A comprehensive review of regional distribution and traditional uses of *Rhododendron campanulatum* in the Indian Himalayas: Implications for sustainable conservation

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Review

Abstract

Background: The Indian Himalayan Region (IHR), one of the world's most prominent biodiversity hotspots, harbors rich alpine and sub-alpine flora that are vital for ecological stability and local livelihoods. *Rhododendron campanulatum* is a key species of significant ecological and cultural importance, widely distributed across temperate and sub-alpine zones at altitudes ranging from 2800 to 4800 m above sea level. Despite its critical role in slope stabilization, hydrological regulation, and habitat structuring, a comprehensive synthesis of its distribution, ecological functions, ethnobotanical relevance, and conservation challenges remains limited.

Methods: A narrative review was performed with a thorough search of published literature on *Rhododendron campanulatum*. The peer-reviewed articles, review papers, book chapter, and reports were searched from main scientific databases such as Google Scholar, Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Taylor & Francis. The literature gathered was analyzed and synthesized in order to understand the distribution, ethnobotanical value, ecological roles, phytochemistry, conservation status and future research needs of the species.

Results: R. campanulatum maintains high-altitude ecosystem integrity through slope stabilization, hydrological regulation, and biodiversity support. Ethnobotanical synthesis indicates differentiated use, with wood for fuel, flowers for food, medicinal, and ritual applications, and leaves for fumigation and related uses. The presence of diverse phenolic compounds like flavonoids and terpinoids in *Rhododendron campanulatum* suggests that the species possess significant antioxidant and stress protective mechanism, which may contribute to its adaptation to harsh high-altitude environments and support its traditional medicinal application. Concurrently, ecological studies demonstrating climate-sensitive growth, regeneration and population dynamics suggest that this species is highly responsive to changing temperature and moisture regimes, making it a useful indicator of climate-driven ecological change in Himalayan tree-line ecosystem. Despite its ecological importance, population assessment from the western Himalayan, revealed a substantial decline in adult density from 2845 stems/ha at 3100 m to 1210 stems/ha at 3550 m, representing a reduction of approximately 57.5%, highlighting the potential demographic shifts along elevational gradient.

Conclusion: R. campanulatum represents a vital socio-ecological resource in the IHR. Climate change, overexploitation, grazing, and invasive species creating a major risk to it, notwithstanding its ecological and medicinal significance. Its natural regeneration and dispersal in the Himalayan region are being affected by these circumstances. Nevertheless, few research has thoroughly evaluated its long-term survival tactics, regeneration dynamics, and conservation status. So, the current study focuses on the Coordinated strategies involving in situ conservation, ex situ propagation, and community-based stewardship in the conservation and sustainable management of this species.

Keywords: Climate change, Ethnobotany, Indian Himalayan region, *Rhododendron campanulatum*, Sustainable Conservation

Background

Comprising approximately 20 % of the nation's geographical area, the Indian Himalaya spans approximately 3,000 km in length and 220-300 km in width and has rightly earned the global epithet as 'Water Tower' of South Asia (GBPIHED 2023). Its steep gradients and wide range of topographic variations render it suitable to host a diverse range of climatic zones ranging from subtropical forests, temperate woodlands to alpine meadows that in turn support a massive share the subcontinent's plant diversity and encompass myriads of species that have great economical and medicinal importance (Moran *et al.* 2025). The immensely varied flora serves several crucial functions such as water regulation, sediment checking, preventing erosion, carbon sequestration and as source of fodder, fuelwood and medicine besides their cultural importance (Bisht *et al.* 2020) which makes them the main focus for community-led conservation initiatives (Karki *et al.* 2024; Banerjee *et al.* 2018; Paul *et al.* 2017).

However, anthropogenic pressures, excessive exploitation of plant resources, rapid urbanization, and increasing rate of climate change are gradually changing its distributions, pushing elevation ranges higher, and altering community composition throughout the Himalayan region (Pandey *et al.* 2021; Das & Lahiri 2018).

In order to assess the species current vulnerability status and plan management strategies that maximize its utility to humans without compromising its sustenance, dedicated interdisciplinary research that incorporates vegetation surveys, oral traditions and communitive-based conservation efforts has become the need of the hour (Mishra *et al.* 2018; Sharma *et al.* 2020). *Rhododendron campanulatum* D. Don (2n = 26) is an evergreen and gregarious shrub of family Ericaceae that stands out as an ecologically significant species of the Himalayan subalpine and treeline communities. This species is currently listed as "Least Concern (LC)" species on the IUCN Red List of Threatened Species (Meena *et al.* 2025).

Botanically, the species typically forms low shrubs (1 m to 2.5 m in height) that bear coriaceous, elliptic-oblong leaves and campanulate to broadly funnel-shaped flowers (white and pale pink to deep rose). The ecological and socio-cultural significance of *R. campanulatum* extends way beyond its remarkable floral arrangement, marking it a crucial component of high-altitude Himalayan ecosystems. Acting as a cornerstone shrub of the treeline ecotone, *R. campanulatum* contributes to stabilizing soil, intercepting snow, and acting as microclimate buffer, thereby, contributing to the watershed-regulation in the Himalayan ecosystem (Koirala *et al.* 2023). As a dominant shrub species, it helps stabilize fragile slopes, regulates hydrological cycles, and provides essential habitat for numerous alpine plants and animals. Its dense canopy and extensive rhizosphere facilitate snow and soil moisture retention, which supports the upward migration of treeline species (Khan *et al.* 2024). Its physiological and phenological sensitivity to precipitation patterns makes it an apt indicator of climate ecological shifts induced by climate change.

Dendroecological and ring-width studies have revealed that its growth patterns provide significant evidence of recent winter and spring warming trends as well as drought signals in the central Himalaya. These findings have important implications for the species' elevational shifts and broader treeline dynamics under ongoing climate change (Panthi *et al.* 2021; Schwab *et al.* 2022).The species holds great ethnobotanical significance among Himalayan communities, particularly for treating colds, coughs, and inflammatory ailments (Bhattacharyya and Sanjappa, 2012). Phytochemical and ethnobotanical surveys have shown that its leaves and flowers contain phenolics and flavonoids, reinforcing its widespread medicinal and cultural uses (Lepcha, 2013).

Despite its multifaceted functions and cultural relevance, the survival of *R. campanulatum* is threatened by several factors, highlighting significant gap in current scientific understanding and conservation efforts. In the Current time frame research regarding of this species focusing majorly in the utilization of the species whereas long-term monitoring of population dynamics, regeneration patterns, and demographic trends throughout its whole Himalayan region is still lacking, and the majority of current research is based on short-term observations. The physiological, biochemical, and genetic mechanisms enabling adaptation to drought, snowpack decrease, and temperature extremes are still poorly understood, despite the documentation of climate-induced changes in distribution and treeline dynamics. Another major aspect of the research such as population genomic databases, adaptive genetic markers, and landscape-level genetic connectivity evaluations is completely disappeared from the current senario. Along with that, climate change is the most critical threat that is gradually leading to upward elevation shifts and modifications in community composition at the treeline (Pu and Lyu 2025). Unplanned exploitation of plant parts, along with uncontrolled grazing, had adversly affected the regeneration of the species, resulting a substantial decline in adult density from 2845 stems/ha at 3100 m to 1210 stems/ha at 3550 m, representing a reduction of approximately 57.5% (Jamloki *et al.* 2022). Forest fires and fierce competition from invasive species such as *Polygonum polystachyum* and *Ageratina adenophora* further destroys its regeneration niches by adverse alteration of soil properties and microclimatic conditions. The situation is made worse due to a lack of awareness among local communities, which makes it vulnerable to range contraction, declining heterogeneity and in some cases, extinction of local populations (Sharma *et al.* 2020).

Given these escalating pressures, a comprehensive review of the current distribution, ethnobotanical importance, recent conservational work and challenges facing by *R. campanulatum* is not only essential for conserving a species of exceptional ecological and cultural significance but also crucial for deepening our understanding of Himalayan ecosystem functioning and its responses to rapidly accelerating climatic and socio-economic transformations. In this context, the present study proposes a holistic, ecology-driven framework that integrates current distribution, traditional ethnobotanical knowledge, recent conservation approaches, major persisting challenges and future directions to promote the effective conservation of the species, while simultaneously strengthening overall forest ecosystem functioning. The core objectives of this study were:

1. To assess the current distribution and ethnobotanical knowledge of *R. campanulatum* in the Indian Himalayan Region (IHR).
2. To evaluate the effectiveness of existing conservation strategies and policies of *R. campanulatum* and identify persisting challenges in implementation.
3. To propose future conservation approaches for enhancing ecological resilience and climate adaptation of *R. campanulatum* in the IHR.

A comprehensive understanding of *R. campanulatum* requires the integration of ecological, ethobotanical, consevation and genom approaches within a single research framework. Ecological studies provide insights into species distribution, habitat preferences, regeneration dynamics, physiological adaptation and response to climate change across Himalayan treeline ecosystem. Ethnobotanical knowledge complement these findings by documenting traditional practices, medicinal application, cultural significance and resource use pattern among the indigenous communities, thereby highlighting the socio-economic value of the species. Conservation research contributes strategies for habitat restoration, population monitiring, ex-situ propagation and climate resilient management. Simulteniously, emerging genomic tools offer oppurtunities to access genetic diversity, population structure, adaptive variation and evolutionary potential, enabling the identification of the resilient population and conservation priorities. Integrating these complementary area of research can facilitate evidence-based conservation planning, strengthen community participation and enhance the long-term adaptive capacity of the species. Such a multidisciplinary framework is essential for ensuring both the ecological persistence of the species and the preservation of the traditional knowledge system associated with it.

