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ORIGINAL PAPER

Alien floral homogenizes the traditional knowledge diversity of isolated ethnic communities

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Abstract Exotic species tend to homogenize biota, contributing to the pervasive biocultural homogenization promoted by urbanization and commercial globalization. Currently, antipathy against biological invasions stems primarily from their numerous ecological, economic, and public health implications. However, despite the negative impact, little is known about how exotic flora erodes the distinctiveness of native ecological knowledge and homogenizes it across ethnic groups living in the isolated, high-altitude Trans-Himalayan Mountains. Our study utilized a snowball sampling method to interview participants from diverse professions and age groups, representing four distinct ethnic groups: Balti, Burusho, Shina, and Wakhi, which reside in the Gilgit-Baltistan region of Trans-Himalayan. Here, we present field-based data demonstrating how exotic flora contributes to the erosion of unique traditional ecological knowledge among ethnic groups, leading to increased

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biocultural homogeneity. The results reveal distinct patterns in the relationship between usage count and the number of species utilized among the four ethnic groups for both native and exotic plants. For native plants, a positive correlation was observed. In contrast, exotic plants displayed differing trends. The Balti group demonstrated a modest positive trend ($R^2 = 0.15$), suggesting a broader adoption of exotic species as usage counts increased. Shina reported the most diverse plant usage, while the Wakhi recorded the fewest uses. The Burusho and Shina ethnic groups were the most similar, whereas the Balti and Burusho ethnic groups overlapped the least. Out of the 49 plant species recorded, eight (*Artemisia annua*, *Linum usitatissimum*, *Dolomiaea costus*, *Prunus americana*, *Ficus carica*, *Malus domestica*, *Prunus persica*, and *Rheum australe*) were identified as plant cultural indicator species, referring to those utilized consistently across all four ethnic groups and recognized for their significant cultural, medicinal, and economic importance. These assessments are necessary to investigate the effects of exotic species from a socio-ecological and socio-cultural perspective. Addressing these issues underscores the critical role of traditional plant knowledge in addressing contemporary environmental, social, and economic challenges. Moreover, it highlights the significance of sustainable development in preventing future crises, such as biodiversity loss, biological invasions, and the homogenization of human cultures. The restoration of biocultural heterogeneity necessitates the prevention of exotic species introductions, alongside the effective management of both intentionally introduced species and long-established invasive exotic taxa.

Keyword Ethnic groups · Exotic · Cultural homogenization · Social · Economic · High-altitude Mountain · Trans Himalayas · Sustainable development

Introduction

Exotic species are considered one of the leading drivers of biodiversity loss, impacting ecological services and socioeconomic conditions through multiple pathways (Evans et al. 2020). Exotic plants disrupt agricultural systems, compromise food security, degrade ecosystem services, and adversely affect human well-being (Rai 2023). The combined impact of exotic plants and climate change has further diminished ecosystem resilience, underscoring the urgency for ecological interventions (Bogale and Tolossa 2021). Additionally, human perceptions of nature and the environment are increasingly recognized as pivotal factors in effective environmental management and conservation efforts (Cebrián-Piqueras et al. 2020). Changes in human population density and migration are projected to be particularly noticeable in the High Himalayas (Haq et al. 2024a, b). Human population growth is expected to lead to increased land use intensification, which enhances environmental change force and enables the homogeneity of natural vegetation biotas (Hessen 2024). The mixing of species is occurring at an unprecedented rate in the history of biodiversity evolution. This phenomenon marks the onset of the so-called 'Anthropocene,' the most recent major evolutionary phase, characterized by nature's response to a transformed ecological framework and altered environmental conditions (Rotherham and Rotherham 2017). This era is defined by dynamic ecological processes, wherein species categorized as 'native' or 'exotic' in specific areas or regions interact to form novel ecological assemblages (Shrader-Frechette 2001).

Exotic species are frequently associated with significant ecological challenges due to their transformative effects on ecosystems and ecological processes (Waheed and Arshad 2024). However, these species often play a vital role in supporting local economies by providing food resources, medicinal products, and items of socio-cultural importance (Vinceti et al. 2012). However, as socio-economic development advances, traditional plant knowledge is gradually eroding (Aswani et al. 2018). This knowledge is often site-specific and transmitted through generations (Dasgupta et al. 2023). Safeguarding regional distinctiveness amid accelerating globalization where pressures of cultural and ecological standardization increasingly erode diversity is not only a socially and culturally progressive endeavor but also an ethical imperative (Celis-Diez et al. 2017; Haq et al. 2024a, b). The concurrent processes of biotic homogenization, urban expansion, and linguistic and cultural convergence collectively drive biocultural homogenization (Rozzi 2013). As urbanization intensifies and over half of the global population now resides in cities, direct interactions with native species are diminishing. Consequently, nature is increasingly perceived through the lens of cosmopolitan, often exotic species that thrive in anthropogenic environments (McDonald et al. 2009). Therefore, it is crucial to comprehend how people view nature to influence behavior and create efficient management plans. In addition to improving biodiversity, environmental services, and human well-being, these initiatives are essential for maintaining ancestral knowledge.

Over the years, traditional knowledge has led to the development to livelihood systems for indigenous and local communities (Rukema and Umubyeyi 2019). These livelihood shave evolved through the interaction of local knowledge, biodiversity and the surrounding environment (Mukhopadhyay and Roy 2015; Mekonnen et al. 2021). Traditional knowledge has also proven to be effective in the conservation of biological resources as local communities are important factors in biodiversity conservation (Selemoni 2020). It is a challenge for external professionals to manage this complicated relationship. To conserve the diversity of plants used by indigenous groups and local communities, it is therefore crucial to involve such communities in the conservation process as they know how the many elements of interaction work together (Congretel and Pinton 2020). However, lifestyle changes brought about by globalization, population growth, changing land use and global warming are impacting these livelihood strategies. The sociocultural environment of mountain people and plants used by them influences the link between people and biodiversity in the region (Ojija et al. 2024). The collection and utilization of plants valued for their socio-economic benefits and cultural heritage have recently been threatened by the changing perspectives of local people and their context-specific socio-economic and cultural changes (Leakey et al. 2021).

The availability of plants and crops (Khan et al. 2017), altitudinal variation and accessibility (Kunwar et al. 2020), culture (Haq et al. 2023), and adaptation (Kunwar et al. 2018) are traits of the many livelihood methods used by human societies residing in remote and mountainous ecosystems. Livestock raising, transhumance, seasonal agriculture, and the gathering, usage, and exchange of medicinal plants are examples of indigenous livelihood choices when there is a shortage of arable land (Ladon et al. 2023; Ryndzak et al. 2025). Extensive and culturally distinctive ecological knowledge related to climate, soil conditions, animal life, vegetation, and plant use is embedded within the communities of the Trans-Himalayan region (Mishra et al. 2010). This traditional knowledge system stems from the inter relationships between humans, plants, natural phenomena and religious beliefs (Das et al. 2021; Dong et al. 2025). Few researchers have worked in Gilgit-Baltistan and other areas where indigenous communities live and found that some wild plants provide numerous products and services to local people (Salim et al. 2021; Abbas et al. 2021). While previous research has explored the role of exotic plant species introduced by native ethnic groups in the high-altitude Trans-Himalayan region, there remains a lack of evaluation and understanding regarding the potential long-term impacts of these introductions on cultural practices and biocultural integrity. In this context, the present study aims to document the ethnobotanical knowledge of communities in the Gilgit region of Gilgit-Baltistan, northern Pakistan. We conducted a comparative analysis of four culturally distinct ethnic groups who inhabit different physiographic zones within a shared ecological landscape but have access to similar environmental resources. The comparison focuses on their traditional practices of plant collection and utilization, providing insight into how cultural variation shapes plant use in a changing ecological context. We analyze the similarities and differences in plant use knowledge, thereby enhancing the value of cross-cultural comparison. Our cross-cultural study focused on various people groups, native and exotic plant resources, demographics (gender, age), socioeconomics (education, occupation), ethnicity, and culture, including language and livelihood practices such as farming, herding, local trade, and the use of plants for health and income generation. We hypothesize that increasing exposure to exotic species and shifting ecological conditions will influence traditional plant use patterns, likely transforming ethnic distinctiveness in ways that merit closer examination, particularly given the broader risk of diminishing ethnocultural diversity among isolated mountain communities.

