frontiers | Frontiers in Forests and Global Change

TYPE Original Research
PUBLISHED 13 December 2024
DOI 10.3389/ffgc.2024.1475620

OPEN ACCESS

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RECEIVED 04 August 2024
ACCEPTED 28 November 2024
PUBLISHED 13 December 2024

CITATION
Thakar A and Dave D (2024) Population assessment, distributional pattern and ethnomedicinal significance of *Dactylorhiza hatagirea* (D. Don) Soo: an endangered species of the Himalayan region.
Front. For. Glob. Change 7:1475620.
doi: 10.3389/ffgc.2024.1475620

Population assessment, distributional pattern and ethnomedicinal significance of *Dactylorhiza hatagirea* (D. Don) Soo: an endangered species of the Himalayan region

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Dactylorhiza hatagirea (D. Don) Soo, a perennial medicinal plant found in the sub-alpine and alpine zones of the Himalayas (2800–4,500 m), is critically endangered due its overharvesting and habitat degradation. The present study aimed at quantifying the population status, distribution, impact of anthropogenic disturbances and ethnobotanical applications of *D. hatagirea* in the Paddar Valley of North-western Himalaya. The research findings indicate the total density and frequency of 0.83 plants m^{-2} and 29.9%, respectively, which is comparatively lower than its associated 99 species belonging to 37 families. Observed decline in density, frequency, Importance Value Index (IVI) and spatial extent between 2022 and 2024, underscore the impact of habitat loss, over grazing and exploitation on the species. Principal Component Analysis (PCA) shows that the environmental factors like soil type and moisture, slope and aspect influence the distribution of *D. hatagirea* across the study sites. Correlation analysis reveals a positive relationship between species density and elevation, with optimal growth occurring at 3500–4000 m on moist, northeast facing slopes ($r = 0.987$). The well-drained, sandy and loamy soil with average moisture content was found to be more suitable for the species growth as compared to clayey soil. Regarding ethnobotanical value the research findings revealed that out of the 102 informants surveyed, 75% were aware of its medicinal properties, primarily using the tuberous roots to treat stomach ailments and enhance libido. However, 45% of respondents identified unsustainable utilization as a major threat, while 27% pointed to additional pressures from immature plant harvesting for its illegal trade and livestock grazing. These findings provide essential insights for decision makers regarding policy development and the involvement of local community for the conservation of *D. hatagirea* and related medicinal species in this ecologically sensitive region.

KEYWORDS

Himalayan orchid, endangered, ethnobotany, anthropogenic disturbance, conservation

1 Introduction

India is home to a vast diversity of medicinal plants, integral to traditional healthcare systems of medicine such as Ayurveda, Siddha and Unani. Over 8,000 recorded medicinal plant species are spread across various ecosystems, from tropical forests to alpine regions (Maikhuri et al., 2017). The Himalayan region, in particular represents a valuable repository of significant medicinal and aromatic plants (Samant et al., 1998; Chauhan, 1990) with many of them facing severe threats and thus listed in Red Data Book of Indian Plants (Wani and Pant, 2023). As a global biodiversity hotspot, the Himalayan region hosts many endemic and high-value species such as *Dactylorhiza hatagirea*, *Picrorhiza kurroa*, and *Nardostachys jatamansi* etc. which contribute significantly to national and international herbal medicine markets (Wani et al., 2024). However, rising demand from pharmaceutical industries, local market and traditional healthcare systems has led to unsustainable harvesting, illegal trade from India to neighboring countries like China, Nepal, Indonesia and habitat degradation posing serious threats to these species (Joshi et al., 2024; Badola and Pal, 2003).

Among these, *Dactylorhiza hatagirea* (D. Don) Soo, a perennial herb distributed across the sub-alpine and alpine zones of the Himalayas from 2,800 to 4,500 m, is particularly endangered due to the decline in population of this orchid (Chauhan et al., 2014; Chandra et al., 2021; Sharma et al., 2022). Widespread threats such as intense grazing, unsustainable harvesting, habitat degradation and limited public awareness have contributed to its population decline (Samant et al., 2001). *D. hatagirea* grows to approximately 50–52 cm in height and inhabits grassy slopes and alpine meadows across various regions in India including Ladakh, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh, as well as parts of Tibet, Nepal, Bhutan, Pakistan, and Afghanistan (Dad and Khan, 2011; Dhar and Kachroo, 1983). In different geographical regions, it is known locally by names such as *'Hathajari'* and *'Hathpanja'* in Jammu Province and Uttarakhand, *'Salam Panja'* in Kashmir Valley, *'Angulagpa'* or *'Wanglak'* in Ladakh, and *'Panchaule'* in Nepal (Ved and Tandon, 2009; Pant and Rinchen, 2012). It is traditionally used to treat various ailments, including stomach pain and is valued for its purported libido enhancing properties. The flowering season of the species occurs from July to mid-August, followed by fruiting in late August to September (Rawal et al., 2018; Malik et al., 2015b; Rana et al., 2011).

Despite its medicinal significance, limited research has been done on its population ecology and ethnobotanical applications within the Paddar Valley of North-western Himalaya. Prior studies have largely focused on other areas of the lesser Himalayas, such as the Pir Panjal range, Kashmir Himalaya and Ladakh (Wani et al., 2021; Mir et al., 2020; Khan et al., 2019; Shaheen et al., 2019; Tali et al., 2019; Warghat et al., 2013; Malik et al., 2015b; Khuroo et al., 2010; Dad and Khan, 2011). However, due to its remoteness and tough terrain this branch of the Greater Himalayan landscape in the Kishtwar district has always remained unexplored regarding the presence, distribution and threats to Rare, Threatened and Endemic medicinal plants species.

