators for *Scrophularia fatmae*: G-H= *Bombus niveatus*).

Pollinator behavior and preferences were observed to differ between species and years. *L. pauxillum* exhibited a preference shift from *Isatis* L. (Brassicaceae) in 2019 to more frequent visits to *S. erzincanica* in 2020. *Halictus* species were primarily observed collecting pollen, while *E. tenax* and *Eristalinus taeniops* (Wiedemann, 1818) (Diptera-Syrphidae) predominantly collected nectar. The sudden population decrease in *S. fatmae* due to abrupt snowmelt in 2020 correlated with a reduction in *B. niveatus* incidence. Analysis of visitation frequency and duration indicated that *H. quadricinctus* and *Halictus* sp. were the most effective pollinators for *S. erzincanica* (Table 3).

Table 3. Pollinators visiting *Scrophularia erzincanica* and *S. fatmae* species, visitation times and frequency of visits during the 2019-2020 flowering periods.

	Average visitation frequency of observations in 2019 and 2020							
	Observation hour							
Pollinators	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00
S. erzincanica	**34 days of observations**							
Halictus quadricinctus	2	17	29	41	26	7	0	0
Halictus sp.	3	13	25	24	12	4	0	0
Eristalis tenax	0	3	3	5	0	0	0	0
Lasioglossum pauxillum	0	4	22	21	7	1	0	0
Total visit	5	37	79	91	45	11	0	0
S. fatmae	**32 days of observations**							
Bombus niveatus	4	12	23	22	14	9	5	1
Overall total	9	49	102	113	59	20	5	1

Pollinators visit intensity scale

Range	Rare (0-10 per hour)	intensive (10-20 per hour)	very intensive (20+ per hour)

L. pauxillum demonstrated consistent visitation across both years, albeit with low frequency. *E. tenax* was observed as infrequent visitors to *S. erzincanica* flowers Statistical analysis revealed significant differences between *B. niveatus,* the pollinator of *S. fatmae*, and the pollinators of *S. erzincanica* (Figure 4 and Table 4). *B. niveatus* was found to be significantly larger than all *S. erzincanica* pollinators, while *S. erzincanica* pollinators exhibited greater size variability.

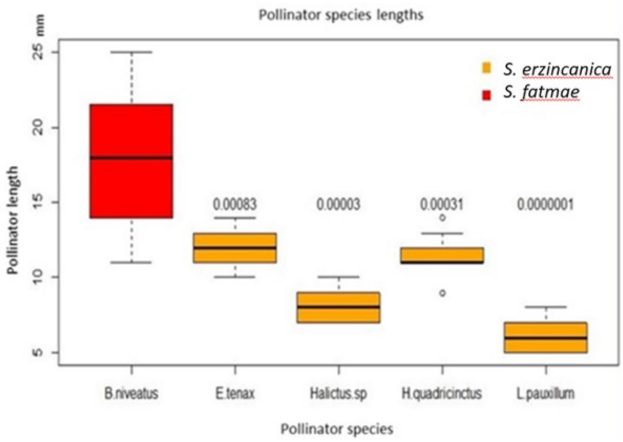

Figure 4. Body length size of pollinators *Bombus niveatus, Eristalis tenax, Halictus* sp., *Halictus quandricinctus* and *Lasioglossum pauxillum*, plant visitors of *Scrophularia erzincanica* and *S. fatmae*. Results are shown as Tukey's box plots (N = 30) for each visitor type. Number above the box indicate P value (Mann-Whitney U-test).

3.3. Pollinator visitation rates

Pollinator activity for *S. erzincanica* and *S. fatmae* was monitored between 09:00 and 17:00 during the 2019 and 2020 flowering periods. The visitation intensity was classified as rare, intensive or very intensive. *H. quadricintus*, exhibited the highest visitation rate, averaging 81 visits, followed by *Halictus* sp (81 visits) and. *L. pauxillum* (55 visits). The peak visitation time for all pollinators occurred between 10:00 and 14:00. For *S. fatmae, B. niveatus* showed consistent pollination activity across both years. The average visitation rates and temporal patterns for *B. niveatus* on *S. fatmae* are also provided in Table 3. Although *Apis mellifera* was occasionally observed visiting *S. erzincanica*, its low frequency was insufficient for quantitative analysis. There was notable interannual variation, with *E. tenax* and *E. taeniops* absent in 2019–2020, while *H. quadricinctus* appeared as a pollinator during this period. The diversity of pollinators and their foraging behaviors may account for *S. erzincanica* being more prone to cross-pollination compared to *S. fatmae*. While *B. niveatus*, the exclusive pollinator of *S. fatmae*, collects only nectar, some *S. erzincanica* pollinators gather both pollen and nectar. Notably, the average time spent by *B. niveatus* in a flower was 3 seconds, whereas *Halictus* sp. spent 14.76 seconds, *H. quadricinctus* 23 seconds, and *E. tenax* 13.31 seconds (Table 4).

Table 4. Visitation time and frequency as well as pollinator activity rate (PAR) and pollinator visiting index (PVI) in *Scrophularia erzincanica* and *Scrophularia fatmae* flowers in 2019-2020.