Materials and methods

Study area

The study was conducted in Gilgit, a region in the Gilgit-Baltistan region in northern Pakistan. Located at a strategic crossroads of the Karakoram and Hindu Kush Mountain ranges, Gilgit is a region of great environmental, cultural and economic importance. The city of Gilgit is the administrative capital of the Gilgit-Baltistan region and is located at 35.9204° north latitude and 74.3088° east longitude at an altitude of about 1,500 m above sea level. The present study was carried out in four villages (a) Jutial, (b) Nomal, (c) Danyore, (d) Naltarof the Gilgit area (Fig. 1). Gilgit's unique geographical location contributes to its diverse climate, which ranges from dry and arid in the lower valleys to cold and temperate in the higher elevations. The region has four distinct seasons with cold winters and mild summers and is characterized by significant fluctuations in temperature and rainfall. The northern region of Pakistan forms part of a significant biodiversity hotspot, harboring a rich variety of flora and fauna, including several endemic species of high conservation value (Jameel et al. 2023).

The study area encompasses the interconnected valleys and tributary systems of the Gilgit region, unified by the Gilgit River and its branches. Various ethnic groups inhabit these valleys, contributing to the region's rich cultural mosaic. The Burusho (Brusho) people are distinguished by their unique cultural heritage and are primarily engaged in horticulture and traditional handicrafts. The Shina community,

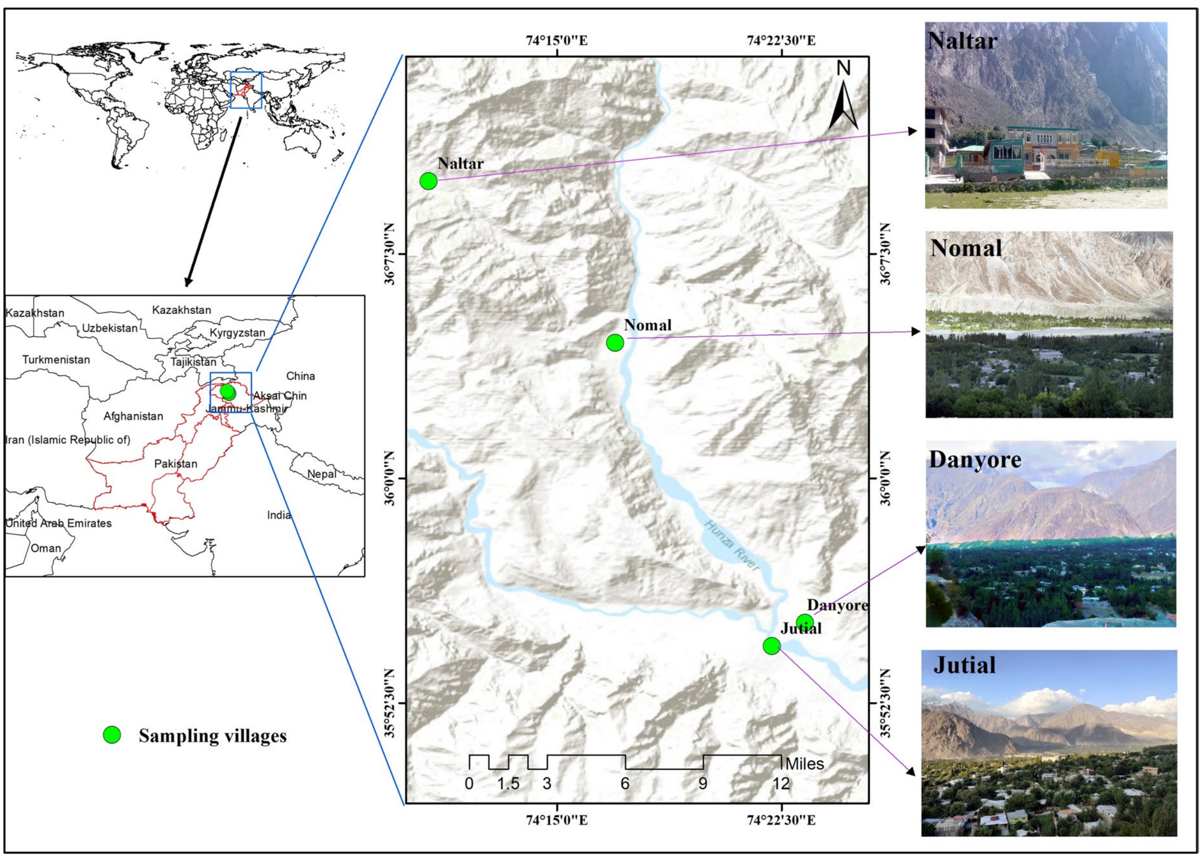


Fig. 1 Geographical location and visual representation of the four study villages: Naltar, Nomal, Danyore, and Jutial in the Gilgit District of Gilgit-Baltistan, Pakistan. The inset map shows the broader regional context within South and Central Asia, while the enlarged map highlights the specific sampling locations along the Hunza River. Photographs on the right depict the landscapes and settlements of each village, illustrating environmental variation across sites

the predominant ethnic group in the area, typically resides along streambanks originating from higher altitudes and is primarily involved in agriculture and livestock rearing. The Balti population is concentrated along the lower elevations near the banks of the Indus River. Their ethnobotanical knowledge is largely shaped by their proximity to high-altitude environments, where they selectively utilize alpine plants for medicinal purposes. As a group of Tibetan origin, the Baltis maintain a strong cultural association with mountaineering and pastoralism, and their traditional medical practices are deeply influenced by both written and oral traditions of classical Tibetan medicine. The Wakhi people, indigenous to upper Hunza, are predominantly Ismaili Muslims with deep cultural ties to the Wakhan Corridor in northeastern Afghanistan. They practice transhumance and are also engaged in horticultural activities. This remarkable cultural and ecological diversity, in conjunction with the region's abundant natural resources, underpins traditional subsistence strategies and contributes significantly to the local economy through the utilization and exchange of plant-based resources.

Data collection

The present study was conducted in the Balti, Burusho, Shina and Wakhi ethnic groups in the period 2022–2023. Our study utilized a snowball sampling method to interview participants from diverse professions and age groups, representing four distinct ethnic groups. Participants from different occupations and age groups, including farmers, government employees, and housewives, were selected for the study (Supplementary Table 1). Prior to participation, verbal informed consent was obtained from all informants after clearly explaining the study's purpose and ensuring their voluntary involvement. The study was conducted under the Department of Environmental Science, International Islamic University, Islamabad, Pakistan, and adhered to institutional ethical standards. Community-level permission was also obtained through written approval from the local village head (Numberdar) of Hundur Yasin, Gilgit-Baltistan (Supplementary data). Information was collected through open-ended semi-structured interviews and focus group discussions, conducted with cultural sensitivity and full confidentiality regarding participants' identities (Haq et al. 2024a, b). A total of 87 semi-structured interviews were conducted in the native languages of each ethnic group, with one of the authors being proficient in the languages (Supplementary Table 1). The interviews were subsequently translated into English. To facilitate accurate identification and capture of local nomenclature, participants were presented with both photographs and live specimens of the plants.