The Paddar Valley's unique ecological setting, characterized by the transition of its Greater Himalayan range into Zanskar range, distinct microclimatic zones and limited accessibility, provides a critical yet fragile habitat for *D. hatagirea*. However, this region is particularly susceptible to pressures from overharvesting for trade by local community and from neighboring Pangi valley of Himachal Pradesh, habitat destruction due to overgrazing and climate change thus facing conservation challenges, intensified by the species slow regeneration rate and restricted distribution (Singh et al., 2024). The present study aims to investigate about the population density, distribution pattern and extent of *D. hatagirea* in the Paddar Valley, influence of environmental variables such as elevation, slope, aspect along with soil type and its moisture content on its distribution and abundance, major anthropogenic threats to the species as perceived by the local population and their level of awareness regarding the sustainable harvesting practices.

2 Materials and methods

2.1 Study area

The current investigation was conducted within the sub-alpine and alpine zones of the Paddar Valley, situated in the North Western Himalaya, India. Paddar Valley is a very remote area covering an expanse of 3,300 km^2 falling in Kishtwar District of Jammu and Kashmir (Figure 1). Geographically, it is located between 33°15′10′′ N to 33°30′10′′ N and 76°02′10″ E to 76°25′15″ E with an elevation gradient of 1,570 to 6,600 m in the Great Himalayan range (Singh et al., 2021). Owing to its broad altitudinal range, the study area presents a unique and varied amalgamation of physiognomic, climatic, and topographic characteristics. The Paddar Valley is renowned for harboring the unique Sapphire mine, locally known as *Neelam Khan*, located near Chiring nallah, one of the tributaries of the Bhot Nallah. The Bhot Nallah ultimately merges with the Chandra Bhaga River, which originates in Himachal Pradesh and meets the valley at Gulabgarh. This sapphire deposit adds to the valley's geological significance, drawing attention not only for its biodiversity but also for its rich mineral resources. For the purposes of our research, we selected four specific sites Ligri, Bujaz, Kabban, and Tun to cover overall heterogenous landscape in different watersheds of the study area. The sites are located along an altitudinal gradient of 3,000–4,000 m and were subject to regular visits and surveys on a monthly basis throughout the growing season. The selected sites are located in these diverse microhabitats, which support the growth and survival of the various rare medicinal plants. They are located at varying altitudes where Kabban and Tun are located toward Himachal Pradesh side whereas; Bujaz and Ligri are situated toward Union Territory of Ladakh and Kishtwar High Altitude National Park side, respectively. They are characterized by distinct ecological niches like meadows, moist grassy slopes except Ligri and riverine stretch, which is crucial for the species habitat. The proximity of these sites to small streams and grazing lands further influences their ecological roles, making them essential for studying its vegetation.

2.2 Vegetation sampling and data collection

Field surveys and sampling activities were conducted from mid-June 2022 to mid-July 2024 at the selected sites of Paddar Valley. To analyze the population characteristics and estimation of threat level, four plots measuring 100 m x 100 m (1 hectare) were marked in the heterogenous population at chosen sites. Two belt transects of 50 m long and 30 m wide were laid for vegetation sampling at each 1 ha plot. These transects were subdivided into three plots, each measuring 10 m x 10 m serving as replicates. Within each plot, ten quadrats measuring 1 m x 1 m were