Literature Search and Review Approach

The current study is a narrative review, and it was aimed at synthesizing the existing knowledge on the distribution, ethnobotanical use, ecological roles, phytochemistry, conservation status and to propose future research priorities of *Rhododendron campanulatum* in the IHR. The specific literature was retrieved from various scientific databases such as google scholar, scopus, web of science, science direct, springer link, Wiley online library, and Taylor & Francis online. Books, book chapters, government documents, institutional publications, and conference proceedings were used to obtain additional information. The review predominantly incorporated recent literature published during 2020-2026 (approximately 80% of the total references) to reflect current scientific understanding and research developments concerning *Rhododendron campanulatum*. Earlier studies were selectively included where they provided foundational insights into the species' taxonomy, biogeography, ecological functions, traditional uses, and conservation history. Such an approach facilitated the integration of both contemporary evidence and established knowledge, thereby ensuring a comprehensive and balanced assessment of the available literature.

Combination of keywords were used to conduct the literature search including "*Rhododendron campanulatum*", "Indian Himalaya", "ethnobotany", "traditional uses", "phytochemistry", "ecology", "climate change", "regeneration", "conservation", "genetic diversity", and "treeline dynamics". Peer reviewed literature and authoritative reports relevant to the aims of the review were given preference. The retrieved literature was analyzed and categorized into primary thematic areas such as distribution and biogeography, ethnobotanical uses, phytochemistry and medicinal uses, ecological importance, conservation, adaptation to climate change, and novel genomic studies. To determine current knowledge, gaps and future priorities for conservation of the species, information from the selected sources was synthesized qualitatively.

Distribution Patterns and Biogeographical Drivers in Indian Himalayan Region

Rhododendron campanulatum is a widespread subalpine shrub of the Sino-Himalayan floristic belt, occurring across the Indian Himalayan Region (IHR) from the western to the eastern Himalaya and extending into neighboring Nepal, Bhutan and south Tibet. Within India its principal occurrences are recorded from Jammu & Kashmir in the west through Himachal Pradesh and Uttarakhand, and eastwards into Sikkim and parts of Arunachal Pradesh, with the species typically occupying montane to subalpine belts between ~2,800 and 4,400 m above sea level depending on local topography and exposure (Table 1).

It frequently forms dense shrublands vegetation near the upper forest limit, where it represents a dominant structural component of Himalayan tree-line ecotones. The distribution of the species is strongly governed by climatic and topographic gradients. Low mean annual temperature, prolonged snow cover, high atmospheric humidity, acidic soil and steep elevational gradients create suitable environmental conditions for its establishment and persistence. The species is most commonly associated with subalpine forest donated by *Quercus leucotrichophora, Q. dilatata, Q. semecarpifolia, Abies pindrow* and other high altitude woody taxa. Toward the upper tree line, it frequently forms extensive krummholz communities that contribute to slope stabilization, snow retention and microclimatic buffering (Singh *et al.* 2025).

Recent elevational studies indicate that regeneration success and leaf functional traits vary systematically along climatic gradients. Seedling abundance tends to increase at higher elevation, while leaf size decreases with increasing altitude, suggesting adaptive responses to colder temperature, stronger winds and shorter growing seasons. Such morphological plasticity enables the species to persist under harsh alpine conditions and may facilitate its gradual upward migration under contemporary climate warning scenarios (Karki *et al.* 2024)

Ecological niche modelling and GIS-based habitat suitability assessments further reveal that the current distribution of the species is closely linked to temperature seasonality, precipitation during the coldest quarter, elevation and topographic heterogeneity. Ensemble machine learning models predict that highly suitable habitats are concentrated in Himachal Pradesh, Uttarakhand, Sikkim and adjacent regions of Nepal and Bhutan (Satish *et al.* 2024).

From a biogeographic perspective, the distribution of this species reflects both historical Himalayan uplifts processes and contemporary climatic control. The species exhibits strong habitat specificity towards cool, moist, high-altitude environments and therefore serves as an important indicator of ecological change in Himalayan tree-line ecosystems. Its distribution pattern highlights the combined influence of altitude, climate, edaphic condition and landscape heterogeneity in shaping Himalayan plant diversity and ecosystem resilience (Sekhar and Srivastava, 2010).

Thus, the altitudinal and ecological distribution of *Rhododendron campanulatum* spans a wide environmental gradient from the moist temperate understory to the subalpine forest and marginally into dry temperate belts, highlighting its remarkable ecological amplitude and adaptive significance within Himalayan Forest ecosystems

Table 1. State wise distribution of *Rhododendron campanulatum* in Indian Himalayan Region

State / Region	Representative Districts	Elevation (m a.s.l.)	Forest Type	Associated Species
Jammu & Kashmir (Union Territory)	Anantnag, Baramulla, Kupwara, Kishtwar, Doda	3,000-4,200	Sub-Alpine Birch-Fir Forest (14/C1b); Moist Temperate Deodar Forest (12/C1a)	*Abies pindrow*, *Betula utilis*, *Picea smithiana*, *Quercus semecarpifolia*, *Rhododendron arboreum*, *Juniperus wallichiana*, *Salix* spp.
Himachal Pradesh	Kullu, Kinnaur, Lahaul &Spiti, Shimla, Chamba	2,800-4,200	Moist Temperate Deodar and Spruce-Fir Forest (12/C1a, 13/C3); Sub-Alpine Birch-Fir Forest (14/C1b)	*Abies spectabilis*, *Picea smithiana*, *Betula utilis*, *Cedrus deodara*, *R. arboreum*, *R. lepidotum*, *Acer campbellii*, *Viburnum cotinifolium*
Uttarakhand	Chamoli, Rudraprayag, Pithoragarh, Bageshwar, Uttarkashi	3,000-4,400	Sub-Alpine Birch-Fir Forest (14/C1b); Moist Temperate Oak-Conifer Forest (12/C1a)	*Abies spectabilis*, *Betula utilis*, *Quercus semecarpifolia*, *R. arboreum*, *Juniperus communis*, *Acer caesium*, *Viburnum grandiflorum*
Sikkim	North Sikkim, East Sikkim	3,000-4,200	Eastern Himalayan Moist Temperate Forest (12/C1a); Sub-Alpine Birch-Fir Forest (14/C1b)	*Abies densa*, *Betula utilis*, *R. arboreum*, *R. barbatum*, *Acer campbellii*, *Tsuga Dumosa*
Arunachal Pradesh	Tawang, West Kameng, Upper Subansiri	3,000-3,800	Temperate Broadleaf-Conifer Mixed Forest (12/C1b); Sub-Alpine Scrub (15/C1)	*Abies densa*, *R. campanulatum*, *R. arboreum*, *Juniperus wallichiana*, *Sorbus microphylla*, *Salix denticulata*
West Bengal (Darjeeling Hills)	Darjeeling, Kalimpong	2,800-3,600	Eastern Himalayan Moist Temperate Forest (12/C1a)	*R. arboreum*, *R. barbatum*, *Abies densa*, *Quercus lamellosa*, *Acer pictum*, *Tsuga Dumosa*

Ethnobotanical Uses in all States of Indian Himalayan Region

Members of the genus *Rhododendron* (Ericaceae), and especially *Rhododendron arboreum* and *R. campanulatum*, have become an integral part of the culture of societies inhabiting the Himalayan regions in terms of food, ritual, construction and a broad spectrum of remedies (Banerjee *et al.* 2018). Local knowledge systems deploy specific plant parts (flowers, leaves, bark, roots, wood) in both alimentary forms squashes, jams, pickles and medicinal preparations, decoctions, pastes, smoked incenses and topical applications. Ethnobotanical surveys and phytochemical investigations highlight a convergence between traditional uses and demonstrable bioactivity: flavonoids, phenolics and triterpenoids dominate the chemical profile and plausibly underpin reported antioxidant, anti-inflammatory, antidiarrheal, hepatoprotective, cardioprotective and antidiabetic effects (Prakash, *et al.* 2023; Kom, *et al.* 2024). To provide a consolidated overview of phytological composition and pharmacological significance of *R. campanulatum,* major phytochemical groups, bioactive compounds and reported biological activities are summarized in Table 2.

Major phytochemical classes and their functional components:

1. **Flavonoids & flavanol glycosides**: Flavonoids are reported abundantly in flowers and leaves, and it can be identified and extracted by HPTLC and GC-MS analyses (Majumder, *et al.* 2024; Jha, *et al.* 2024). Flavonoids are linked pharmaceutically to antioxidant, anti-inflammatory, hepatoprotective, antidiarrheal and cardioprotective effects through free-radical scavenging, inhibition of pro-inflammatory enzymes and modulation of vascular markers. Experimental studies have shown that major flavonoid isolates such as Quercetin, Rutin, Quercetin-3-O-glycosidesderivatives have a potential effect on Anti-nociceptive (analgesic) activity. Experimental studies further suggest that flavonoid rich extracts may support traditional applications related to liver disorders and general health promotion (Singh, *et al.* 2024).