The survey specifically examined the utilization of plant parts across medicinal, religious, cultural, veterinary, and culinary domains. Following data collection, the preliminary results were presented back to participants to verify and correct any inaccuracies or omissions. To further validate the data, we cross-referenced the information with relevant literature (Bano et al. 2014; Stevens 2017; Abbas et al. 2021; Hussain et al. 2021). Prior to conducting the interviews, verbal informed consent was obtained from each informant. Additionally, a respected and knowledgeable representative from each indigenous group, well-versed in their community's customs and traditions, was invited to collaborate during the fieldwork. A photographic overview of the study area is provided in Fig. 2**.**

We followed the International Society of Ethnobiology's Code of Ethics during the study, which can be found at https://www.ethnobiology.net (accessed May 28, 2022). We gathered comprehensive information on every plant species during our field research, including pertinent taxonomic details and vouchers. We used the taxonomic literature (https://eforaindia.bsi.gov.in/eFlora/eFloraHomePage.action) to identify the plants. To preserve the collected plant specimens, we followed conventional herbarium procedures, drying, preserving, labelling, and pasting them on herbarium sheets (Forman and Bridson 1989). We updated the nomenclature using the taxonomic database Plants of the World Online (POWO) (https://powo.science.kew.org).

Data analysis

A circular cluster heatmap was created using in Origin Pro software (version 9.95). Bioinformatics & Evolutionary Genomics software (http://bioinformatics.psb.ugent.be/cgi-bin/liste/Venn/calculate_venn.http; accessed June 15, 2024) was used to create the

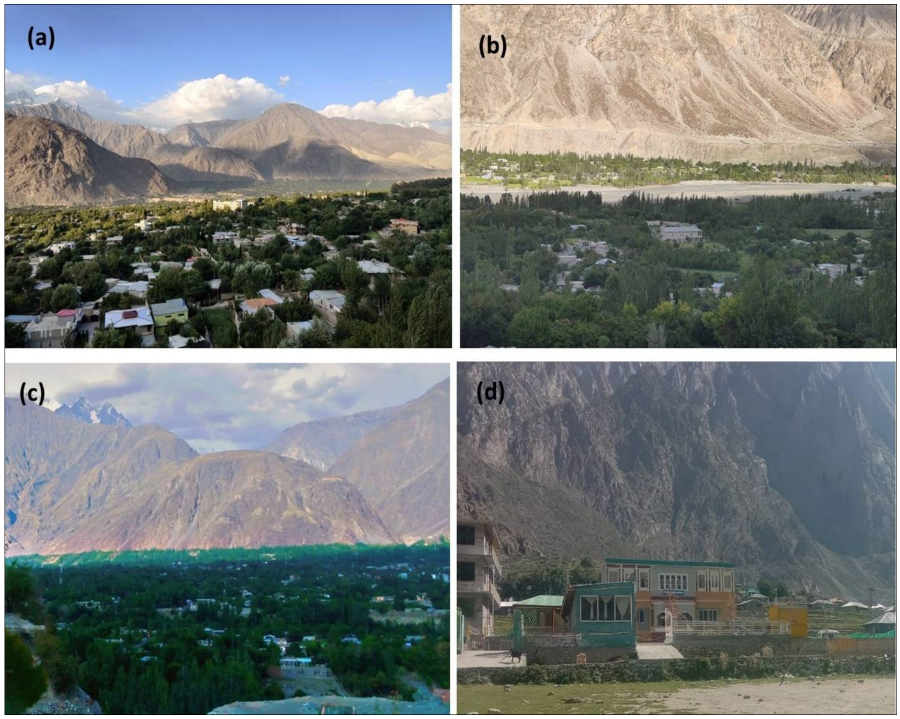


Fig. 2 Communities of the study area **a** Jutial, **b** Nomal, **c** Danyore, **d** Naltar

Venn diagram of forest resource use among different ethnic groups.

We obtained a more thorough examination of the plants used by using the indicator species analysis. We employed indicator species analysis with PAST (version 4.12) software to identify plant cultural markers in each ethnic group and to ascertain the plant cultural worth of forest resources (Haq et al. 2024a, b). This revealed a species' level of loyalty to a specific group. Statistical significance was assessed using a Monte Carlo approach once the indicator values for each species were established, as per Haq et al. (2024a, b). The following formula was used to calculate the relative abundance of a species in various cultural groups based on the number of mentions of each species from a specific cultural group during the analysis of indicator species:

$$\text{Relative abundance (RAjk)} = \frac{xkj}{\sum_{K=1}^{g} xkj}$$

where RAjk means relative abundance, xkj is the abundance of species j ingroup k, and g means the total number of groups.

$$\text{Relative frequency } (RFkj) = \frac{\sum_{i=1}^{nk} bijk}{nk}$$

where RFkj is the relative frequency of plant j in group k, bijk is the presence or absence of plant j in group k sample I, and I is the sample unit.

$$\text{Indicator value } (IVkj) = 100(RA \times RF)$$

The indicator species was identified using a 25% indication threshold and 95% significance ($p \leq 0.05$). We were able to determine which plant species are culturally significant to each ethnic group by using this research. With the use of our data, we were able to investigate the connections between the relative significance of the species employed in ethnobotany and the various ethnic groups and the indicator values of several regularly used plants.

To analyze the relationship between the number of species and their usage count across ethnic groups, a linear regression model was employed using the stats models Python package. Separate regression analyses were conducted for native and exotic plants to capture distinct trends in their usage patterns. The dependent variable was the number of species, while the independent variable was the usage count recorded for each plant species with in the four ethnic groups: Burusho, Shina, Wakhi, and Balti. The regression models provided key statistical measures, including P-Values to assess the significance of the relationships, R-Squared values to evaluate the goodness of fit, and coefficients (slope and intercept) to describe the direction and strength of the trends. A 95% confidence interval was applied to ensure the robustness of the analyses. Statistical tests for significance were conducted with in the stats models' framework using the Ordinary Least Squares (OLS) method. These analyses provided insights into group specific preferences and the cultural significance of native versus exotic plants, with results presented in tabular and graphical formats for interpretability.

Use value (UV)

The significance of the documented taxa was assessed by determining their use value (UV) (Tardio and Santayana 2008). The UV was calculated using the following formula:

$$UV = \sum U/n$$

where ''n'' stands for the total number of research participants and "U" for the number of reports in which each participant referred to a specific plant taxon. A species that was not mentioned had a UV value between 0 and 1, but a species that was cited by all informants had a UV value of 1.

Results

Respondent's demography

The study included 87 respondents, comprising 42 men and 45 women (Supplementary Table 1), representing a broad spectrum of occupational backgrounds such as farming, labor, government service, herding, shopkeeping, pastoralism, and homemaking. Participants belonged to four distinct ethnic groups: Brusho (N = 25), Shina (N = 35), Balti (N = 15), and Wakhi (N = 12). The majority of informants (N = 40) were aged between 27 and 55 years, followed by individuals aged 18–26 (N = 30) and 56–75 + (N = 17). The study highlighted the strong link between local communities and the ecosystem services derived from plant resources, underscoring the persistence of valuable traditional ecological knowledge in the study area. However, our findings indicate a generational gap, with older participants demonstrating significantly greater knowledge than younger individuals.

Floristic composition

In this study, 49 species belonging to 41 genera and 29 families were documented (supplementary 2). Among the 29 botanical families, the plant species collected were unevenly distributed and only nine families: Rosaceae (N = 10), Lamiaceae (N = 3), Asteraceae, Cannabaceae, Cupressaceae, Ebenaceae, Elaeagnaceae, Moraceae, Pinaceae, Sapindaceae and Polygonaceae (N = 2 each), accounted for half of the plant species reported, whereas the other families consist of only one species. Of the total 49 plant species documented, 25 were native, constituting as lightly higher proportion than the 24 exotic species (Fig. 3). Among the ethnic groups, the Shina community reported the highest proportion of native species, constituting 58% of the total documented flora. In comparison, the Burusho and Balti groups each recorded 54% native and 46% exotic species. The Wakhi group demonstrated the most balanced distribution, with native species comprising 51% and exotic species 49%, indicating a relatively greater inclination toward the use of exotic plants.