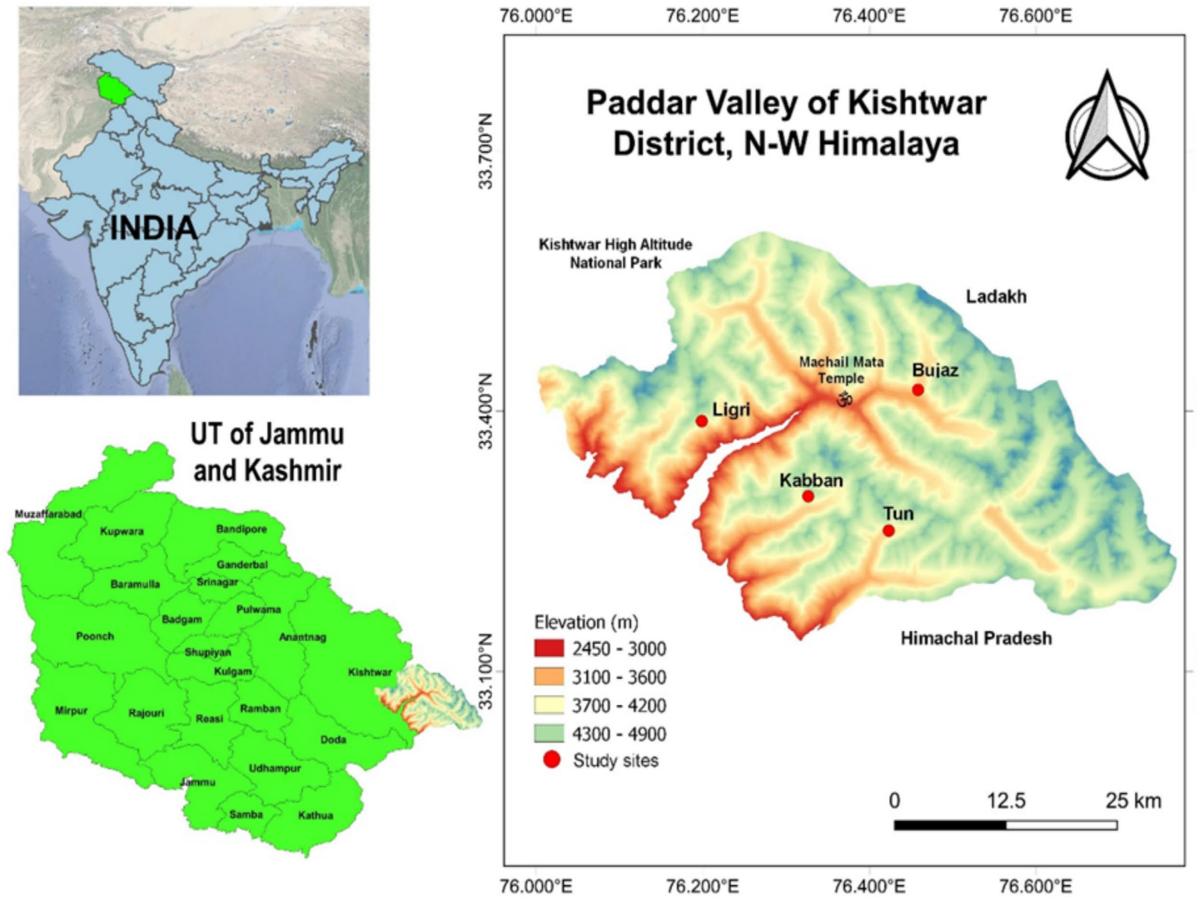

FIGURE 1
Study area: Paddar Valley, J&K in N-W Himalaya.

randomly laid (Kershaw, 1973). Thus, a total of 240 quadrats (1 × 1 m) were laid during each field survey. The mean value obtained from the plots of each transect were used for the quantitative assessment of the particular vegetation type. For every quadrat, total number of individuals of associated species were recorded and their identification was done using flora and other reference books (Dhar and Kachroo, 1983; Gaur, 1999; Naithani, 1985; Pusalkar and Singh, 2012; Rai et al., 2017). Key community attributes including frequency (F%), density (D), abundance (A), relative frequency, relative dominance, relative density, A/F ratio, and the Importance Value Index (IVI) were calculated. The IVI was determined by calculating the relative abundance, relative frequency and relative dominance, which includes the evenness of distribution of individuals among species in a community and the basal area of each individual (Mishra, 1968; Curtis and McIntosh, 1950). Furthermore, several important indices such as the (Shannon and Wiener, 1949), Simpson's Index of Dominance (Simpson, 1949) and the Sørenson Similarity Index (Sørenson, 1948) were computed using the formula given below:

$$Density = \frac{Total\ number\ of\ individuals\ of\ a\ species\ in\ all\ quadrats}{Total\ number\ of\ quadrats\ studied}$$

$$Frequency\% = \frac{Total\ number\ of\ quadrats\ in\ which\ species\ occurred}{Total\ number\ of\ quadrats\ studied} \times 100$$

$$Abundance = \frac{Total\ number\ of\ individuals\ of\ a\ species\ in\ all\ quadrat}{Total\ number\ of\ quadrats\ in\ which\ the\ species\ occurred}$$

$$A / F\ ratio = Abundance / Frequency$$

$$Relative\ density\% = \frac{Density\ of\ the\ species}{Total\ density\ of\ all\ the\ species} \times 100$$

$$Relative\ Frequency\% = \frac{Frequency\ of\ the\ species}{Total\ frequency\ of\ all\ the\ species} \times 100$$

$$Total\ frequency\ of\ all\ the\ species$$

$$\text{Relative dominance\%} = \text{Total basal / canopy cover of the species} \\ /\text{Total basal cover of all the species} \\ \times 100\,(\text{Basal cover refers to the surface area occupied by the stem of a plant}) \\ \textit{Importance Value Index}\,(I.V.I) = \textit{Relative frequency} + \textit{Relative density} + \\ \textit{Relative dominanceShannon Wiener}\,(1949)\,\textit{Index}\,(H) \\ = -\Sigma(ni/N)\,2log2(ni/N)$$

$$\textit{Where}\,(H) = \textit{Index of species diversity and ni is the} \\ \textit{IVI of a species and N the total IVI value of all species}$$

$$\textit{Simpson's}\,(1949)\,\textit{Index of Dominance}\,(D) \;=\; 1 - \sum_{N(N-1)} n(n-1)$$

Where n is the total number of individuals of a particular species

N represents the total number of individuals of all species

$$\textit{Sørensen index}\,(1948)\,QS\% = 2C / A + B \times 100$$

$$\textit{Where ``A'' represents the species count in area } 1, \\ \textit{``B'' signifies the species count in area } 2, \textit{and} \\ \textit{``C'' denotes the number of species shared between} \\ \textit{area } 1 \textit{ and area } 2.$$

The canopy cover of the species along with its biomass (dry weight) was determined to calculate the relative dominance. The A/F ratio, which serves as an indicator of the spatial distributional patterns of the species within a community was computed based on the procedures outlined by Curtis and Cottam (1956). The A/*F* values were categorized as follows: A/*F* < 0.025 (indicating a regular distribution), A/F ranging between 0.025 and 0.05 (random distribution) and A/*F* > 0.05 (indicative of a contagious distribution). For the calculation of soil type and moisture content, soil samples were collected during field surveys from the selected sites at different depths: the upper layer (0–20 cm), the middle layer (20–30 cm), and the lower layer (30–40 cm). The soil was classified as sandy, loamy, clayey, etc. based on its texture and feel. The samples stored in waterproof, airtight sachets with a capacity of fifty grams and later kept for air-drying process at room temperature for the determination of moisture content by comparing their wet and dry weights (Jackson, 1958). The site characteristics such as slope, elevation, and aspect of the study area was estimated in the field using inbuilt Global Positioning System (GPS) of G Shock watch and open access android application Locus Map that was later confirmed using Digital Elevation Model in Q GIS open software.