2. **Phenolic acids and general phenolics** (coumaric acid, gallic acid, high total phenol content): Phenols are reported abundantly in flowers of *R. campanulatum* and it can be identified and extracted by HPLC and GC-MS analyses (Jha, *et al.* 2024). Phenolic compounds are the major phytochemical constituents in *R. campanulatum*. Commonly Phenolic compounds are extremely effective in antimicrobial activities as these compounds interact with microbial cell membranes, increase permeability, and cause leakage of cellular components which ultimately cause death to it. So, this species used in traditional medicine for the treatment of common cold, sore throat and fever and also as aromatic incense showed anti-bacterial activity. High total phenolic content is abundantly found in flower juice and extracts which has a strong antioxidant capacity and supports uses in wound healing and antisepsis. Along with that the flower juices are major source of this compound (Subba *et al.* 2023).

3. **Triterpenoids**: Another interesting phytochemicals groups can be the triterpenoids which includes ursolic acid, betulinic acid, lupeol, β-sitosterol. These chemical components are highly beneficial for anti-protozoal and anti-viral activity. Specifically, β-sitosterol affect the membrane of protozoa by disrupting the sterol biosynthesis which ultimately cause the death of it. Similarly, ursolic acid, betulinic acid target the parasitic mitochondria disrupting its energy mechanism. Experimental evidences suggest that, triterpenoids derivatives such as3-O-acetylursolic acid also demonstrate antidiabetic potential by inhibiting the α-glucosidase content. The bark and leaves of the tree have the shown the maximum presence of this component. The presence of these metabolites may partially explain the traditional use of these species as a heart tonic and general medicinal plant in Himalayan communities (Rawat *et al.* 2018; Kaur *et al.* 2023).

4. **Saponins, tannins and glycosides:** Contribute to the antidiarrheal/anti-enteropooling activity (tannins reduce intestinal secretion; saponins can modulate motility) documented for ethyl-acetate flower fractions in rodent models. Experimental studies indicate that tannins may reduce intestinal secretion, while saponins can influence gastrointestinal motility. Such findings provide scientific support for traditional preparations used to manage digestive disorders, including flower-based formulations and locally prepared beverages (Rawat *et al.* 2024).

5. **Alkaloids and other terpenes/anthraquinones:** Alkaloids and related compounds occur in comparatively lower concentration but contribute to the chemical diversity of the species. Several studies have associated these metabolites with analgesic/antimicrobial properties. However, their occurrence and biological significance in *Rhododendron* remain insufficiently investigated and require further phytochemical characterization (Bhattacharyya and Sanjappa 2012).

6. **Grayanotoxins/andromedotoxins (nectar/honey derived toxins):** Nectar and honey derived from *Rhododendron* can contain grayanotoxin. These compounds affect voltage-gated sodium channels and may cause cardiovascular and neurological symptoms when consumed in excessive quantities, a condition commonly referred to as “Mad Honey Poisoning”.

Reported symptoms include dizziness, hypotension, nausea, cardiac irregularities and temporary neurological disturbances. Although such toxicity is generally associated with concentrated honey products, awareness of these compounds is important when considering the medicinal or commercial utilization of rhododendron-derived products (GBPIHED 2023).

Table 2. Major phytochemical groups, bioactive compounds and reported biological activities of *Rhododendron campanulatum*

Phytochemical Group	Major Compounds	Reported Bioactivities	Analytical Method	References
Flavonoids & Flavanol Glycosides	Quercetine, Rutin, Quercetin-3-O-glycosides	Anti-oxidant, Anti-inflammatory, Analgesic, Hepatoprotective	HPTLC, CG-MS	Singh, *et al.* 2024
Phenolic Compounds	Gallic Acid, Coumaric Acid	Anti-oxidant, Anti-microbial	HPTLC, CG-MS	Subba *et al.* 2023
Triterpenoids & Sterols	ursolic acid, betulinic acid, lupeol, β-sitosterol	Antidiabetic, Anti-inflammatory, Antiviral	CG-MS, LC-MS	Rawat *et al.* 2018; Kaur *et al.* 2023
Saponins, tannins and glycosides	Mixed Secondary Metabolites	Antidiarrheal, Gastroprotective	Phytochemical Screening	Rawat *et al.* 2024
Alkaloids, terpenes & anthraquinones	Various Compounds	Analgesic, Antimicrobial	CG-MS	Bhattacharyya and Sanjappa 2012
Grayanotoxins	Grayanotoxin Derivatives	Toxicological Significance (Mad Honey Poisoning)	Chromatographic Analysis	GBPIHED 2023

State-wise ethnobotanical patterns (Indian Himalayan states)

This synthesis integrates the regionally specific practices, indicating the predominant plant parts used, principal therapeutic uses and the leading phytochemical classes implicated. mainly in J&K, Uttarakhand, Himachal, Sikkim, Arunachal and West Bengal (Darjeeling) (Table 3; Figure 1) (Das and Lahiri 2018).

Jammu & Kashmir: In the high-altitude regions of Jammu & Kashmir, *R. campanulatum* is locally known and valued particularly for its wood and fuel uses. For example, subalpine communities harvest its branches and stems for fuel, charcoal and small-scale carpentry when other fuelwoods are absent (ENVIS Bulletin 2023). Ethnobotanical interviews in Himachal and adjacent Kashmir note the species' leaves are sometimes combined with tobacco for inhalation to relieve hemicrania and colds (GBPIHED 2023).

Himachal Pradesh: In Himachal Pradesh, particularly in the Dhauladhar range (Kangra district) and Kinnaur, ethnobotanical studies document both *R. campanulatum* and *R. arboreum* as culturally and economically significant (Kala 2011; Arora 2019). In Kangra district, *R. arboreum* flowers are collected for chutney, jams, syrups, and as decorative material, "flowers, whether fresh or dried, are used to make chutney. Ornamentally the flowers are used for decorating houses and temples". Meanwhile *R. campanulatum*, occurring at higher elevations (> 3,200 m), is used more for fuelwood and structural uses by temporary settlers, as fewer other woody species are available in the high zone. Local names such as "pink-brass" and "gulabi buransh" reflect cultural recognition (Bhattacharyya and Sanjappa 2012). The flowers and buds of *R. arboreum* in Himachal are also used in medicinal preparations: for example, the aqueous extract of flowers is used as a natural colorant and food adjunct; dried flowers fried in ghee are traditionally used in dysentery. Additionally, flowers are traditionally utilized in chutneys, syrups, jams and ornamental decoration associated with local cultural practices.

Uttarakhand: In Uttarakhand's Kumaon and Garhwal districts, rhododendron flowers, especially of *R. arboreum* (locally "buransh"), is deeply embedded in local culture and subsistence systems. The state tree of Uttarakhand, *R. arboreum*, is used to make "buransh juice" and other traditional food products from its vibrant red flowers, marketed locally and consumed as a therapeutic drink (Bisht 2024). Additionally, the shrub *R. campanulatum* (locally "simru") appears at timberline elevations (3,000-3,600 m) and provides fuelwood for shepherds and animal shelters; especially because it burns even when damp (GBPIHED 2023). Ethnobotanical surveys reveal that the buds of *R. arboreum* are consumed as vegetables, raw or mixed with salt/chili (local "athani/remoli" snack) (Upreti and Joshi 2017). Traditional medicinal uses include flower juice for gastrointestinal disorders, headaches and women's ailments along with the leaves and bark are used for medication in skin disorders and for fish-bone expulsion (Bisht *et al.* 2020). These uses underscore the plant's dual role as food and medicine in the mountainous livelihoods of Uttarakhand (Arora 2019).

Sikkim & Darjeeling (West Bengal): Despite being less frequently cited than *R. arboreum* and other taxa, *R. campanulatum* is regarded as an important species in the Himalayan state of Sikkim where its parts such as fried corolla are served as local delicacy while the leaves of *R. anthopogon* and *R. lepidotum* are burnt as incense in monasteries. Similarly, the dry twigs of *Rhododendron* species (including *R. campanulatum*) are used as ritual fuel during religious ceremonies (Norbu and Choudhury 2017: Sundriyal *et al.* 2003).

Arunachal Pradesh: In Arunachal Pradesh, particularly in districts such as Tawang and West Kameng, the high-elevation rhododendron species are incorporated into indigenous medical and spiritual practices. While specific documentation for *R. campanulatum* is limited, ethnobotanical reviews show that several shrub-Rhodos are used as insect repellents, incense, and for skin diseases by Monpa communities. Leaves and flowers may be burnt in ritual fumigations to drive away pests and as part of Buddhist ceremonial offerings. Similar to other Himalayan regions, *R. campanulatum* wood is occasionally utilized as a local resource in alpine pastoral landscapes.

Uses other than ethnobotanical

The significance of *Rhododendron campanulatum* for the Himalayan societies extends far beyond its role in providing livelihoods, medicine and food. The species plays an important role in the rural economy, art and crafts, religious rituals and local commerce (Kala 2011; Arora 2019; Bisht *et al.* 2020). Its stems and large branches are used as a source of fuelwood, charcoal, or turned into fine grain and workable density wood which is further used to make small implements and hand-tool fittings (kukri/khukri handles), pack-saddle components and lightweight boxes used to carry foodstuffs (Upreti & Joshi 2017; Kumar & Rana 2019). In this way, the species supplies for various local rural needs thereby make up for the dearth of commercial timbers that are very expensive to transport to such remote zones. Rhododendron wood is an integral part of the local carpentry traditions in Uttarakhand, Chamoli and Pithoragarh districts, various villagers create several household items from this readily available species (Mishra *et al.* 2018).