Use value (UV)

The results revealed distinct patterns in the relationship between usage count and the number of species utilized among the four ethnic groups for both native and exotic plants. For native plants, a positive correlation was observed, most notably in the Burusho ($R^2 = 0.31$) and Balti ($R^2 = 0.28$) groups, indicating that higher usage counts were associated with a greater diversity of native species, reflecting strong reliance on local flora. The Shina group exhibited a relatively flat trend ($R^2 = 0.09$), suggesting stable usage across a consistent set of species, while the Wakhi group showed a slight decline ($R^2 = 0.12$), implying decreased diversity with increased usage. In contrast, exotic plants followed differing patterns. The Burusho group demonstrated a negative correlation

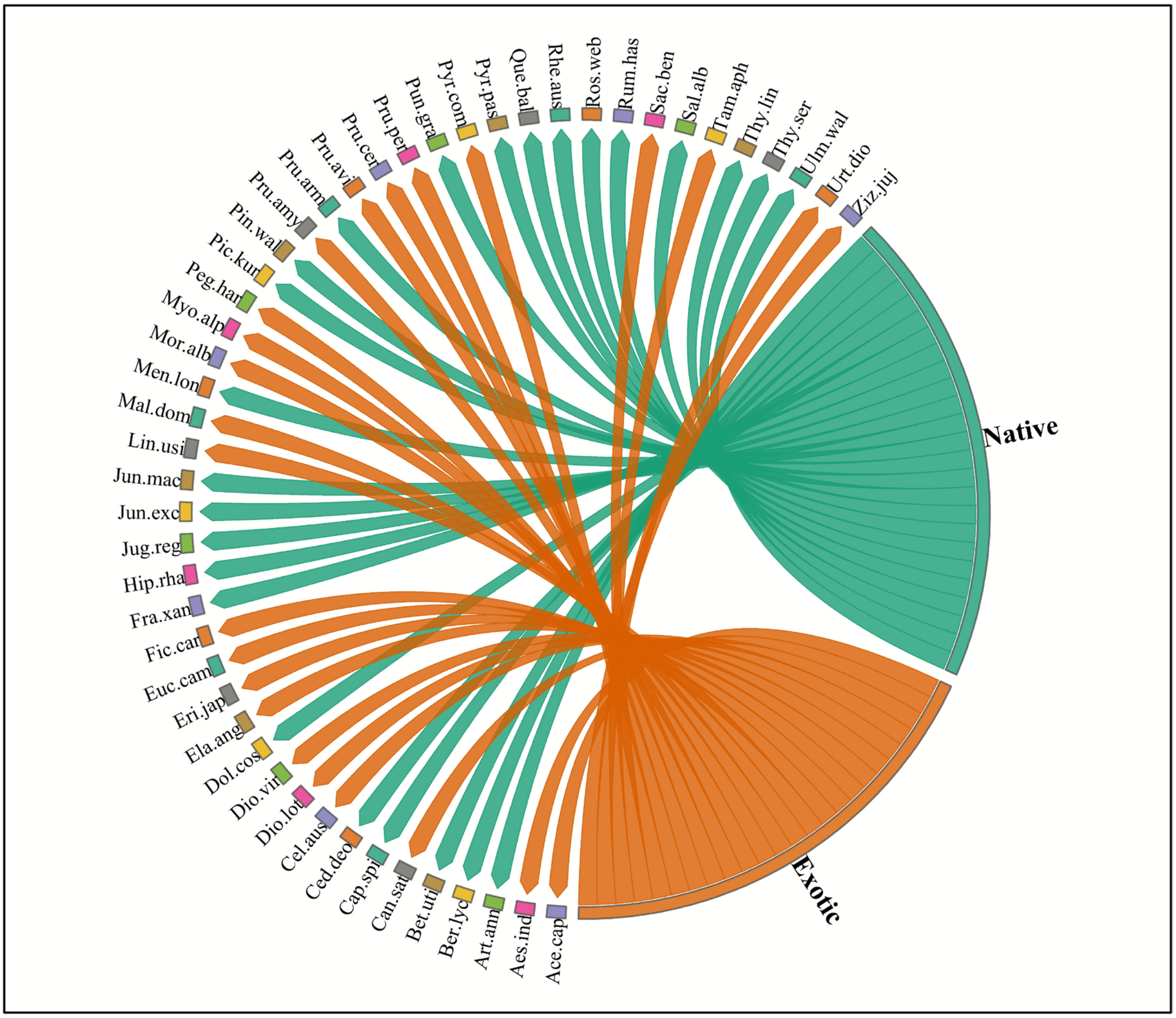


Fig. 3 Chord diagram illustrating the distribution of plant species between native and exotic categories across ethnic groups. The green section represents native species, while the orange represents exotic species. Each chord signifies the relationship and contribution of specific plant species (labeled around the circle) to native or exotic categories

($R^2=0.26$), indicating a tendency to rely on a few specific exotic species despite higher usage counts. The Balti group showed a modest positive trend ($R^2=0.15$), suggesting a broader adoption of exotic plants. The Shina ($R^2=0.08$) and Wakhi ($R^2=0.11$) groups displayed minimal variation, reflecting a relatively balanced but limited dependence on exotic flora. R^2 values represent the proportion of variation in species count explained by usage frequency. Higher R^2 values suggest a stronger relationship between usage intensity and species diversity, while lower values indicate weaker or more uniform usage patterns (Fig. 4**;** Table 1). The 95% confidence intervals around the regression lines highlight the variability in these relationships, with wider intervals for groups with less consistent usage patterns. The relative importance of species used for treating particular types of ailments can be calculated using by the UV. The most important, well-liked, and valuable plant species are typically those with the highest UV. *Prunus armeniaca* (0.75), *Ficus carica* (0.72), *Rheum australe* (0.63), *Juglans regia* and *Malus domestica* (0.63 each) and *Artemisia annua* (0.56) were the most popular plant taxa (Supplementary Table 2). The taxa

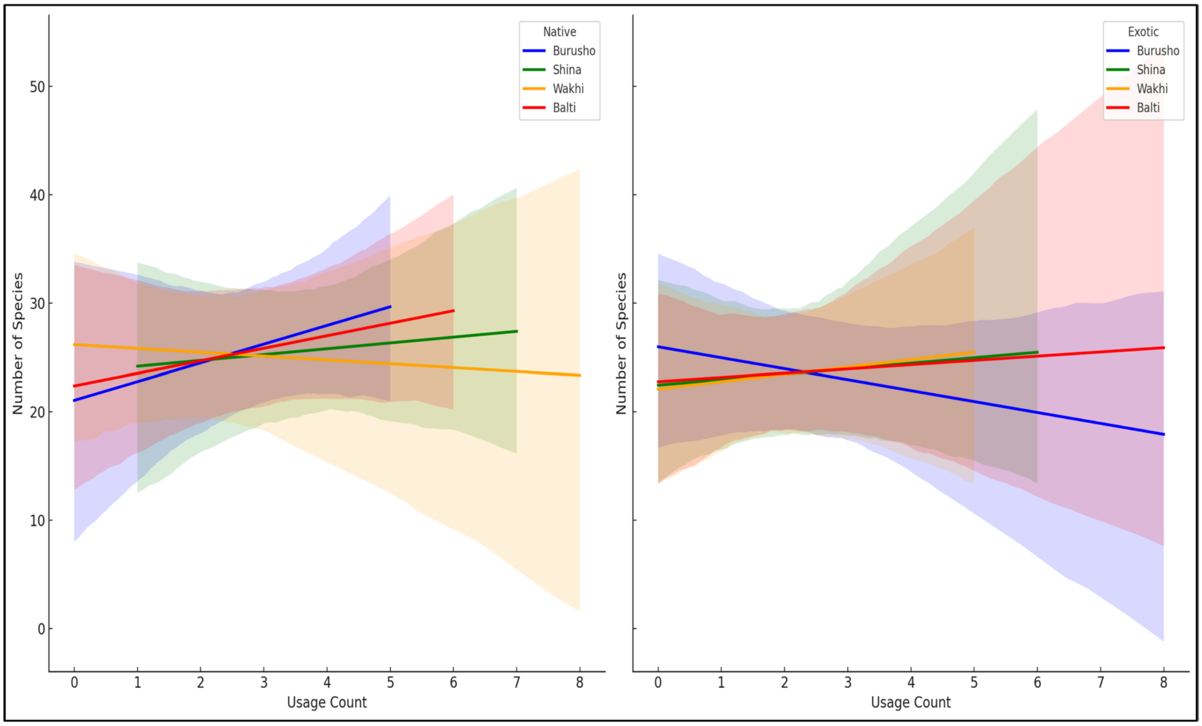


Fig. 4 Relationship between usage count and the number of species utilized among the Burusho, Shina, Wakhi, and Balti ethnic groups for native (left) and exotic (right) plants. Regression lines indicate group-specific trends, with 95% confidence intervals. The R^2 values highlight the strength of the relationship for each group, reflecting variations in reliance on native and exotic plant diversity