Pollinators	Number of visits	Total visit time (s)	Average visit time (s) = PAR	Visit frequency (%)	Pollinator index	Visiting Time (s) in flower (min - max)	Purpose of visit
Lasioglossum pauxillum	20	191	10.05	0.09	0.91	3-160	N
Halictus quadricinctus	45	1042	23.16	0.68	15.64	4-130	N-P
Halictus sp.	45	664	14.76	0.67	9.89	4-60	N
Eristalis tenax	16	213	13.31	0.24	3.19	6-26	N
Bombus niveatus	50	147	2.94	1.00	2.94	1-5	N

N – nectar, P – pollen.

Additionally, the visitation frequency of *S. erzincanica* pollinators was higher. Despite a low visitation rate (fewer than three visits per hour), *B. niveatus* successfully visited more than half of the blooming flowers in a single visit. The greater number of flowers per individual plant and the more diverse pollinator community observed in *S. erzincanica*, relative to *S. fatmae*, suggest an adaptation to short flower residence times and stigma receptivity. *H. quadricinctus* exhibited higher visitation frequency, while *L. pauxillum* had consistently low visitation rates across both years. Insect activity, including that of pollinators, began in the first week of May in the *S. erzincanica* habitat. Figure 5 illustrates the floral morphology of *S. erzincanica* (A-B) and *S. fatmae* (C-D), focusing on staminodes. Images A and B show *S. erzincanica* flowers, which feature dark-colored staminodes and pollen-bearing structures. In contrast, *S. fatmae* flowers (C and D) exhibit pink-purple coloration with visible reproductive organs. Both species have distinct floral morphologies, with *S. erzincanica* showing a more compact arrangement of reproductive organs, whereas *S. fatmae* has a more open structure. Nectar accumulation in *S. erzincanica* was observed at the base of the corolla tube, just below the staminodes. Pollinators such as *E. tenax* accessed the nectar by extending their proboscises through the openings on either side of the staminodes and into the corolla tube, which acted as a guide. Comparing pollinator body sizes to flower sizes (Figure 4, Table 4), it was found that the body sizes of pollinators were significantly larger than the flowers, with the pollinator mouthparts filling the corolla opening, indicating the importance of elongated mouthparts in nectar access.

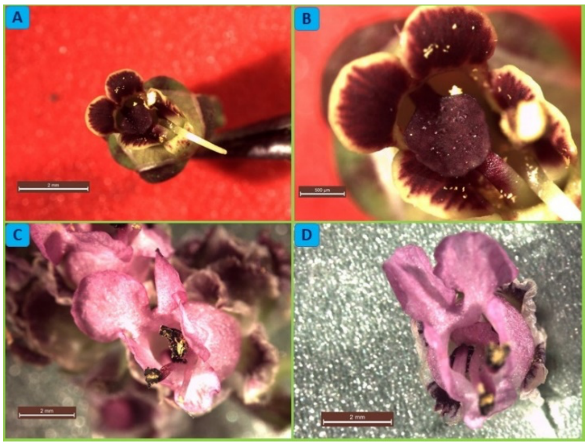

Figure 5. Appearance of flowers and staminodes (A-B: *S. erzincanica*; C-D: *S. fatmae*).

The intricate relationship between *Scrophularia* species and their pollinators presents a fascinating case study in plant-pollinator coevolution. Our investigation into *S. fatmae* and *S. erzincanica* reveals distinct adaptive strategies shaped by their respective ecological niches. *S. fatmae*, thriving at higher altitudes, exhibits a prolonged flowering period, a common adaptation among alpine species to maximize reproductive success in challenging environments [6, 29]. Also, several alpine species exhibit long flowering periods to adapt to harsh environments. This species' clustered floral distribution and more conspicuous flowers appear to compensate for reduced pollinator diversity and visit frequency. The study's findings align with previous research indicating that environmental factors significantly influence pollinator activity, with humidity levels exceeding 50% restricting insect visits [30-31]. The observed bottom-to-top visitation pattern of *B. niveatus* on *S. fatmae* and the horizontal movements of pollinators on *S. erzincanica* underscore the importance of floral architecture in shaping pollinator behavior [32-33]. These observations not only contribute to our understanding of *Scrophularia* pollination ecology but also highlight the need for further research into nocturnal pollinator activity and the potential impacts of climate change on these delicate plant-pollinator relationships. *S. fatmae* and *S. erzincanica* exhibit diurnal flowering and strong odor during the day, but show no signs of nocturnal flowering. Previous studies have also reported that Scrophularia species are visited by diurnal bees and flies rather than nocturnal moths [21-33]. However, we consider this a limitation and suggest that nocturnal observations should also be investigated to eliminate rare nocturnal visitors. The absence of certain key pollinators like *Halictus* sp. and *E. tenax* in a different area in 2020 (3 km from the 2019 site), and the emergence of *H. quadricinctus* as the effective pollinator in 2020, may be explained by the wide geographical distribution of *S. erzincanica*. The presence of other *Halictus* species in the region suggests potential pollination by additional *Halictus* species in distinct valleys and at different elevations. Further extended observations and entomological studies on pollinator distribution in the province are necessary to elucidate these patterns comprehensively.