To document the data concerning the indigenous medicinal applications of species, we conducted a comprehensive survey that involved door-to-door visit in villages and focused group discussions. To collect the local information, we employed a semi-structured questionnaire along with snowball sampling approach in the local Paddari dialect with the help of some local youths. A total, of 102 individuals, (*n* = 102; 62 males and 40 females) aged between 29 to 75 participated in interviews across various villages situated within the Kabban, Machail and Gandhari watersheds located in the Paddar Valley. The respondents were primarily farmers from Hindu and Buddhist communities, reflecting the region's demographic profile. Their education levels varied with 57% (*n* = 58) of the participants lacking formal education, while 40% (*n* = 41) had attained basic primary education upto high school. A smaller proportion of 3% (*n* = 3) had completed higher secondary education or higher. The major occupation of the respondents was farming and local employment which includes engaged in Government funded schemes for road construction and as porters during seasonal Machail mata yatra. The respondents also included community based local healers known as Vaidyas and Amchis, as they tend to have the deep knowledge of traditional practices used to cure body ailments like cough, stomach pain, bone fracture, diarrhoea etc. The elderly people and women were also identified who hold extensive knowledge about medicinal plants used in households and were also involved in the process of making local alcohol known as '*Chhang*'. Prior informed consent was obtained from all the participants before the collection of data and the major questions focused on gathering comprehensive information about the medicinal plants local names and their traditional medicinal uses. Respondents were enquired about specific features of important plants used by them and in particular to *D. hatageria*, parts of plants used along with season of collection and their natural habitat.

2.3 Statistical analysis

The acquired data were analyzed using the statistical software PAST version 4.03 to perform an analysis of variance (ANOVA) test at both 95 and 99% significance levels. The variables used in the ANOVA included sites, population density, soil moisture and year of data collection.

3 Results

3.1 Species occurrence and spatial distribution

The analysis of the plant communities indicated *D. hatagirea* (Figure 2) as part of a diverse community comprising of 99 herbaceous species, taxonomically spread across 70 genera and 37 plant families (Supplementary Tables S1–S4). *D. hatagirea* exhibits restricted habitat distribution within the study area, primarily occupying areas distinguished by moist grassy and open meadows along with rocky slopes (Table 1). Other prominent herbaceous species found in association with *D. hatagirea* at the study sites includes *Gaultheria tricophylla, Swertia ciliata, Rhodiola himalensis, Gentiana carinata, Corydalis cashmeriana, Potentilla indica, Sibbaldia cuneata, Anaphalis triplinervis, Pedicularis gracilis*. The density of *D. hatagirea* ranged from 0.33 to 1.76 plants m^{-2} and its IVI was lower as compared to other coexisting species (Supplementary Tables S1–S4). Specifically, the IVI of the *D. hatagirea* was calculated as 1.48 at Ligri, 2.44 at Bujaz, 5.43 at Kabban and 2.17 at Tun (Table 2). The other diversity indices

FIGURE 2
(A) Mature plant of *Dactylorhiza hatagirea*, **(B)** Inflorescence (Raceme) of the plant, **(C)** Dried tubers for sale.

TABLE 1 Habitat preferences and site characteristics of *Dactylorhiza hatagirea* population.

Study sites	Altitudinal gradient(m)	Geocoordinates	Slope(^{0})	Aspect	Habitat preference
Ligri	3,300–3,800 m	33° 20′ 19.29″ N, 76° 09′ 38.78″ E	35–45	NE	Moist grassy, rocky slope
Bujaz	3,200–3,600 m	33° 25′ 11.47″ N, 76° 26′ 53.08″ E	20–30	NE	Open meadows with ortho-fluvial zone
Kabban	3,500–4,000 m	33° 17′ 19.44″ N, 76° 19′ 48.18″ E	15–25	NE	Herbaceous meadows along stream
Tun	3,000–3,400 m	33° 12′ 32.19” N, 76° 23′ 53.19″ E	30–40	SE	Moist grassy slope with tall forbs

TABLE 2 Community attributes of *Dactylorhiza hatagirea* and its threat assessment in Paddar Valley.

Study sites	Frequency (%)	Density (plants/m^2)	A/F ratio	IVI	Status	No. of associated species	Dominant species
Ligri	3.3	0.73	0.05	1.48	CE* CE**	28	*Gaultheria tricophylla* Royle, *Swertia ciliata* (D. Don ex G. Don) B.L. Burtt
Bujaz	33.3	0.5	0.04	2.44	CE* CE**	37	*Rhodiola himalensis* (D.Don), *Gentiana carinata* (D.Don ex G.Don) Griseb
Kabban	60	1.76	0.04	5.43	En* CE**	40	*Corydalis cashmeriana* Royle., *Potentilla indica* (Andrews) Th.Wolf
Tun	23.3	0.33	0.06	2.17	CE* CE**	45	*Anaphalis triplinervis* (Sims) Sims ex C.B.Clarke, *Pedicularis gracilis* Wall. ex Benth

A/F, abundance-frequency ratio; IVI, importance value index; CE, critically endangered; En, endangered; *Extent of occurrence; **Population estimation.

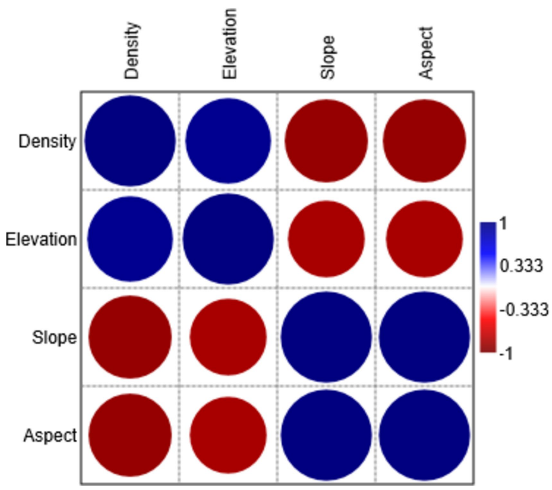

FIGURE 3
Corelation matrix for density with various environmental variables.

like Simpson index of dominance (D), Shannon-Wiener diversity index (H^{-}), and the Sørenson similarity index (QS) varied between 1.37 to 2.96, 0.74 to 0.98 and 0.86 to 1.2, respectively. The soil moisture data collected from different sites at variable depths showed significant variability ($p < 0.05$).