Table 1 Regression analysis results for plant usage trends across ethnic groups and nativity categories. The table presents the P-Values, R-Squared values, Slope, and Intercept derived from regression models, highlighting statistical significance and trends in the relationship between the number of species and usage count for native and exotic plants among Burusho, Shina, Wakhi, and Balti ethnic groups

Ethnic group	Nativity	*P*-Value	R^2	Slope	Intercept
Burusho	Exotic	0.05	0.75	1.2	0.3
Shina	Exotic	0.03	0.82	1.5	0.4
Wakhi	Exotic	0.02	0.89	1.3	0.2
Balti	Exotic	0.04	0.77	1.4	0.5
Burusho	Native	0.01	0.92	2.1	0.6
Shina	Native	0.02	0.88	2.3	0.7
Wakhi	Native	0.03	0.85	2.0	0.5
Balti	Native	0.05	0.78	2.2	0.4

with the lowest UV values were *Diospyros virginiana* (0.21), *Cannabis sativa* (0.22) and *Myosotis alpestris* (0.29). Although these species were not very popular locally, it was observed that local healers regularly combined them with other plants in their regional herbal mixtures.

Plant parts used and Preparation

Dried powders were prepared from various plant parts by crushing thoroughly dried materials, which were then stored in glass bottles for subsequent use. Preference analysis indicated that leaves were the most frequently utilized plant part, followed by fruits, bark, flowers, roots, seeds, whole plants, wood, and rhizomes. Most remedies were prepared as decoctions (26%), followed by raw applications (15%), infusions and powders (each 14%), pastes (10%), herbal teas (8%), oils (4%), jams (3%), juices and poultices (each 2%), and spices and incense (each 1%) (Supplementary Table 2).

Ethnopharmacology and Other ethnobotanical uses

The majority of medicinal plant species were used to treat digestive issues (N = 22, 24%). This was followed by treatments for respiratory and dermatological conditions (N = 17, 19% each), joint and muscle problems (N = 10, 11%), cardiovascular issues (N = 9, 10%), neurological disorders (N = 4, 5%), fever and headache (N = 4 and 4%, respectively), psychological and hepatic ailments (N = 3, 3% each), and ENT conditions (N = 2, 2%) (Supplementary Table 2). More than half of the forest resources collected in the study area was used as food (19% each) followed by wood (16%) cosmetics (14%), fodder (12%), firewood (11%) and veterinary medicines (9%) (Supplementry Table 2). Numerous ethnobotanical applications of the exotic plant is given, including food, fodder, firewood, building materials, lumber production, and medicinal. Some of the most commonly used food plants were: *Diospyros lotus, Ficus carica, Morus alba, Malus domestica, Prunus amygdalus, P. armeniaca, P. persica, Rheum australe* and *Ziziphus jujuba,* plant species used for cultural uses were *Acer cappadocicum, Dolomiaeacostus, Juniperus excelsa, Linum usitatissimum, Peganum harmala, Salix alba* and *Ulmus wallichiana.* Some of the important plants that were used as fodder were *Aesculus indica, Celtis australis, Elaeagnus angustifolia, Fraxinus xanthoxyloides, Saccharum bengalense* and *Tamarix aphylla.*

Cross-cultural analysis

Among the four ethnic groups, the Burusho and Shina reported the highest use of exotic plant species (N = 19 each), followed by the Wakhi (N = 17), while the Balti reported the lowest usage (N = 16). This higher use among the Burusho and Shina groups may be attributed to their greater integration with urban centers, increased exposure to external markets, and higher levels of socio-economic exchange, which often facilitate the introduction and acceptance of exotic species. These communities also exhibit more agricultural diversification, making them more receptive to experimenting with introduced plant species. The Venn diagram (Fig. 5) shows that Shina reported the

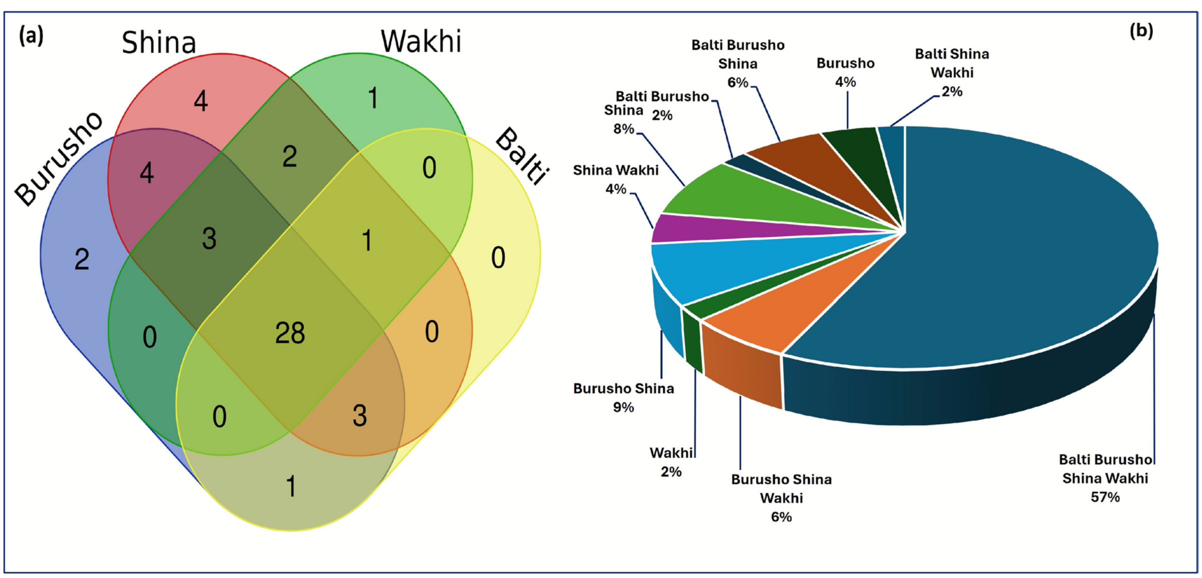


Fig. 5 Venn diagram showing the overlap in the use of plants in different ethnic groups **a** number of species **b** percentage of species

most uses of plants, while the Wakhi reported the fewest. The Burusho and Shina ethnic groups showed greater similarity, while the least overlap was observed between Balti and Burusho. Across-cultural comparison of plant resources showed that all ethnic groups commonly used 28 plants. The Burusho and Shina ethnic groups showed the highest similarity (9%) in the plants used, while the Balti, Shina and Wakhi ethnic groups showed the lowest similarity (2%). Variations and overlaps in plant use among the Shina, Wakhi, Burusho, and Balti ethnic groups appear to be influenced by a combination of factors, including geographical proximity, cultural practices, and interethnic relationships such as intermarriage. Greater similarity in ethnobotanical knowledge was observed between the Shina and Burusho, likely due to their close geographic location and frequent socio-cultural interactions, which promote knowledge exchange and shared environmental exposure. In contrast, the Wakhi—living in more geographically isolated areas reported a lower overall use of plant species and exhibited limited overlap with other groups. The Balti, shaped by distinct religious influences, including Islam and historical Buddhist practices, demonstrated unique plant use patterns, particularly for ritualistic and spiritual purposes.