The role of flower morphology in pollinator attraction and efficiency emerges as a critical factor in this study. *S. erzincanica*'s less conspicuous flowers appear to compensate through intense odor emission and mimicry facilitated by the staminode and corolla lip, a strategy that aligns with research on color-based mimicry in pollinator attraction [34]. Furthermore, staminodes are of ecological importance as potential pollinator attractants, consistent with findings in Scrophularia from the Iberian Peninsula [21, 22, 24].. The study's findings regarding pollinator size relative to flower structure support the concept that effective pollinators should be larger than the floral opening between male and female organs [35]. The study's focus on body size as a key parameter in pollinator performance, including foraging efficiency is consistent with existing literature [36-37]. However, the authors astutely note that other factors, such as proboscis length, may be equally important depending on the research scope [38-40]. The identification of specific pollinators for each species, *B. niveatus* for *S. fatmae* and a community including *H. quandricinctus*, *Halictus* sp., and *E. tenax* for *S. erzincanica*, represents a significant contribution to the field. This specificity in pollinator-plant relationships underscores the complexity of these ecological interactions and suggests potential implications for conservation strategies in the face of environmental changes. *A. mellifera* was observed to make occasional visits to *S. fatmae* flowers, likely due to beekeeping activities in nearby low-altitude villages. However, pollinators generally exhibited greater interest in *Erysimum opiz* (Brassicaceae), *Onobrychis cornuta* (L.) Desv. (Fabaceae), and *Pedicularis comosa* L. (Orobanchaceae) species. The observed differences in pollinator assemblages and sizes may be attributed to the species' distinct altitudinal distributions. *S. fatmae* occurs at an average altitude of 3,000 m, while *S. erzincanica* inhabits altitudes ranging from 1,200 to 2,800 m. This variability in distribution altitudes, spanning different insect life zones, suggests adaptability in *S. erzincanica* to attract pollinators of varying sizes.

The multifaceted functions of staminodes in the genus *Scrophularia* present an intriguing area for further investigation. While their precise roles remain incompletely understood, the current study provides compelling evidence for their importance in pollinator specialization, nectar guidance, and possibly nectar theft prevention. The observation that the staminode in *S. erzincanica* creates an image resembling a flying insect (Figure 5) supports existing literature on floral mimicry as a pollinator attraction strategy [41-43]. The authors' hypothesis that staminode placement at the corolla entrance serves multiple purposes, including high pollinator selectivity, prolonged pollinator residence, and maintenance of stylus position, opens avenues for future research. The authors rightly emphasize the need for controlled, long-term studies to fully elucidate the mechanisms governing these movements. This comprehensive approach to understanding *Scrophularia* pollination ecology, encompassing aspects of floral morphology, pollinator behavior, and environmental factors, provides a solid foundation for future research. As climate change continues to alter ecosystems, such studies and studies of species genetic diversity [44] will be critical in predicting and mitigating impacts on plant-pollinator relationships, particularly for species with specific pollinator dependencies or adapted to challenging environments. Long-term monitoring studies conducted by Körner et al. [45] in the Alpines show that unexpected temperature increases and dry periods can pose serious ecological threats, especially to high-altitude-adapted plant and animal communities, and that such risks can only be reliably determined by long-term observations.

The adaptation of *S. fatmae* to snow-accumulating depressions plays a crucial role in its life cycle, with observations highlighting the impact of snowfall and temperature-related snow melt on the species.

4. Conclusion

This study investigated the relationships between two rare, endemic *Scrophularia* species from Erzincan, Türkiye, *S. fatmae* and *S. erzincanica* and their insect pollinators, addressing a gap in Turkish ecological research. Findings showed different pollinator communities for each species. The high-altitude *S. fatmae* was primarily pollinated by *B. niveatus*, which was effective even under challenging conditions like low temperatures and high winds. *S. erzincanica*, found over a wider range, attracted a more diverse set of pollinators, including *H. quadricinctus*, *Halictus* sp., and *L. pauxillum*. *Halictus* species were identified as the most effective for *S. erzincanica*. The research highlighted the importance of flower shape and structure for pollinator attraction and successful pollination. The presence of staminodes in both species was found to be crucial for guiding pollinators and increasing contact with reproductive parts, thus promoting cross-pollination. The study also indicated that a good fit between pollinator body size and the flower opening is important for effective pollen transfer. Environmental factors, such as temperature, humidity, and wind, directly influenced pollinator activity. The study's data also provide insights into the potential threats of climate change, as seen with an unexpected temperature rise affecting *S. fatmae*'s blooming and development. In summary, this research contributes valuable knowledge to pollination biology and ecological adaptations in endemic plants by showing how floral traits, pollinator behavior, and environmental conditions interact to shape plant reproduction. The findings underscore the importance of understanding plant-pollinator interactions for biodiversity conservation. Future long-term and regional studies are needed for a more complete understanding.

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