The average soil moisture ranges at Ligri, Bujaz, Kabban, and Tun varied from 38.31 ± 1.12 to 59.75 ± 1.12%, 54.63 ± 1.04 to 79.11 ± 1.10%, 39.82 ± 1.12 to 57.05 ± 1.03% and 25.48 ± 1.06 to 41.92 ± 1.86%, respectively. The well-drained, sandy, and loamy soil with average moisture content was found to be more suitable for the species growth compared to clayey soil, and the species is mostly found on the N-E aspect. The correlation analysis depicts positive relation of species density with elevation ($r = 0.987$), while negative relation with slope and aspect (Figure 3). The higher elevation corresponds to the elevation range of 3,500–4,000 m, which is suitable for its growth along with moist and grassy north-east slopes. The north and east aspect creates the microclimatic conditions favorable for the species maximum growth due to the less amount of sunlight. Based on the analysis of population density, soil moisture, and elevation across the study sites, a one-way ANOVA revealed significant differences between the groups ($p = 0.01$), indicating that these variables vary substantially across the sites. The components of variance calculated by Interclass Correlation Coefficient show that about 71% of the total variation can be attributed to differences between site characteristics (ICC = 0.71151), depicting that the environmental factors like soil moisture, aspect and elevation have a strong influence on species density and its distribution. The omega^2 value of 0.5522 further indicates that around 55% of the variance is explained by the differences in these factors, reflecting a moderately large effect size. The Principal Component Analysis (PCA) highlighted clear differentiation in environmental factors influencing the distribution of *Dactylorhiza hatagirea* across the study sites (Figure 4). The majority of the variance in determining population density was strongly associated with soil moisture, habitat preferences. The Kabban and Bujaz sites exhibited close clustering, indicating similar environmental profiles, particularly high soil moisture and similar habitat preferences, which are favorable for the growth of *D. hatagirea*. In contrast, steep slopes characterized the Tun site, indicating that terrain-related factors play a crucial role in the variation observed at this site. The isolated position of Ligri in the biplot suggests unique environmental conditions with limited influence from the measured variables. The positive correlation between soil moisture and population density, and the inverse relationship between slope and density, suggest that *D. hatagirea* prefers habitats with well-drained, moderately sloped terrain and adequate moisture availability. These findings underscore the critical influence of both topographical and edaphic factors on the species distribution patterns in the north-western Himalaya, offering valuable insights for its conservation and management in this region.

Levene's test for homogeneity of variance ($p = 0.07666$) showed that the variances between the groups were not significantly different, satisfying the assumption of equal variances. Even under the assumption of unequal variances, Welch's F-test confirmed the significance of the results ($p < 0.05$), demonstrating that the group differences remain robust. The variability in density, moisture, and elevation between the study sites suggests that the environmental factors play an important role in influencing the distribution *of Dactylorhiza hatagirea* across the different locations. This provides crucial insight into the species habitat preferences and the environmental conditions necessary for its growth.

3.2 Ethno-medicinal usage and threats to *Dactylorhiza hatagirea*

During the ethnobotanical study, it was noted that 75% of the participants demonstrated awareness of its medicinal properties, while 25% lacked knowledge of its therapeutic uses. Ethno-medicinal insights on the species were acquired through interviews conducted with a sample size exceeding one hundred informants. The local residents primarily utilized the tuberous roots of the plant to prepare powders and pastes for to cure stomach pain and to enhance libido among men (Table 3). Approximately 45% of the respondents identified over utilization of the species as the primary and major threat for its declining population. Another 27% of respondents highlighted the potential threat posed by anthropogenic pressure like extraction of immature plants for local consumption and illegal trade to Pangi Valley of Himachal Pradesh along with overgrazing. The trampling of immature individuals during grazing by livestock also causes decline in population. In contrast, 28% mentioned factors like absence of conservation measures and a lack of awareness among the local population as significant reasons contributing to the species decline from its natural habitats (Figure 5). Approximately 80% of the informants interviewed emphasized the urgent necessity for the conservation of this species whereas only 20% indicated that there is no requirement for conservation efforts.

4 Discussion

4.1 Comparative analysis and dominance patterns

Dactylorhiza hatagirea is recognized as an endangered species across regions like India, Nepal, and Bhutan (Dar and Khuroo, 2020;