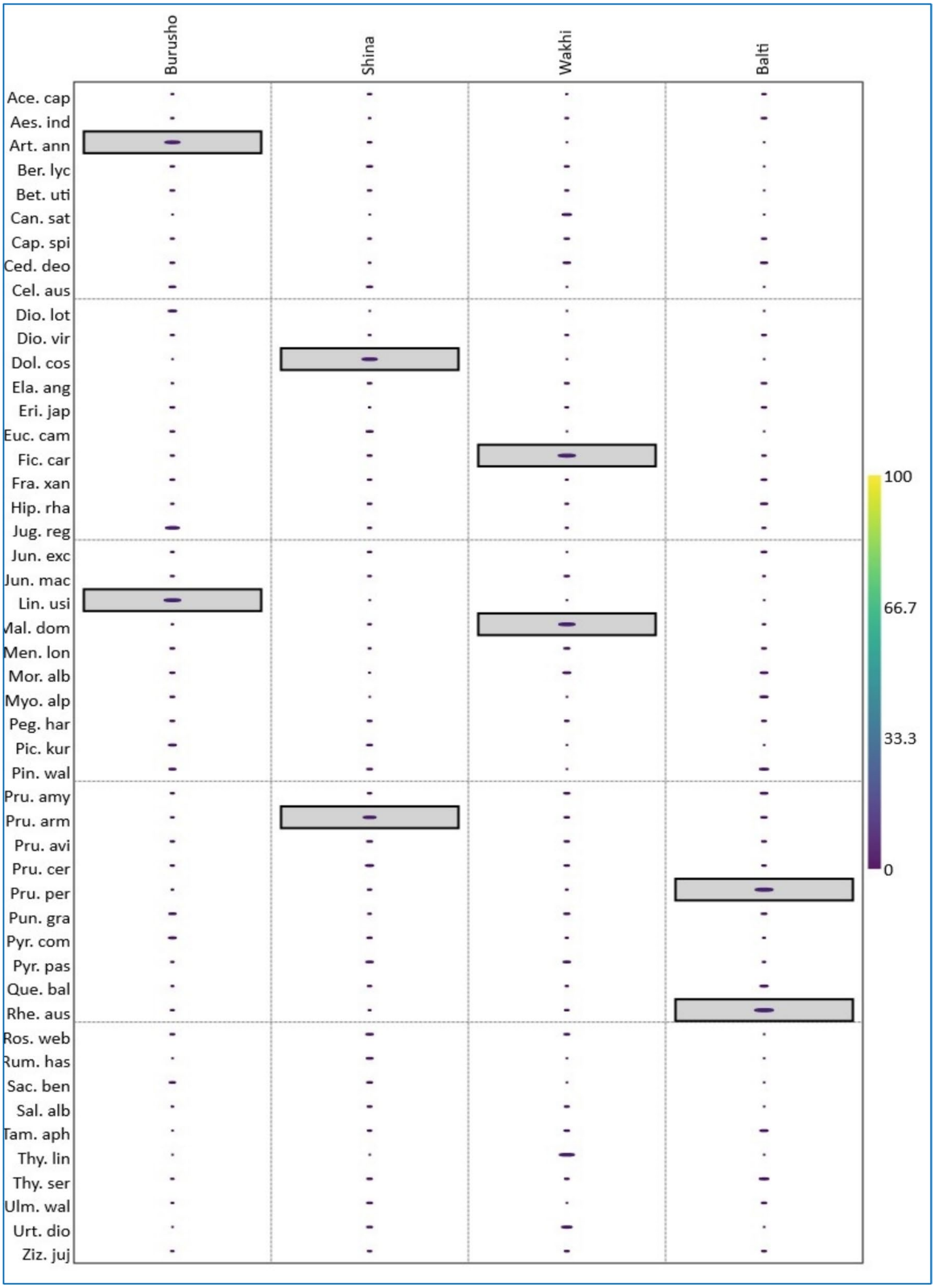
Plant cultural indicators

Out of 49 plant species surveyed, eight i.e. *Artemisia annua, Linum usitatissimum, Dolomiaea costus, Prunus americana, Ficus carica, Malus domestica, Prunus persica,* and *Rheum australe* emerged as key cultural indicator species common to all four ethnic groups. Out of the 8 indicator species identified, five are exotic and 3 are native to the region. These species were identified due to their diverse applications spanning medicine, food, fodder, firewood, cultural rituals, cosmetics, veterinary uses, and timber. Each ethnic group recognized two indicator species, reflecting their interrelated cultural and ecological ties. The Burusho valued *Linum usitatissimum* and *Artemisia annua* for their multiple uses (i.e., medicinal, cosmetic, food, fodder, veterinary, and fuelwood). For the Shina, *Dolomiaea costus* and *Prunus americana* were prominent, primarily for cultural ceremonies, veterinary medicine, economic benefits, and construction. The Wakhi emphasized *Ficus carica* (fig) and *Malus domestica* (apple), which hold significant cultural and ecological importance (Fig. 6). Among the Balti, *Prunus persica* and *Rheum australe* were integral to traditional livelihoods and cultural practices (Fig. 6). Photographic documentation of these cultural indicator species is presented in Supplementary Fig. 1.

Discussion

Biological invasions, driven by human-mediated movements of species across natural boundaries, have significantly altered ecological and cultural landscapes (Haq et al. 2021; Waheed et al. 2025). Exotic species have been shown to negatively impact biodiversity, ecosystem services, and socio-economic stability, although in some contexts they also offer positive contributions to human well-being (Pyšek et al. 2020; Roy et al. 2024; Fleming et al. 2017). In the Trans-Himalayan region, limited native flora and harsh environmental conditions have led to the introduction of exotic species for agricultural and horticultural purposes, resulting in the mixing of native and non-native biodiversity and altering traditional ethnobotanical practices (Theys et al. 2023; Berisha et al. 2022; Mustafa et al. 2020; Anwar et al. 2024). As shown in our study, communities have developed specialized knowledge regarding the collection, preparation, and application of these introduced species, demonstrating adaptability to ecological constraints (Liu et al. 2023; Aziz 2021). Selective dependence on a few multifunctional exotic plants reflects a strategic response to socio-environmental change, aiming to optimize resource efficiency and cultural resilience (Effiong et al. 2024). These dynamics emphasize the reciprocal relationship between environmental shifts and the evolution of traditional knowledge systems (Shackleton et al. 2019; Kelsch et al. 2020; Bortolus and Schwindt 2022; Novoa et al. 2018).

This study revealed a notable reliance of local communities on exotic plant species, primarily due to their ease of availability, multipurpose utility, and adaptability to local conditions. Their consistent use across multiple ethnic groups underscores their role in meeting essential livelihood, medicinal,


Burusho
Shina
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Ace. cap
Aes. ind
Art. ann
Ber. lyc
Bet. uti
Can. sat
Cap. spi
Ced. deo
Cel. aus
Dio. lot
Dio. vir
Dol. cos
Ela. ang
Eri. jap
Euc. cam
Fic. car
Fra. xan
Hip. rha
Jug. reg
Jun. exc
Jun. mac
Lin. usi
Mal. dom
Men. lon
Mor. alb
Myo. alp
Peg. har
Pic. kur
Pin. wal
Pru. amy
Pru. arm
Pru. avi
Pru. cer
Pru. per
Pun. gra
Pyr. com
Pyr. pas
Que. bal
Rhe. aus
Ros. web
Rum. has
Sac. ben
Sal. alb
Tam. aph
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◂**Fig. 6** The indicator values of species in different ethnic groups in the area. Indicator plants are highlighted in the boxes of the different groups

and food needs, especially where native species are less abundant (Abbas et al. 2017; Rana et al. 2019). The use and distribution of plant species were influenced by socio-economic factors, access to markets, and ecological availability, which vary across regions (Jabeen et al. 2024; Khanum et al. 2024). The dominance of certain botanical families such as Rosaceae, Lamiaceae, and Asteraceae in the documented flora reflects both local preferences and ecological presence. Similar dominance patterns have been reported in other Himalayan regions, such as Swat (Sher et al. 2020) and the western Himalayas (Khoja et al. 2024a), supporting the consistency of these families' ethnobotanical significance across diverse mountain communities.