Among its non-timber uses are its floral displays used during seasonal festivals, to decorate temples and households while the flowers are also used to prepare small-scale processed foods especially in the Darjeeling-Sikkim complex and parts of Arunachal Pradesh (Das and Lahiri 2018; Banerjee *et al.* 2018). Fresh and dried corollas are collected to prepare regional sherbets, jams and local brews (e.g. Guranse in Darjeeling), which serve both as cultural beverages and as valuable local products sold to trekkers and tourists thereby providing a modest source of income to small vendors and self-help women groups along popular trekking routes (Lepcha 2013; Angmo *et al.* 2012). Flower trusses and loose petals are widely used as temple offerings, monastery decorations and wedding garlands highlighting their role in culture besides being an additional source of income to hilly communities (Norbu and Choudhury 2017; Yonzon & Wangdi 2018). The bright colored petals of its flowers are used in several eastern localities (North Sikkim, Darjeeling, Kalimpong), to make pickles or processed into syrups and confectionery that fetch them more profit than earned from selling raw flowers (Lepcha 2013; Angmo *et al.* 2012).

In addition to various uses of its flowers, *R. campanulatum* wood is used to prepare packaging and domestic products. The thin, pliant leaves and splints of the plant have been used since times immemorial as platters or linings for storing butter, cheese and apples; an indigenous packaging solution since it checks loss of moisture while offering mild preservative benefits (Acharya & Rokaya 2010; Bomzon 2012). Dried twigs and fibre from related grasses are used with rhododendron trusses to make ropes or garlands for houses and temple decoration in the Monpa communities of western Arunachal and West Bengal (Darjeeling) (Norbu & Choudhury 2017). In many districts across Himachal and Uttarakhand, small-scale cottage industries process its wood to prepare gift boxes, ornamental goods and souvenirs that are sold to visitors during the flowering season (Sarmah & Arunachalam 2011; Pandey *et al.* 2021).

Rhododendron stands are especially of great use in remote areas where LPG supply is limited. Its cut branches are used for cooking and heating as its wood turns into charcoals readily making it a preferred choice as cooking fuel. In addition, the wood is used in a variety of handicrafts (Chandola *et al.* 2011; Sundriyal *et al.* 2003). However, the local stands of Rhododendron growing near inhabitation and pilgrimage destinations experience a steep rise in their seasonal demand. To check their excessive exploitation and allow regeneration, the inhabitants in few districts have devised certain ways such as rotational harvesting and taboos associated with deforestation. However, the efficacy of this check is dubious in the light of the rising infrastructural demand (GBPIHED 2016-2023; Bisht *et al.* 2020).

The species has several specialized applications to its credit. In parts of the western Himalaya comprising Kullu, Kinnaur, Chamba, rhododendron wood is traditionally used to manufacture handles for agricultural knives (khukri) and similar hand tools since it is tough and light simultaneously; such items feature in both household toolkits and as locally crafted souvenirs (Upreti and Joshi 2017; Kumar and Rana 2019). In tribal pockets of Arunachal and Nagaland, small rhododendron trunks and root buttresses were used traditionally to make carved handles and various ornamental items. However, the recent times have experienced a decline in handicraft especially with the advent of factory-made handles. However, the craft is still prevalent among elder artisans. (Norbu & Choudhury 2017). Additionally, in some pastoral zones the durable, water-resistant bark and twigs have been used as temporary wicks for lighting hearths or as linings in animal bedding (Bhattacharyya and Sanjappa 2012).

In Uttarakhand and Sikkim, flowers and branches are integral to seasonal rites and are placed around shrines, carried in processions, or tied to household lintels for auspiciousness; in monastery settings in Arunachal the smoke from burning rhododendron foliage (often mixed with juniper) is used for fumigation and as an offering, signifying purification and serving antiseptic purposes in traditional belief systems (Norbu and Choudhury 2017; Das and Lahiri 2018). These ritual functions maintain demand for floral and foliar material independent of medicinal markets and help sustain local norms that regulate collection (for example, prohibitions on harvesting during certain festival periods) (Kala 2011).

Finally, *R. campanulatum* plays a role in landscape management and informal ecosystem services. As a dense shrub at treeline and on morainic slopes, its vegetation slows runoff, traps sediments and provides fodder shelter for small-scale pastoralism; in some transhumant systems the plant's structural material is used to repair temporary corrals and trail markers (Mishra *et al.* 2018; Arora 2019). Such ecological-functional uses while not strictly "utilization" in the economic sense underscore the plant's multifunctionality within upland socio-ecological systems and justify its inclusion in local silvicultural planning and conservation initiatives that balance material use with stand persistence (Bisht *et al.* 2020; Kala 2011). The non-medicinal uses of *Rhododendron campanulatum* across Indian Himalayan states encompass fuel and charcoal production, small-scale carpentry and tool handles, packaging and household platters, floral foods and beverages (with local commercialization), ritual and decorative applications, incense and fumigation, and landscape-level services such as slope stabilization and fodder shelter. These uses vary by district Uttarakhand and Himachal emphasize wood-based crafts and fuel; Sikkim and Darjeeling prioritize floral processing and ritual consumption; Arunachal combines ritual fumigation with utilitarian applications yet all reflect a shared dependence on the species' availability and a need for carefully designed community-based management to reconcile livelihood benefits with long-term conservation (Arora 2019; Kala 2011; Bisht *et al.* 2020).

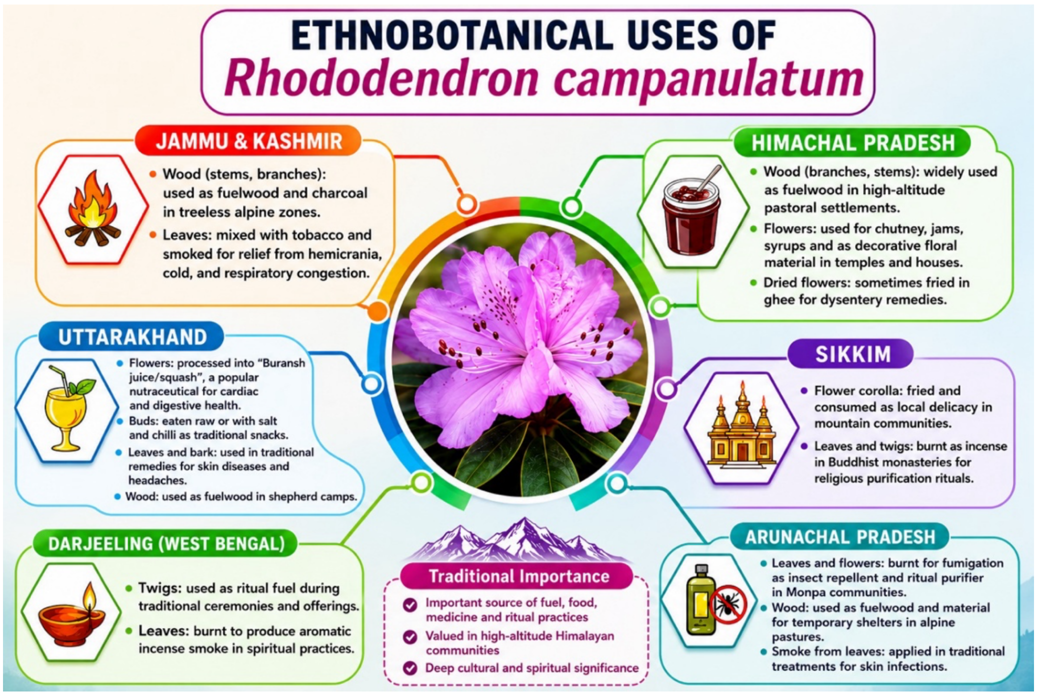

Figure 1. State-wise major traditional ethnobotanical uses of *Rhododendron campanulatum* across the Indian Himalayan region.

Table 3. State wise ethnobotanical uses of *Rhododendron* species with special emphasis on *R. campanulatum*

State / Region	Major Rhododendron Species	Primary Ethnobotanical Uses	Ethnic / Local Communities	References
Jammu & Kashmir	*R. campanulatum*, *R. lepidotum*	Fuelwood, incense for rituals, treatment for fever, cough and skin ailments; dried leaves used for aromatic smoke and insect repellent; used in high-altitude shelters due to availability and combustibility even when damp.	Gujjar, Bakarwal, and Ladakhi tribes	Rawat *et al.* (2017)
Himachal Pradesh	*R. campanulatum*, *R. arboreum*	Flowers used in local drinks, chutneys, squashes, and jams; dried corolla fried in ghee for dysentery; leaves applied for headache and wounds; twigs used as incense and for house decoration; wood used for charcoal and craft items like khukri handles, gunstocks, and gift boxes.	Gaddi, Kinnaura, and Pangi communities	Bhattacharyya, (2011)
Uttarakhand	*R. campanulatum* (“Simru”), *R. arboreum* (“Buransh”)	Fresh flowers used to prepare local sherbet and squash believed to prevent altitude sickness; petals consumed as snacks; juice used as tonic for heart diseases, diabetes, and dysentery; bark decoction for menstrual disorders; wood for fuel and fencing; floral extracts used in Ayurvedic formulations (e.g., *Arborium Plus*).	Bhotiya, Jaunsari, and Tharu tribes	Negi *et al.* (2013)
Sikkim	*R. campanulatum*, *R. arboreum*, *R. fulgens*	Leaves and flowers burned as incense in monasteries; flowers used in religious offerings, decorative ropes, and pickles; leaves mixed with juniper and pine for purification smoke; occasional medicinal use in stomach and liver ailments.	Lepcha, Bhutia, and Tibetan Buddhist communities	Singh & Lachungpa, (2003)
West Bengal (Darjeeling &Kalimpong)	*R. campanulatum*, *R. arboreum*	Flowers used to prepare syrup and chutney; branches and leaves used as incense and decoration during cultural festivals; firewood for traditional cooking and drying of medicinal herbs.	Nepali and Lepcha communities	Paul *et al.* (2010)
Arunachal Pradesh	*R. campanulatum*, *R. thomsonii*, *R. wightii*	Leaves used in fumigation to repel insects and evil spirits; flowers offered in Buddhist rituals; bark used for treating cough, colds, and bronchitis; stems used for firewood and fence construction.	Monpa, Sherdukpen, and Nyishi tribes	Deb *et al.* (2022)
Nagaland and Manipur (fringe Himalayas)	*R. arboreum*, *R. dalhousiae*	Flowers and leaves used in rituals, fermented beverages, and remedies for fever and dyspepsia; symbolic in harvest festivals.	Angami and Naga tribes	Singh *et al.* (2020)