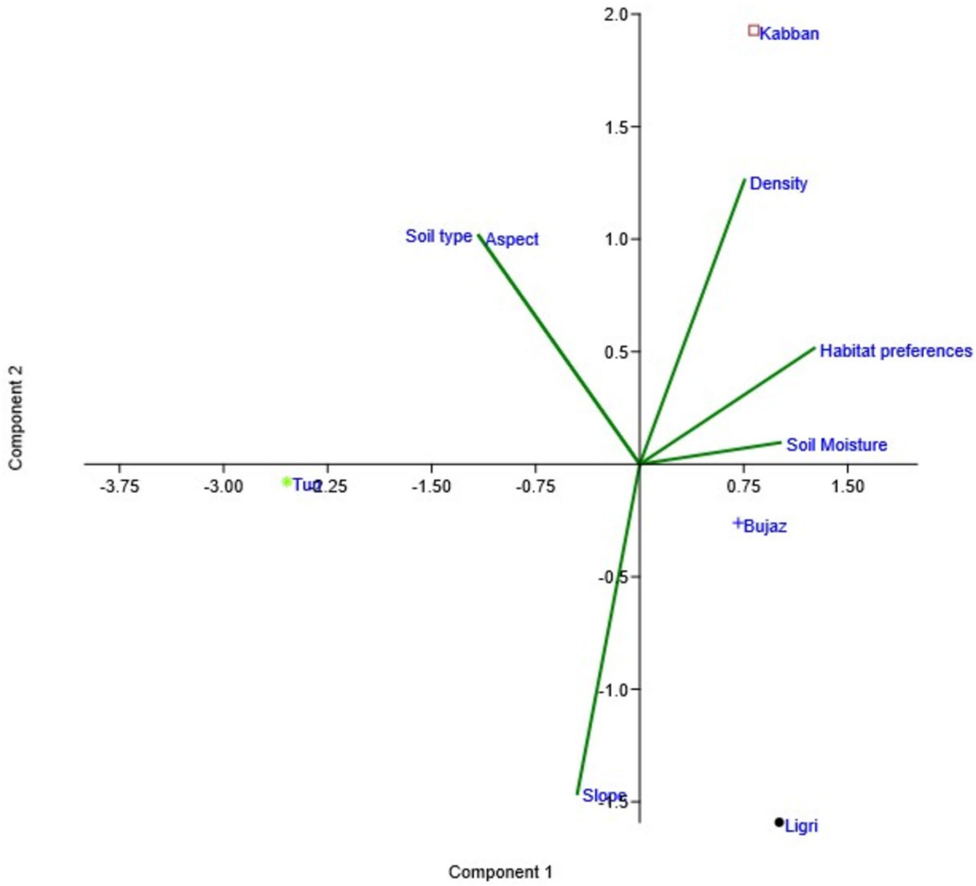

FIGURE 4
PCA Biplot illustrating the relationship between site characteristics and population density.

TABLE 3 Ethno-medicinal uses and other attributes on the usage of *Dactylorhiza hatagirea* in the study area.

S. No.	Parts used	Consumption in the form of	Uses
1.	Leaves and tuber	Powder	Gum infection, fever and stomach pain
2.	Tuber	Powder	To treat erectile dysfunction and sexual stamina
3.	Tuber	Powder with milk	Aphrodisiac
4.	Tuber	Paste	Skin infection, eternal cut and wound

Hamid et al., 2019, 2020). Its vulnerability across various Himalayan states such as Himachal Pradesh, Uttarakhand and Union Territory of Jammu and Kashmir demonstrates the fragility of medicinal flora in high-altitude ecosystems (Kumar et al., 2021a; Dyani et al., 2022). Its classification as *'Critically Rare'* and *'Critically Endangered'* by IUCN (International Union for Conservation of Nature) and CAMP (Conservation Assessment and Management Plan) further emphasizes the urgent need for effective management (CAMP, 2003; Chauhan, 2022; Kumar et al., 2021b). Our study revealed that the highest density and frequency of *D. hatagirea* was found to be at Kabban site with 1.7 plants m^{-2} and 60% respectively, on the other hand the lowest values were documented at Tun and Ligri (0.33 plants m^{-2} with 23.3% and 0.73 m^{-2} with 3.3% respectively). The higher frequency and density at the Kabban are attributed to lower level of human-induced disturbances, as there are very few hamlets in the Kabban watershed, whereas sites with pronounced anthropogenic influence and excessive grazing exhibited the decreased value. In the present study, the overall density of *D. hatagirea* ranged from 0.33 to 1.76 plants m^{-2} that is considerably lower than the various studies documented in other parts of Western Himalaya thus highlights the urgent need for conservation measures in the region.

In our study the Principal Component Analysis clearly shows the differentiation in environmental factors that influence the distribution of *Dactylorhiza hatagirea* across different sites. The positive correlation between soil moisture and population density suggests that the species prefers habitats with well-drained soil, moderately sloped terrain and adequate moisture availability in the soil. The aspect influences the microclimatic conditions, such as sunlight exposure and wind direction which in turn impact temperature and soil moisture availability. The south-facing slopes, which receive more sunlight, may offer warmer and drier conditions potentially making them less favorable for the growth of *D. hatagirea*. In contrast, slopes with

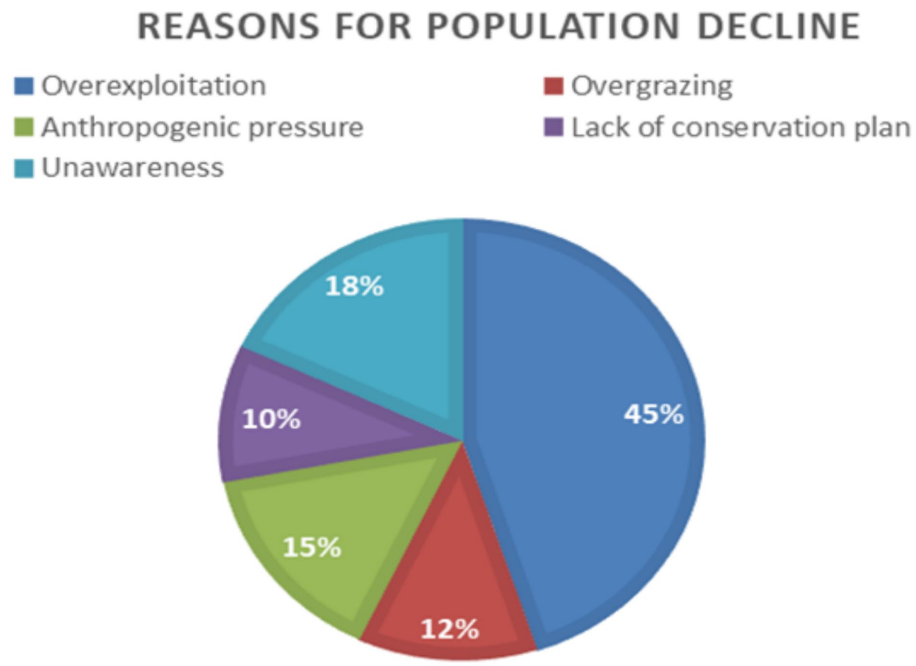

FIGURE 5
Local's perception about the potential threats to *Dactylorhiza hatagirea* population.