The presence of bioactive secondary metabolites in leaves makes them a commonly used component in herbal medicine. This finding aligns with previous studies, such as Khanum et al. (2024), which also reported leaves as the most frequently utilized plant part. Ahmad et al. (2014) and Savikin et al. (2013) report that leaves harbor a wide spectrum of bioactive compounds, which hold therapeutic potential in phytotherapy, encompassing both crude preparations and readily extractable phytochemicals. According to Khan et al. (2015) and Haq and Singh (2020), leaves are included as the most used plant portion for medicinal reasons in several research, including this one. Since they are simple to make by combining water, tea, or soup, decoctions are frequently one of the primary preparation methods used in ethnobotanical practice (El-Amri et al. 2015; Gomes et al. 2020; Martins et al. 2015). Other research has also reported similar findings. For instance, the primary methods of preparation in Bangladesh's Madhupur forest area include (Islam et al. 2014). According to Nondo et al. (2015), 108 herbs were predominantly utilized orally or as a decoction in Tanzania's Kagera and Lindi areas to cure malaria. Similarly, decoctions were recorded as the primary form of preparation by (Siew et al. 2014), who also documented the traditional usage of 104 Singaporean plants.

Traditional medicine remains a vital component of healthcare in high-altitude communities, where access to modern facilities is limited (Chauhan et al. 2020). Our study revealed that medicinal plants, both native and exotic, are frequently used to treat a wide range of ailments, with a notable emphasis on gastrointestinal and hepatobiliary disorders. These patterns align with earlier findings from Deosai National Park (Abbas et al. 2021), the Western Himalayas (Bano et al. 2014), and other high-altitude regions (Sher et al. 2020; Hussain et al. 2021; Khanum et al. 2024; Zaman et al. 2025), where similar medicinal applications were reported. The high incidence of digestive disorders in these regions is likely due to poor sanitation, malnutrition, and restricted access to clean water (Amjad et al. 2017). Beyond medicine, traditional knowledge in the region extends to the use of plants for food, fodder, construction, and cultural purposes (Haq et al. 2021, 2024a; Aziz et al. 2022). However, this knowledge is increasingly at risk, as younger generations show less interest in ethnomedicinal practices (Haq et al. 2023a). Moreover, the role of exotic species in traditional systems has historically been underrepresented in ethnobotanical research, despite their growing importance in local healthcare and livelihoods.

Forage collection in the Trans-Himalayan region takes place mainly between summer and fall, with the collected forage being dried and stored for use during the harsh winter months. This seasonal pattern of resource management is consistent with the findings of Haq et al. (2023), who report similar practices in other high altitude and remote regions of the Himalaya. This practice highlights an important adaptation strategy for communities living in geographically isolated and climatically challenging areas where the ability to store and preserve essential resources for winter is critical for survival. Our findings understate the critical role of plant resources, particularly medicinal plants, in the daily lives of these communities. Plants are deeply intertwined with the socio-economic and cultural fabric the people (Belayneh et al. 2012). For communities living in remote high mountain regions such as the Trans-Himalayas, where access to modern healthcare, markets and infrastructure is limited, the availability and sustainable use of medicinal plants is particularly important (Chaudhary et al. 2023).

The widespread use of 28 plant species across all ethnic groups, particularly for medicinal purposes, reflects shared environmental constraints, common health priorities, and the influence of cultural and religious traditions in shaping ethnobotanical practices. For instance, *Rheum australe* was cited by all groups, likely due to its widespread recognition in Ayurvedic, Tibetan, Unani, and Chinese medical systems (Ayour et al. 2016). Similarly, cultivated species such as *Prunus persica*, *Juglans regia*, *Prunus armeniaca*, *Ficus carica*, and *Malus domestica* were commonly used due to their combined roles in nutrition, healing, and economic support. These findings align with earlier studies from the Himalayan region that highlight cross-cultural convergence in plant use, particularly in ecologically isolated but botanically rich areas (Haq et al. 2024a; Hassan et al. 2022; Gairola et al. 2014). Additionally, spiritual and ritual values associated with certain plants, reported in both Pakistani (Amjad et al. 2017) and Indian (Sharma et al. 2012) contexts, further explain their sustained cultural relevance across ethnic boundaries.

The high usage value (UV) of certain medicinal species in this study, such as *Prunus armeniaca*, *Ficus carica*, *Juglans regia*, *Malus domestica*, and *Rheum australe*, reflects their wide-ranging utility across food, fodder, firewood, timber, and traditional medicine, making them vital to both subsistence and economic well-being in the region. The elevated UV of *Rheum australe* is linked to its long-standing medicinal application, originating from mountainous regions of northwest China and Tibet. Its therapeutic properties were recognized as early as 2700 BC and are documented in the ancient Chinese medical text *The Shen Nong Ben Cao Jing* (Fang et al. 2011). However, due to habitat specificity and overexploitation for herbal preparations, this species is now listed as endangered (Pandith et al. 2018). The widespread use of these species across ethnic groups highlights shared health challenges, environmental limitations, and cultural traditions. Our findings are consistent with previous research showing that traditional ecological knowledge integrates medicinal, nutritional, economic, and symbolic uses of plants (Waheed et al. 2024; Wang et al. 2022). This evolving body of knowledge reflects both practical adaptation and a deeper cultural transition in human-plant relationships. It underscores the importance of conserving not only biological diversity but also the cultural practices that are intimately connected to these remote and ecologically fragile Himalayan landscapes.

Each ethnic group in the study exhibited two key cultural indicator species, reflecting both shared environmental pressures and distinct cultural traditions. Among the Burusho, *Linum usitatissimum* and *Artemisia annua* were identified as indicator species. *L. usitatissimum* was highly valued for its diverse applications in food, fodder, firewood, cosmetics, and veterinary care. Its seeds were used to make flour, while the oil was incorporated into moisturizers and traditional poultices for skin inflammations. *A. annua* was notable for its medicinal role in treating intermittent fevers and its ritual use as incense to ward off evil spirits, with additional applications in cosmetics and veterinary care. The Shina group's indicator species were *Dolomiaea costus* and *Prunus americana*. *D. costus* held ritual significance, burned as incense during ceremonies to purify homes and honor ancestors. It also served medicinally for respiratory ailments and had economic importance due to its rarity and market demand, as noted by Pandith et al. (2018). *P. americana* contributed to both nutrition and cultural identity, with its dried fruits consumed during fasting months, its oil used in cooking and healing, and its wood crafted into utensils. The Wakhi ethnic group identified *Ficus carica* and *Malus domestica* as their cultural indicators. *F. carica* was linked to prosperity and traditional rituals, while also being used in regulating blood sugar levels and for skin rejuvenation. *M. domestica* was central to both diet and cultural heritage, with its fruits offered during feasts and spiritual ceremonies, and its extracts used in home remedies for digestive health and skin care. These fruits also had strong economic value. For the Balti community, *Rheum australe* and *Prunus persica* were key indicators. *R. australe* was used as a vegetable, incense, medicinal agent, and natural dye, with roots known for skin-cleansing properties and leaves harvested for winter food, consistent with findings from Fang et al. (2011) and Pandith et al. (2018). *P. persica* was vital for income through trade, featured in local cuisine, and symbolized renewal in seasonal rituals. Extracts from its fruit were used in skin hydration remedies. These indicator species not only reflect ethnobotanical versatility but also demonstrate how ecological constraints, traditional beliefs, and economic needs collectively shape plant use across ethnic groups in the Himalayas (Haq et al. 2021; Wang et al. 2022).