Current conservation work on *Rhododendron campanulatum*

Recent research suggests that effective conservation of *Rhododendron campanulatum* requires a transition from conventional protection-oriented approaches towards adaptive, evidence-based conservation frameworks that simultaneously address ecological resilience, population viability and climate-change adaptation. Studies on natural regeneration in alpine forests of Himachal Pradesh demonstrated that successful recruitment of *R. campanulatum* is strongly influenced by site specific environmental factors, particularly soil moisture, snowfall, nutrient availability, solar influx, aspect and elevation (Moran *et al.* 2023). These findings highlight the importance of habitat-quality assessments and ecological restoration of degraded sites as essential components of long-term population viability management. Restoration efforts therefore prioritize the maintenance of suitable microhabitats and regeneration niches that support seedling establishment and population persistence under changing environmental conditions.

Conservation experiences from the broader Himalayan region further demonstrate that both in situ and ex situ approaches are necessary to safeguard declining rhododendron population. Early conservation initiatives emphasized the establishment of protected area, arboreta, botanical garden, reserved forests and community-managed conservation landscape, complemented by tissue-culture-based propagation and ex situ multiplication programs aimed at restoring threatened population (Singh *et al.* 2003; Paul *et al.* 2005). While these approaches remain valuable for preserving genetic resources and reducing extinction risk, contemporary conservation biology increasingly recognizes that passive protection alone may be insufficient in rapidly changing mountain ecosystem. Instead, integrated conservation strategies combing ecological restoration, assisted regeneration, habitat connectivity enhancement and long-term demographic monitoring are now considered more effective for maintaining viable population.

The growing influence of climate change further reinforces the need for adaptive management framework. Recent ecological studies revealed that *R. campanulatum* exhibits remarkable phenotypic plasticity along altitudinal gradients, with significant modifications in leaf morphology, growth form and dominance patterns at higher elevation (Naidu *et al.* 2026). Such adaptive responses indicate a substantial capacity to tolerate harsh alpine conditions and suggest that the species may possess inherent resilience to environmental fluctuation. However, continued warming, altered snowfall regimes and habitat fragmentation may exceed this adaptive capacity in certain regions, necessitating protective conservation interventions. In this context, assisted migration and climate-informed restoration have emerged as potential tools for facilitating population persistence in areas projected to become climatically unsuitable. Similarly, adaptive management approaches that integrate periodic monitoring of regeneration success, demographic trends and habitat conditions can provide an effective mechanism for adjusting conservation actions in response to emerging ecological challenges.

Community participation remains equally important for the long-term conservation of *R. campanulatum.* Given its cultural, medicinal and livelihood significance across Himalayan communities, conservation outcomes are likely to be enhanced through community-based conservation framework that incorporate traditional ecological knowledge, participatory monitoring, suitable harvesting guidelines and local stewardship initiatives. Such approaches not only reduce anthropogenic pressures but also strengthen social support for conservation interventions. Consequently, current conservation strategies for this species are progressively evolving from species-focused protection toward an integrated landscape-level framework that combines ecological restoration, population viability assessment, adaptive management, assisted migration evaluation, ex situ conservation and community participation. This multidimensional approach offers the greatest potential for ensuring the long-term persistence of the species simultaneously maintaining the ecological integrity and ecosystem services of Himalayan tree-line landscape.

Integrating traditional Knowledge into Conservation Practice

Adaptive management frameworks informed by ecological, physiological and demographic studies are increasingly being recognized as important tools for this species conservation. The species contributes significantly to soil stabilization, slope protection and water retention, highlighting its ecosystem-service value beyond its botanical importance (Sharma *et al.* 2016). Conservation planning is therefore moving towards a holistic view that links species-level responses with landscape functions, such as erosion control, watershed protection and microclimatic buffering (Table 3).

Protected areas in the IHR, including rhododendron-rich reserves and sanctuaries (e.g., Shingba *Rhododendron* Sanctuary in Sikkim), contribute to provide the primary framework for in-situ conservation. However recent studies suggest that the effectiveness of these protected areas can be enhanced through complementary measures including ecological restoration of degraded habitats, community-based monitoring, assisted regeneration and long-term demographic assessments. Furthermore, climate-driven upwards shifts in treeline species distributions indicate the potential importance of adaptive conservation strategies, including habitat connectivity enhancement and assisted migration assessment to maintain viable populations under future climatic scenarios. Collectively, these approaches emphasize a transition from passive protection towards adaptive and participatory conservation framework capable of supporting the long-term persistence of *R. campanulatum* in a rapidly changing Himalayan environment (Singh *et al.* 2009).

Table 4. Major stakeholders conducting research and conservation activities on *Rhododendron campanulatum*

State / Institute	**Major conservation & research actions (current/focus)**
Sikkim Forest Dept. / State Govt.	Varsey Rhododendron Sanctuary, community awareness, habitat protection, eco-tourism linked conservation
Himachal Pradesh (state)	Cultural/state emblem status in locales; localized protection; monitoring concerns re: overharvest & habitat loss
Uttarakhand (state) / Valley of Flowers NP	Protected high-altitude reserves, floristic surveys, integration with medicinal plant conservation
Arunachal Pradesh & NE States	In situ protection, arboreta, ex situ collections; emphasis on conserving high rhododendron diversity
GB Pant Institute of Himalayan Environment & Development (GBPIHED)	Dendroecology, treeline expansion studies, long-term monitoring and policy briefs
Botanical Survey of India / Regional Universities	Floristic inventories, population/regeneration studies, seed biology and nursery protocols
TREELINE-II / Collaborative Research Projects	Species distribution modelling, ensemble climate projections, integrated monitoring frameworks
Local communities / Community groups	Participatory conservation, sustainable harvest rules, traditional knowledge on medicinal uses

Recent Advances in Research of *Rhododendron campanulatum*

Contemporary research on *Rhododendron campanulatum* in the Indian Himalayan Region (IHR) combines long-term ecological monitoring, population and functional-trait studies, dendroecological and ring-width analyses, seed biology and germination trials, niche and species-distribution modelling, and participatory ethnobotanical work, all of which together aim to characterize the species' regenerative potential, adaptive traits and vulnerability to current and projected drivers of change, several studies document upward shifts in population structure and alarming expansion at treeline ecotones consistent with regional warming trends, while ring-width and dendroecological records have been used to reconstruct seasonal climate signals and link growth variation to recent winter-spring warming and drought events in the central and western Himalaya, providing empirical evidence that the species' demography and treeline dynamics are sensitive to climatic variability (Panthi *et al.* 2021; Schwab *et al.* 2022; Singh *et al.* 2018).

Physiological Adaptation & Stress Response Mechanism: Recent physiological studies on *Rhododendron campanulatum* show a clear shift from simple descriptive observations to a deeper understanding of how the species copes with environmental stress at both the whole-plant and molecular levels. Seasonal field investigations conducted in the Indian Himalaya demonstrate that *R. campanulatum* experiences significant winter water stress even under persistent snow cover, particularly in treeline environments of Uttarakhand and Himachal Pradesh (Singh *et al.* 2025). This stress is alleviated through conservative stomatal regulation, osmotic adjustment, and maintenance of low leaf water potential, highlighting the strong interaction between cold and drought stress at high elevations (Rawat *et al.* 2013). Reciprocal transplant and elevation-gradient studies from the central and western Himalaya further indicate that these physiological traits are shaped by long-term local adaptation rather than short-term changes. (Singh *et al.* 2018). As suggested by biochemical studies, cold tolerance in alpine *Rhododendron* species is attributed to abscisic acid-mediated signaling, calcium-dependent pathways, and tight control of reactive oxygen species; mechanisms that collectively ensure photosynthetic operation and reduce oxidative damage during prolonged exposure to freezing temperatures (Bisht *et al.* 2020; Rawat *et al.* 2013). Elevation-based comparisons of physiological traits confirm the influence of climatic gradients on stress-response pathways in *R. campanulatum* (Panthi *et al.* 2021).