northern or eastern aspects generally retain more moisture, contributing to conditions feasible for its growth and higher density. The varying densities observed between study sites can thus be partially attributed to these microclimatic conditions, suggesting that the species may have a preference for cooler, more shaded aspects in regions with high moisture availability. Thakur et al. (2021) also identified similar ecological and topographic determinants which affects the occurrence and population density of *D. hatagirea* in the Himalayan region. Similarly, in other region of western Himalaya like Tungnath in Uttarakhand, the density ranges from 2.66 to 3.2 individuals m^{-2} (Nautiyal et al., 2004), 0.7–1.8 individuals m^{-2} by Giri and Tamta, (2010). 2.02–2.19 plants m^{-2} from a protected area and 1.13–1.64 plants m^{-2} from an unprotected area of Western Himalaya by Bhatt et al. (2005) and Mehta et al. (2021). These findings confirms that density and population are strongly impacted by both abiotic and biotic pressures. The other 99 plant species belonging to 37 families which have been found associated with *D. hatagirea* in the study area have also been documented as the dominant flora with *D. hatagirea* in the alpine and sub-alpine ecosystems of the western Himalaya by Kala (2005), Chandra et al. (2018), Gairola et al. (2014), Sekar et al. (2014), Khajuria et al. (2017), Mehta et al. (2020), and Kumar et al. (2022).

A notable finding in our study is the observed decline in density from 0.83 to 0.66 plants m^{-2} between 2022 to 2023, a shift likely due to untimely snowfall in mid- July of 2023 and early pastoralist movement into high-altitude meadows owing to the early melting of snow in March month of the same year. This change exemplifies how climatic fluctuations along with anthropogenic disturbances can disrupt the distribution of the species. These findings underscore the urgent need for immediate conservation measures to protect *D. hatageria* in the region. In the whole western Himalaya, Thakur et al., 2021 and Jamloki et al., 2021 also observed that the changes in weather pattern due to climate change has led to the decrease in density and overall distribution of *D. hatagirea*. The significant decline of other valuable species like *Aconitum heterophyllum*, *Taxus wallichiana*, *Dolomiaea costus* and *Picrorhiza kurrooa* in the Himalayan region over recent decades has been attributed to climate change and habitat loss due to unsustainable harvesting (Malik et al., 2021; Hamid, 2020). In recent decade, a notable reduction in occurrence and geographic distribution of orchids as a whole has been observed in the western Himalayan region (Kumar et al., 2021a; Kuniyal et al., 2021).

Diversity indices, including the Simpson index of dominance (D) and Shannon-Wiener index (H^{-}) provide insights into community structure changes over time. The Shannon diversity index (1.37 to 2.96), aligns with findings documented from other Himalayan regions, such as Tungnath with 1.79–2.28, 1.96–3.12 and 2.73–3.35 in Kedarnath wildlife sanctuary (Semwal et al., 2010; Jamloki et al., 2021), 1.47 to 2.52 in the Nanda Devi Biosphere Reserve, Uttarakhand; 2.39 to 4.63 in Uttarakhand Himalaya (Tambe and Rawat, 2010; Rawat, 2005; Goraya and Ved, 2017). In Sikkim Himalaya the diversity index ranges from 1.44 to 2.48 (Kandel et al., 2019; Pandey et al., 2018; Khadka et al., 2016; Saikia et al., 2017), followed by 1.02–2.17 in Rama Valley, Pakistan (Shaheen et al., 2019) and 3.37 in Nepal Himalaya (Khadka et al., 2016; Kunwar et al., 2021; Singh et al., 2021). Variations in the Simpson index (0.74 to 0.98) and Sørenson similarity index between sites (30 to 70%) highlight how microclimatic and topographic differences influence species dominance and similarity. High similarity in geographically close areas (e.g., Kabban and Tun) suggests that species composition and structural similarity are reinforced by spatial proximity and similar environmental conditions. Such metrics affirm that *D. hatagirea* distribution is distinctly shaped by both environmental and anthropogenic pressures, underlining the urgency for targeted conservation efforts. These findings align with those reported by Khadka et al. (2016) from Nepal, where the dominance of *D. hatagirea* was attributed to its high Simpson's Index (0.65) compared to other coexisting species (Singh et al., 2019). The Simpson's index of dominance observed in the current study exceeds the values (0.62–0.72) documented in Tungnath Himalaya by Singh and Chaturvedi, 2017; Malik and Nautiyal, 2016. The Sørenson similarity index between the sites exhibited notable variability, with the lowest similarity recorded between Ligri and Kabban (30%) and the highest observed between Kabban and Tun (70%). The increased levels of similarity can be attributed to shorter geographical distances between areas, comparable topographical features, and similar climatic conditions.