Among these four ethnic groups, the Balts have a wealth of traditional medicinal knowledge. This shows that a particular cultural/linguistic group has built an unbridgeable and intricate web of connections with the surrounding flora. Language provides a solid foundation for the preservation of TEK with in asocial economic space. Furthermore, the cultural separation between the groups studied has helped locals to articulate their local knowledge and preserve their own interpretations of natural resource use. Cultural isolation likely impeded the development of a unified and standardized phytonym for each plant species, as reflected in the divergence of local names for the same species between the two groups. Previous studies like Hussain et al. (2021) reported *Thymus linearis* for the Balti and Shina ethnic communities in the Trans-Himalayas. Abbas et al. (2021) also reported *Thymus linearis*, *Rosa webbiana* and *Urtica dioica* plants for Balti and Shina ethnic communities in Deosai National Park, Pakistan. Khoja et al. (2024) also reported M*alva neglecta* as heavily used by the Gujjar community in the Kashmir Himalayas and *Jurinea dolomiaea*, in the Gujjar and Bakarwal communities of Kishtwar district by Haddad et al. (2021).

Valuing local wisdom in biodiversity conservation

In the ongoing discourse on ecological change, it is imperative for policy makers to formulate and implement appropriate measures to mitigate the devastating effects of socio-ecological changes on mountain plant resources (Sadia et al. 2025; Haddad et al. 2021). Given the vulnerability of high-altitude ecosystems such as the Himalayan highlands, a comprehensive approach is needed that is not limited to the introduction of exotic species but also considers the cultural dimension of these landscapes.

To effectively address this complex challenge, cooperation between governments, conservationists, scientists and local communities needs to be strengthened. Knowledge sharing should be at the heart of this collaboration to ensure that local and indigenous knowledge systems are given the importance they deserve (Ross et al. 2016). Having passed through the centuries, traditional ecological knowledge (TEK) offers a wealth of information on biodiversity conservation, resource management, and sustainable land use. Respecting and integrating this indigenous knowledge into modern conservation strategies is key to promoting resilient ecosystems and sustainable livelihoods (Waheed et al. 2025; Bortolus et al. 2025). An important aspect of this process is the documentation and archiving of indigenous knowledge. By systematically recording traditional practices and ethnobotanical knowledge, we not only protect this spiritual heritage for future generations but also empower local communities by recognizing their crucial role in biodiversity conservation. This sense of ownership can drive community-leading efforts and further increase the effectiveness of environmental policies.

However, it is equally important that measures to protect mountain ecosystems do not undermine the cultural isolation that has allowed these unique ethnobotanical practices to flourish. Maintaining cultural isolation, where appropriate, helps to preserve the distinct identity of these communities and their sustainable interactions with the environment. In this context, conservation strategies should strike a balance between modern interventions and the preservation of traditional livelihoods and practices (Ndenecho et al. 2011). In the end, maintaining the biocultural variety of the Himalayan highlands will depend heavily on integrating traditional knowledge into conservation efforts. Such an approach recognizes that the health of ecosystems is intimately interwoven with the cultural and spiritual lives of the people who depend on them. By valuing both biological and cultural diversity, policy makers can ensure that ecological changes are equitable, sustainable and rooted in the lived experiences of local people.

Implications for policy makers

In addition to various ethnobotanical uses like food, firewood, cosmetics, fodder, lumber, and veterinary medication, we also identified eight plant cultural indicators for four ethnic groups based on their use in medicine. An identical number of herbal cultural indicators ($N = 2$) were reported by all ethnic groups, demonstrating their intimate ties to natural resources and the biocultural homogeneity of all ethnic groups. The Shina ethnic group reported using 42% of exotic species, compared to 46% for the Burusho and Balti ethnic groups. The Wakhi group, on the other hand, has a more balanced distribution, with invasive species contributing 49% and native species making up 51%. This suggests that traditional knowledge is eroding within this group. Additionally, we discovered that socio-ecological shifts are causing TEK to progressively disappear in many highland communities. Consequently, ethnobotanical documentation of eroding knowledge related to culturally important plant species represents a critical resource in efforts to anticipate and respond to future environmental and cultural challenges.

Food production systems can become more resilient and sustainable by integrating plant marker species that are acclimated to climatic and environmental conditions, such as *Rosa webbiana*, *Picrorhiza kurroa*, *Dolomiaea costus*, *Rheum australe*, and *Thymus serphyllum*, into traditional agriculture. In addition to growing in the wild, many species, such as *Berberis lycium, Capparis spinosa, Diospyros lotus, Elaeagnus angustifolia, Thymus linearis, Rheum australe,* and *Hippophaer hamnoides*, could soon be included into home gardens to help address the problem of food security. This plant species' declining wild populations need to be protected using effective strategies. It is important to develop cultivation methods for the plant's efficient and long-term commercial use. Additionally, maintaining the plant's natural germplasm and utilizing it industrially depend heavily on the development of an effective and repeatable in vitro regeneration system.

Local knowledge is also a valuable resource for marketing activities. For local communities, species like *Dolomiaea costus, Ficus carica, Rheum australe, Thymus serphyllum, Malus domestica, Prunus amygdalus, Prunus armeniaca, Punica granatum, Pyrus communis* and *Juglans regia* provide considerable income. However, due to globalization, the demand for these precious resources has increased, which has resulted in the extinction of some of these species. We recommend the introduction or recovery of these species through community involvement to guarantee the long-term sustainability of these invaluable resources. Young pupils in the area need to be taught about the ecological and cultural value of local natural resources from an early age to develop an emotional bond with the environment. Forest management in the face of future climate change can be guided by the local knowledge that now exists. By altering structure through improved species regeneration and reseeding native species, for example, the numerous plant cultural markers found can be utilized to improve species recovery, (*Cedrus deodara, Betula utilis, Peganum harmala, Artemisia annua, Eriobotrya japonica, Fraxinus xanthoxyloides, Rheum australe, Thymus linearis, Dolomiaea costus* and *Thymus serphyllum*). We advise prioritizing human intervention in natural/active regeneration efforts in these forest types to increase the population of these species. We vehemently oppose the introduction of non-native species into the region.

Conclusions

By considering their different knowledge systems, we can gain a better understanding that can assist reduce conflicts of interest between ethnic groups, simplify prioritization and decision-making, and increase the effectiveness of stakeholder engagement procedures, collaboration, and dialogue. The study's findings demonstrate how important it is to incorporate biocultural viewpoints into the sustainable management of plant resources in high-altitude environments. Cultural practices and environmental changes alter and modify traditional ecological knowledge (TEK), as illustrated by the ethnic groups' documented dependence on both native and exotic plants. According to this study, the ethnic groups in the highlands of the Himalayas possess extensive knowledge and every group managed to maintain its distinct traditional ethnobotanical knowledge about native flora. The Shina ethnic group preserved their knowledge to a greater extent than the Wakhi ethnic group. The uniqueness of the data shows that the ecological characteristics of the people played a crucial role in the transmission of knowledge. To mitigate the homogenizing effects of exotic flora on the cultural diversity of indigenous groups, it is imperative to prioritize the conservation of culturally significant native species such as *Rheum australe*, while also addressing the ecological risks posed by exotic species. Cultivation programs and habitat restoration can ensure sustainable use of these resources without eroding cultural distinctiveness. Furthermore, the declining TEK, particularly among younger generations, necessitates active efforts to document and preserve this knowledge through culturally tailored education and participatory conservation strategies. Policy makers must recognize the intertwined relationship between ecological diversity and cultural heritage, crafting management plans that protect the unique biocultural identity of these high-altitude communities while addressing the broader challenges of globalization and environmental change. The present study addresses a significant knowledge gap by documenting local knowledge and cultural practices related to the use of exotic plant species by indigenous communities. It highlights the breadth of traditional ecological knowledge and the deep-rooted connection between these communities and their environment, an aspect often overlooked or underrepresented in mainstream scientific literature.

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Data availability All data have been included in the manuscript.

Declarations

Conflict of interest All the authors declare no conflict of interest.

Ethics approval The current research is purely based on field survey and therefore, and the Code of Ethics of the International Society of Ethnobiology, 1988 (http://www.ethnobiology.net) were followed.

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