Regeneration Patterns and Implications for Conservation: The ability of *Rhododendron campanulatum* to spread at Himalayan treeline areas depends collectively on climate, plant form, and seedling success rate. Various field studies affirm a rise in the number of young plants at higher altitudes and subsequent adaptation of leaf traits suggesting an upward shift towards colder climate (Karki *et al.* 2024). Studies on seed production and seedling survival further show that successful regeneration is strongly influenced by harsh alpine conditions. Factors such as temperature, moisture availability, and snow cover play a major role in determining the seedlings survive rate, making recruitment highly sensitive to climate variability (Singh *et al.* 2024). Research on plant form and structure indicates that *R. campanulatum* develops smaller leaves and reallocates biomass between shoots and roots to offset high-altitude stress. These changes help seedlings establish in cold, resource-limited environments over long periods (Naidu *et al.* 2025). Population-level studies also reveal that *R. campanulatum* shows stable and continuous regeneration across a wide elevational range. Unlike many other Himalayan species that struggle to regenerate at higher elevations, this species maintains healthy population structures, indicating greater resilience to environmental stress (Rana *et al.* 2023). At the community level, regeneration success is further shaped by local conditions such as soil properties, disturbance history, and vegetation succession, meaning that small-scale habitat differences can strongly influence where seedlings establish.

Applied Conservation Genomics: Recent progress in conservation genomics of *Rhododendron campanulatum* shows a clear shift from simply generating genetic data to actively using this information for conservation planning. Early genomic studies have successfully mapped the chloroplast and mitochondrial genomes of *R. campanulatum*, revealing differences in genome structure and identifying genes that appear to be under natural selection at high altitudes. These genes are likely linked to survival in cold and stressful mountain environments and can serve as useful genetic markers for monitoring populations, identifying adaptive variation and evaluating climate resilience in future conservation programme (Rawat *et al.* 2021).

Recent advances in molecular genetics and genomics have substantially improved our understanding of evolutionary processes, adaptive potential and conservation requirement within the genus Rhododendron. Genetic diversity constitutes the fundamental basis of species resilience under rapidly changing environmental condition, particularly in climate-sensitive alpine ecosystems where habitat fragmentation and elevational shifts increasingly threaten population persistence. Early molecular investigations employing RAPD markers in threatened Himalayan Rhododendron species revealed relatively low levels of genetic diversity, high polymorphism and distinct phylogenetic clustering among species, suggesting restricted gene exchange and increased risk of outbreeding depression in fragmented population (Mondal and Kumar De, 2025). Similar patterns have been observed across several Rhododendron taxa, highlighting the necessity of genetic assessments as a prerequisite for conservation planning.

More refined molecular approaches have recently been applied to *R. campanulatum,* a keystone treeline species of the Himalaya. Using genomic survey sequencing, Meena *et al.* (2025a) generated the first comprehensive genomic resource for the species, identifying over 223000 perfect SSRs and developing novel polymorphic markers for population level analyses. Their findings revealed relatively low genetic diversity (He=0.28; Ar=1.91), coupled with substantial genetics differentiation among population (FST=0.173), while the majority of genetic variation (83%) was retained within populations. The dominance of heterozygous individuals (FIS= -0.268) and the presence of two genetically distinct population clusters indicate ongoing evoluationary divergence despite restricted overall diversity. These results suggest that isolated Himalayan population may possess unique adaptive genetic variants that warrant separate conservation attention. Complementary SSR-based studies utilizing cross-species marker transferability from *R. arboreum* similarly demonstrated moderate genetic diversity and high genetic differentiation (FST= 0.467) among population of *R. campanulatum,* further emphasizing limited gene flow and need for landscape-level conservation strategies to maintain connectivity among fragmented habitats (Meena *et al.* 2025b).

Evidence from broader *Rhododendron* research further supports the importance of integrating genetic and ecological perspective. Investigating the *R. arboreum* species complex across Nepal, Noshiro *et al.* (2026) demonstrated that genetic divergence was accompanied by significant modification in leaf indumentum and wood anatomical traits along elevational gradients. Such findings indicate that genetic differentiation may reflect local adaptation rather than simple geographic isolation. These observations are particularly relevant for *R. campanulatum,* whose population occur across diverse treeline environments characterized by pronounced climatic variability.

The ecological significance of conserving adaptive genetic variation becomes increasingly evident under climate change scenarios. Studies in the Western Himalaya have documented rapid upward expansion of *R. campanulatum* krummholz communities at approximately 1.4 m/year in response to recent warming trends, indicating ongoing shifts in species distribution and tree-line dynamics (Singh *et al.* 2018). Such range adjustments may alter gene flow patterns, create novel selection pressures and potentially reduce genetic connectivity among population. Consequently, conservation efforts must not only protect existing population but also preserve their evolutionary potential to adopt to future environmental changes.

Comparative evidences from endangered congeners further demonstrates the utility of molecular markers for conservation decision-making. For example, EST-SSR analyses of *Rhododendron longopedicellatum revealed* high within-population genetic diversity and clear population structuring, enabling the identification of priority populations for genetic conservation and restoration interventions (Cao *et al.* 2022). Similar approaches could be effectively employed in *R. campanulatum* to identify evolutionarily significant units (ESUs), assess adaptive genetic variation and guide restoration programs. At the same time, population-level genetic studies using molecular markers have revealed that many rhododendron species still retain substantial genetic variation, though this diversity is unevenly distributed across landscapes. Research from both global and Indian Himalayan contexts highlights that preserving this genetic variability is essential for reducing the risks of inbreeding, loss of adaptability, and long-term population decline (Kumar *et al.* 2024).

Despite these promising developments, genomic resources remain scarce across most *Rhododendron* species. Recent reviews have emphasized substantial knowledge gaps regarding genetic mapping, adaptive trait loci, molecular mechanism underlying stress tolerance and the application of genomic-assisted breeding and conservation tools (Rawat *et al.* 2024). For *R. campanulatum*, future research should focus on whole-genome sequencing, landscape genomics, transcriptomic analyses of climate-responsive genes and the identification of adaptive markers associated with drought tolerance, temperature resilience and regeneration success. Integrating such genomic information with ecological monitoring, habitat suitability modelling and traditional conservation practices would facilitate the development of climate-smart conservation strategies. Ultimately, conservation genomics offers a powerful framework for preserving genetic diversity, enhancing adaptive capacity and ensuring the long-term persistence of *R. campanulatum* within the rapidly changing Himalayan tree-line ecosystem.

Ecological Framework and Habitat Based Adaptation: Recent ecological studies on *Rhododendron campanulatum* have helped to clarify how differences in habitat conditions and climate shape its survival and adaptation at Himalayan treelines. Experimental studies where plants were moved across elevations show that their performance depends more on the surrounding environment than on their place of origin. This indicates that local climate and site conditions strongly filter which populations thrive, rather than simple “home advantage” of native locations (Mainali *et al.* 2023). These findings provide evidence that habitat-specific climatic conditions are important drivers of adaptation in *R. campanulatum.*

Field investigations along altitude gradients further reveal consistent variation in functional traits such as **leaf** size, structure, and seedling establishment with increasing elevation. These trait modifications represent adaptive responses that allow plants to maintain growth and survival under colder temperature, shorter growing seasons and greater environmental stress. Similar patterns have been reported by Indian researchers working on Himalayan tree-line vegetation, emphasizing the importance of plant functional traits in ecological adaptation across mountain ecosystem (Singh *et al.* 2018; Karki *et al.* 2024).

Physiological studies provide additional evidence for these adaptive strategies. Detailed investigation of plant water relations indicates that *R. campanulatum. Experiences* substantial winter water stress despite the presence of snow cover. Because frozen soils restrict water uptake, plants maintain cellular function through osmotic adjustment and regulation of internal water balance, thereby reducing the risk of desiccation during prolonged cold periods (Singh *et al.* 2025). These physiological mechanisms complement observed trait adjustments and collectively from an integrated adaptation strategy that enhances survival in alpine environments.

At the population level, regeneration studies show that *R. campanulatum* generally maintains stable recruitment across elevational gradients, suggesting a relatively high degree of ecological resilience compared with several co-occuring species (Rana *et al.* 2024). The combination of functional trait plasticity, physiological stress tolerance and sustained regeneration indicates that the species possess multiple mechanisms for coping with environmental variability.

At broader spatial scales, habitat suitability models integrating GIS and climate variables predict potential shifts and contraction of suitable habitats for alpine rhododendrons under future climate change scenario. These projections suggest that although *R. campanulatum* currently exhibits considerable adaptive capacity, long-term persistence may be challenged by continued warming and altered habitat availability. Ecological synthesis from the Indian Himalaya further indicate that changing temperature regimes, soil processes and biotic interactions collectively influence shrub expansion, tree-line dynamics and ecosystem functioning (Sandeep & Khanduri, 2024).

Taken together, current evidence supports a conceptual ecological framework in which climatic gradients influence plant functional traits and physiological responses, which in turn determine regeneration success, population persistence and habitat adaptation. This integrated perspective highlights the importance of linking ecophysiology, functional trait variation, population dynamics and climate-based habitat modeling to better understand and conserve *R. campanulatum* under future environmental change.

Advances in Propagation Biology: Recent progress in the propagation biology of *Rhododendron campanulatum* shows a clear shift toward developing practical and scalable methods for conservation and restoration. Researchers are now focusing on species-specific techniques, especially containerized nursery systems and micropropagation, to support large-scale plant production outside natural habitats (Katanskaya *et al.* 2025). Such approaches are increasingly recognized as important tools for ex situ conservation, population reinforcement and ecological restoration programmes in the Himalayan region.