The assessment of the species status in the region is based on its population estimation that aligns with the IUCN Red List categories (Hamid, 2020). Our findings indicate a low density and decreased spatial extent of *D. hatagirea*, highlighting the constrained distribution of species and increased vulnerability to exploitation in the Paddar Valley, a pattern observed by Semwal et al. (2010) in Uttarakhand. The decreased spatial distribution was determined by analysing the presence or absence of species by revisiting the sampling locations each year and its density across sites. In ecological research, the Importance Value Index is a frequently used metric providing a concise overview of a species ecological significance within a specific ecosystem (Körner, 2007; Rawat et al., 2010; Sharma et al., 2014). IVI is a valuable index required to prioritize species conservation efforts, to species possessing lower IVI warranting higher conservation precedence as compared to those with higher IVI values. In our study these values were notably higher as compare to the study conducted by Jamloki et al. (2021) within the Kedarnath Wildlife Sanctuary, where the exploitation of *D. hatagirea* is much higher than in the Paddar Valley. The lower IVI value across all sites may be attributed to its overharvesting and over grazing leading to reduced mature plants. While, higher IVI could signify reduced competition and increased resource utilization among coexisting species (Kandari et al., 2011; Singh, 2008; Kukshal et al., 2009). The analysis of dispersion patterns determined by the A/F ratio, revealed that *D. hatagirea* exhibited a clustered distributional pattern in Tun, whereas a random distribution was observed in the Ligri, Kabban and Bujaz regions of the Paddar Valley. The occurrence of both contagious and random distribution is a characteristic often observed in alpine vegetation (Jamloki et al., 2021). The clustered distribution pattern within a species may be attributed to limited modes of seed dispersal. Alternatively, the clustering of these species could result from the availability of microhabitats appropriate for their growth in patches.

4.2 Ethnobotanical and ecological implications

The reduction of *D. hatagirea* to small, fragmented populations in the western Himalayas underscores the extensive anthropogenic pressures on its habitat (Bhattarai et al., 2014). About 45% of the key informants including local Vaidyas and Amchis, noted a heavy reliance on this species for traditional medicines, but also identified overharvesting as the primary factor for its population decline. The leaves and tubers of this species are used in powdered form to treat erectile dysfunction in men and to cure various body ailment in the study area. It is also used as a cooling agent for body in other regions (Ganie et al., 2019; Ahmad et al., 2017; Chand et al., 2015; Malik et al., 2015a). Thus, its overharvesting practices combined with limited sustainable use measures along with over grazing and trampling limits the species regenerative capacity. Similar trend has been documented by Singh et al. (2022) in lower areas of Paddar Valley and in the western Himalaya by Dutta et al., 2022 and Singh et al., 2019. Previous research shows that human-induced disruptions have adverse effects on rare and native plant species resulting in a reduction in their population size and overall vitality (Thakur et al., 2021; Pandey et al., 2018; Negi et al., 2017; Pandey et al., 2019; Wani et al., 2021; Shrestha et al., 2021).

The detrimental impact of overexploitation and excessive grazing on the species decline and regeneration capability is widely recognized (Kala, 2000; Giri and Tamta, 2010; Malik and Bhatt, 2016; Malik et al., 2016; Haq et al., 2019). Livestock overgrazing and trampling have adverse effects on the aboveground plant structures and disrupt the species life cycle (Bhatt et al., 2005). The substantial utilization of this species for pharmaceutical purposes has significantly decreased its population placing it at risk of getting extinct (Swarts and Dixon, 2009; Malik and Bhatt, 2015a; Malik et al., 2021). Our present research also reveals that factors including overutilization, overgrazing besides absence of awareness amongst local communities are contributing to the recent population decline of *D. hatagirea* in its natural environment. These findings highlight the critical need for immediate conservation measures to safeguard this endangered species.

5 Conclusion and conservation implications

The current investigation highlights the critical conservation status of *Dactylorhiza hatagirea,* which exhibits the lowest dominance among all documented plant species in the study area. The observed decline in density, frequency, and Importance Value Index (IVI) at Tun, Ligri, and Bujaz sites underscores the species vulnerability, necessitating immediate conservation interventions. The areas proximity to the Kishtwar High Altitude National Park and Union Territory of Ladakh from the Buzun and Bujaz- Hagshu-Dharlang watersheds respectively, adds further urgency for collaborative efforts between the Forest Department and local communities.

Comparative analysis with previous studies reveals a consistent downward trajectory in *D. hatagirea* population across the Himalayas, driven by insufficient awareness, excessive livestock grazing, overexploitation and the absence of effective conservation strategies. Public awareness campaigns by involving other researchers working on large mammals like snow leopards in the region, could synergize conservation efforts and importance of this threatened species. Key conservation measures to be undertaken in the area include promoting sustainable harvesting practices, regulating livestock grazing and determining the carrying capacity of alpine pastures. The Jammu and Kashmir Sheep Husbandry Department in collaboration with the Forest Department should regulate livestock numbers grazing in these ecologically fragile areas during summer grazing seasons. Additionally, establishing check-posts at Machail and Sohal villages in summer which is the peak time of many people visiting the area due to religious tourism could help monitor and curb the illegal trade of medicinal plants.

To further support conservation, the Agriculture Department should promote agro-techniques for the large-scale cultivation of *D. hatagirea*. This would not only facilitate reintroduction into natural habitats but also address the demand for its use in local medicinal markets creating a sustainable model for both ecological and economic benefits.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The study involving human participants was approved by the Ethical Committee of the SOITS, Indira Gandhi National Open University, New Delhi. The study was conducted in accordance with local legislation and institutional requirements. Written informed consent was obtained from all participants to participate in this study.

Author contributions

AT: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. DD: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors acknowledge the Kishtwar Forest Division of the Jammu and Kashmir Forest Department for granting the necessary permissions to conduct fieldwork. Additionally, gratitude is extended to Pradeep Kumar in field surveys and the local populaces of Paddar Valley for sharing their traditional knowledge about various medicinal plants.

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 Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1475620/full#supplementary-material

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