Early micropropagation studies have confirmed that *R. campanulatum* can be successfully grown under laboratory conditions using seedlings raised from seeds. Carefully balanced plant growth regulators have been shown to stimulate reliable shoot formation and multiplication, making in vitro propagation a feasible option for this species (Ahmad *et al.* 2025). These findings are consistent with studies on related *Rhododendron* species, where flower buds and nodal segments were found to regenerate efficiently, widening the range of plant parts that can be used for propagation. Further research on alpine *Rhododendron* species has demonstrated that different genetic types respond differently to hormone combinations. This highlights the need for customized propagation protocols rather than a single standard method for all species or populations.

Specifically for *R. campanulatum*, seed-based tissue culture studies have shown that selected auxin-cytokinin combinations improve seed germination, callus formation, and shoot multiplication, strengthening the basis for large-scale propagation. Under optimized laboratory condition, germination and shoot induction rates have generally exceeded 70-80%, indicating considerable potential for mass multiplication. However, successful transfer from laboratory to field conditions remains the major hindrance for practical conservation application (Chauhan *et al.* 2021).

Root formation and post-culture survival remain key challenges. Recent studies emphasize that proper auxin treatments significantly improve root development, while associations with ericoid mycorrhizal fungi enhance acclimatization and survival after transfer to soil (Sharma *et al.* 2025). Similar outcomes have been reported by Indian researchers working on Himalayan rhododendrons, who noted improved rooting success and field survival when micro-propagated plants were gradually hardened under controlled nursery conditions (Chandra *et al.* 2022).

Collectively, available evidence suggests that restoration of this species through natural regeneration is feasible in high-altitude habitats, particularly in open tree-line environments where regeneration success may exceed 50%. However, relatively low seed germination rates (39.57%) at 29% capsule moisture content and habitat-dependent seedling establishment limit the scalability of direct-seeding approaches (Singh *et al.* 2021). Seed based propagation is constrained by relatively low germination success (39.57%), while natural regeneration remains highly dependent on favorable micro site condition, with maximum regeneration success reaching 52.78% in suitable habitats (Moran *et al.* 2025). In contrast, micro propagation offers more efficient multiplication strategy, producing up to 4.6±0.3 shoots per explants under optimized culture condition. However, the prevalence of type III survivorship and high seedling mortality suggests that successful restoration depend not only propagation efficiency but also on improving post-establishment survival (Qazi *et al.* 2023).

Comparative studies indicate that acclimatized plantlets generally exhibit lower survival rates under nursery conditions, although survival tends to decline under harsh alpine field environment, emphasizing the importance of post-planting management and site selection. Beyond laboratory multiplication, recent-oriented research increasingly emphasizes integrating propagated seedlings into degraded tree-line habitats through assisted regeneration and ecological restoration programmes. Containerized nursery systems are considered more cost-effective and operationally feasible than large-scale tissue culture for routine restoration activities, whereas micropropagation remains particularly valuable for conserving genetically important or poorly regenerating populations. Long-term monitoring of reintroduced populations, including survival, growth performance, reproductive success and genetic diversity is now regarded as essential for evaluating restoration effectiveness and ensuring sustainable population recovery.

Collectively, these studies indicate that propagation research of this species is transitioning from experimental feasibility to applied conservation relevance, providing robust tools for population reinforcement, habitat restoration and climate-resilient conservation planning in the Himalayan region.

Conservation Challenges of *Rhododendron campanulatum* in the Indian Himalaya

Although the species is found widespread across the temperate and sub-alpine belts of the India spanning the states of Himachal Pradesh, Jammu & Kashmir (now a UT), Uttarakhand, Sikkim and Arunachal Pradesh, its conservation represents a multifaceted challenge involving several dimensions such as ecological sensitivity, socio-economic dependency, institutional fragmentation and erratic climate change patterns.

Ecological Sensitivity and Climate Change: The foremost conservation difficulty arises from the inherent ecological sensitivity of the environment in which *R. campanulatum* thrives. The Himalayan treeline and sub-alpine scrub zones (2,800-4,200 m a.s.l.) are among the most climatically dynamic and structurally fragile ecosystems on the subcontinent. Here, steep environmental gradients compress temperature, moisture and soil changes into narrow elevational bands. Small alterations in microclimate weather due to global warming or local disturbance can therefore produce disproportionate ecological responses. Shrub-dominated communities dominated by *R. campanulatum* are particularly vulnerable because they depend on specific snow cover regimes, soil acidity and mycorrhizal associations. Prolonged snow-free winters, erratic freeze cycles and altered monsoon intensity disrupt root development and expose roots to desiccation. Field studies across the central Himalaya show that the species' radial growth is highly sensitive to winter minimum temperatures and pre-monsoon moisture. Consequently, even marginal climatic shifts can lead to contraction or upward displacement of viable habitat, challenging conservation planning that historically treated altitudinal belts as relatively static (Singh et al, 2025: Panthi et al, 2021).

Recent evidence further suggests that the Himalayan is warming faster than the global average, making tree-line species like *R. campanulatum* particularly vulnerable to climate change. Dendroclimatological studies indicate that while warmer winters may enhance radial growth in some location, excessive drought stress and irregular snowpack conditions can cause decline and mortality in others. Predictive species distribution models forecast an upslope shift of suitable habitat by approximately 300-500 meter under mid-century climate scenario. However, such migration is constrained by factors including soil depth, slope character, limited dispersal ability, increasing the risk of "mountain-top extinction". In addition, Phenological data also reveal earlier flowering and possible mismatches with pollinator activity, risking reduced seed set. These findings highlight that climate-induced ecological disturbances cannot be addressed solely through protected-area designation and may require adaptive conservation intervention such as assisted migration, climate-resilient restoration and the use of locally adapted genotype, although these approaches remain largely untested for the species (Sharma et al, 2023: Telwala et al, 2013).

Climate-related pressures are further compounded by disturbance factors operating within tree-line ecosystem. Fire incidence in mid-altitude pine forests has increased markedly in recent decades and fire lines frequently extend upward into sub-alpine scrub dominated by *R. campanulatum*. Although the species exhibits some resprouting ability, intense fires destroy the humus-rich topsoil critical for seedling establishment. Simultaneously, expansion of migratory pastoralism and unregulated grazing by goats and yaks reduce seedling survival in open slopes where livestock trample regeneration sites. Grazing also suppresses associated understory species, leading to compositional simplification of communities that once harbored diverse shrubs and herbs. In many treeline villages, traditional rotational grazing systems that formerly allowed habitat recovery to have broken down due to socio-economic change and the erosion of customary institutions (Mina *et al.* 2023).

Habitat Fragmentation and Infrastructure Development: Across the western and central Himalaya, habitat fragmentation represents the second critical challenge. Rapid urbanization, expanding rural settlements, hydropower projects, and road building have altered deep into once-continuous rhododendron thickets. The Himalayan Road network promoted as a conduit for development and tourism has led to the removal of large stands along cut slopes for soil stabilization, firewood and construction material. Fragmentation isolates populations, reducing gene flow, and increases edge effects such as wind exposure and soil erosion. Fragmented sub-populations also experience drastic demographic bottlenecks that erode genetic diversity over time. Since *R. campanulatum* is predominantly insect-pollinated, reductions in patch connectivity among habitat patches can limit pollen movement further impair reproductive success. The resultant genetic isolation can lower adaptive potential under rapid climate change, rendering small remnant patches more vulnerable to local extinction (Liang *et al.* 2022: Sharma & Kala, 2016). The effects of habitat fragmentation are further intensified by the rapid growth of high-altitude tourism, trekking, and pilgrimage activities. Although these activities contribute substantially to the local economics, assisted infrastructure development including lodges, hotels, roads and waste disposal site, often occurs within ecologically fragile sub-alpine habitats. These activities in these zones leads to soil compaction, trail erosion and pollution that degrade rhododendron habitat. Seasonal trampling by thousands of pilgrims along routes such as the Valley of Flowers or Kedarnath reduces seedling establishment near trails. Litter accumulation and unmanaged campfires frequently ignite accidental burns.

Tourist demand for floral souvenirs further stimulates unregulated collection. Despite awareness campaigns, enforcement remains weak due to the sheer remoteness and seasonal influx of visitors. Consequently, balancing infrastructure development and tourism-based livelihoods with long-term habitat conservation remains a major management challenge throughout the Indian Himalayan (Gurung *et al.* 2023).

Socioeconomic Dependence and Cultural Change: Local communities throughout Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh depend heavily on rhododendron shrubs for basic energy and subsistence needs. The wood of *R. campanulatum* burns efficiently, producing high-quality charcoal and heat even at low oxygen pressure qualities highly valued in high-altitude villages where alternative fuels are expensive. Extraction for fuelwood, incense sticks, tool handles and decorative craft items remains widespread. Ethnobotanical surveys reveal that most households in sub-alpine villages harvest branches annually, often before flowering, preventing regeneration. In economically marginal districts, the plant also provides supplemental income through small-scale sale of dried flowers and wooden souvenirs to tourists. This extraction creates a landscape-level depletion pattern, especially around roads and pilgrimage corridors. The situation is exacerbated owing to a lack of replantation efforts and effective alternatives that can take anthropogenic pressure off the species. Additionally, the remoteness of these high-altitude regions coupled with dearth of requisite manpower makes implementation of sustainable harvesting guidelines a futile exercise (Singh & Samant,2025: Paul *et al.* 2019). The anthropogenic pressures mention earlier are increasingly influenced by rapid socio-economic transitions occurring throughout the Himalayan region. Migration, education and greater market integration have altered traditional lifestyles, leading to the gradual erosion of customary resource-management systems such as rotational harvesting, seasonal restrictions and ritual prohibitions that historically regulated rhododendron use. As younger generation increasingly shift towards wage employment and urban-centric livelihoods, community involvement of natural resources may decline, increasing the risk of opportunistic extraction. Simultaneously, expanding tourism and pilgrimage activates the demand for rhododendron related products including floral decoration and other handicrafts. Although these products provide important economic opportunities, their commercialization may accelerate harvesting pressure unless supported by formal resources assessment, harvesting quotas and sustainable management framework (Uprety *et al.* 2023: Negi *et al.* 2024).

Despite the cultural prominence of rhododendrons, specific ecological knowledge about sustainable harvesting and regeneration remains uneven among local communities. Many villagers are unaware that cutting branches before flowering prevents seed set, or that bark removal invites fungal infection. Educational outreach through schools, monasteries and community centers could build awareness of the species' ecological role and promote voluntary protection. Where such initiatives have been piloted, such as eco-clubs in Sikkim, they have led to measurable reductions in cutting. However, scaling them across thousands of dispersed villages requires long-term investment and collaboration between forestry departments, NGOs and local educators (Angmo et al,2025: Phuntsog et al, 2024). Another critical challenge lies in integrating both scientific and traditional management paradigms. Indigenous and local knowledge systems have historically sustained rhododendron populations through ritual prohibitions, seasonal harvest rules and cultural respect. Yet, formal conservation frameworks often marginalize or overlook these institutions. The result is reduced local legitimacy and compliance. Bridging this divide requires participatory governance where community elders, monks, women's groups and scientists co-design management plans. Documentation and validation of traditional practices such as selective pruning and sacred grove protection can enrich scientific management while ensuring cultural continuity (Khanyari et al,2023: Bhatt et al, 2024).

Knowledge Gap and Monitoring Deficiencies: Effective conservation planning is impeded by significant data deficiencies. Existing ecological records regarding this species are fragmentary, confined to floristic surveys or limited transects. Baseline information on population size, age structure, genetic diversity, pollination biology and regeneration ecology is scarce. Without such data, assessing population trends or setting quantitative conservation targets remains speculative. Taxonomic uncertainties arising from morphological plasticity and overlapping characters further complicate monitoring and identification. Moreover, long-term phenological datasets that could detect climate-linked shifts are limited to a few research stations. The absence of open-access databases integrating ecological, genetic and ethnobotanical information hinders coordinated research across states (Lahiri and Dash, 2021: Saha *et al.* 2025). Another persistent challenge is the paucity of quantitative monitoring. Unlike flagship fauna, plant species seldom attract sustained funding for demographic surveys. Periodic vegetation inventories, if conducted, often use differing methodologies, making temporal comparison difficult. Without consistent data, it is impossible to ascertain whether observed local declines reflect natural population cycles or anthropogenic impact. Remote-sensing tools have potential for large-scale mapping of rhododendron cover, but spectral confusion with other shrubs hampers accuracy. Citizen-science initiatives could complement formal monitoring, yet participation in remote mountain regions remains low. Establishing standardized protocols for population censuses and involving trained local monitors could fill this gap, but requires institutional commitment (Chen et al, 2024: Zhou et al, 2023).

Policy, Governance and Institutional Constraints: Despite being recognized as the state flower in several Himalayan regions and playing a significant ecological role in forest ecosystems, *R. campanulatum* continues to suffer from an inadequate policy and institutional framework governing its utilization. The species provides multiple ecological services such as soil stabilization, biodiversity support and livelihood opportunities through non-timber forest products (NTFPs). However, government intervention regarding systematic collection, sustainable harvesting, value addition and organized marketing of its flowers remains limited. In many Himalayan states, the harvesting and trade of rhododendron flowers for products such as juice and squash are largely carried out through informal channels without structured regulation or support. There is also no clearly defined minimum support price (MSP) or standardized procurement mechanism, which leaves local collectors dependent on middlemen and fluctuating market prices. As a result, despite its commercial potential and cultural significance, the absence of a strong policy framework restricts equitable income generation and sustainable management of the species (Chauhan *et al.* 2021: Bhardwaj *et al.* 2025). Along with policy inefficiency, constraints limited manpower, funding shortages and poor coordination among research institutes further hinder conservation implementation. Field stations often lack specialized expertise in alpine ecology or the equipment required for monitoring high-elevation plots. Communication gaps between academic researchers and forest department officials prevent timely translation of scientific findings into policy. While the GBPIHED and Botanical Survey of India conduct valuable surveys, their data dissemination is slow and fragmented. Funding cycles of most government schemes are short, incompatible with the long ecological timescales required to assess shrub regeneration or climate adaptation. Furthermore, jurisdictional overlaps between state forest departments and community panchayats sometimes generate conflict over authority, discouraging cooperative management (Choudhary *et al.* 2024: Thapa *et al.* 2023). *R. campanulatum* transcends political boundaries, occurring across India, Nepal, Bhutan and Tibet. However, conservation efforts remain nationally siloed. Differences in research capacity, legal frameworks and language impede coordinated management across the species' range. Trans-boundary conservation corridors or data-sharing platforms are minimal. Consequently, populations near international borders, which often harbor high genetic diversity, receive little coordinated attention. Establishing regional networks under the Himalayan Biodiversity Forum could harmonize methodologies, enable genetic exchange among ex situ collections, and promote unified Red List reassessments (Bhattacharya et al, 2025: Ahmad et al,2025). Conservation funding in mountain regions competes with infrastructure and livelihood priorities. Rhododendrons, being shrubs rather than timber trees, rarely receive priority in budget allocations. Short-term project cycles encourage output-oriented metrics (number of saplings planted) rather than long-term ecological outcomes. Moreover, overlapping priorities wildlife conservation, eco-tourism, hydropower development creates policy contradictions. For instance, roads built to facilitate tourism in rhododendron valleys simultaneously degrade habitat. Reconciling such conflicts demands integrated landscape planning and cross-sectoral dialogue, which are still nascent (Ali et al, 2024: Nepal et al, 2025).

Genetic Erosion and Connectivity Challenges: Genetic studies in *R. campanulatum* reveal profound population diversity linked to topographic isolation. For this species, fragmented mountain ranges separated by deep valleys likely restrict gene flow, creating micro-endemism and locally adapted ecotypes. Habitat fragmentation and selective logging amplify this isolation, causing gradual genetic erosion. Conservation corridors that connect sub-alpine patches are rarely considered in regional land-use planning. Maintaining landscape connectivity is crucial not only for pollen and seed dispersal but also for enabling altitudinal migration under warming conditions. Establishing trans-boundary biological corridors that integrate protected areas and community forests is therefore vital but administratively complex, involving multiple states and local governance bodies (Ma *et al.* 2024; Naidoo *et al.* 2025).

Ex situ Conservation Challenges: Although several botanical gardens and research institutions maintain *R. campanulatum* collections, ex situ conservation faces its own set of challenges. *R. campanulatum* seeds have short viability and are difficult to store in conventional seed banks, requiring living collections or tissue culture for long-term preservation. Many existing ex situ collections under-represent genetic diversity because they derive from a few easily accessible populations. Clonal propagation via cuttings is slow, and tissue-culture protocols are still being optimized. Furthermore, limited coordination among gardens leads to redundancy rather than complementarity in reintroduction of the species in new area of similar climatic condition. Without genetic characterization of source populations, ex situ material may not reflect adaptive variation necessary for reintroduction or climate-change research (Singh *et al.* 2024: Dhar *et al.* 2023).

Emerging Threats and Economic Valuation: Although less documented, there are early warnings of biotic stress from fungal pathogens and invasive plant species in disturbed rhododendron habitats. Warmer and wetter conditions favor the proliferation of leaf-spot fungi and root rot pathogens that attack stressed shrubs. Disturbance corridors also allow colonization by invasive forbs such as *Polygonum* and *Rumex*, which compete with young rhododendron seedlings for light and nutrients. The absence of long-term phytopathological surveillance means outbreaks often go unnoticed until mortality becomes evident. Integrating plant health monitoring into existing forest-health programs is therefore an emerging necessity (Xie et al,2024: Singhal et al, 2023). Conservation strategies often falter because they fail to demonstrate tangible economic value to stakeholders. The ecosystem services provided by *R. campanulatum*, such as slope stabilization, carbon sequestration, and aesthetic tourism, remain largely unquantified. Without economic valuation, policymakers underestimate the cost of degradation and the benefits of conservation. Payments for ecosystem services or community-based eco-certification schemes could provide financial incentives for protection, but such mechanisms have yet to be developed in Himalayan forestry. Integrating rhododendron conservation into broader climate-finance programs (e.g., REDD+ and green tourism certification) could mobilize new resources while empowering local custodians (Mameno et al, 2024: Joshi et al, 2025).

Future Perspectives and Policy Directions

Climate-resilient Conservation and Ecological Restoration: As climate change accelerates, traditional static conservation models are increasingly inadequate. Future strategies must adopt climate-informed and adaptive management approaches. Predictive modeling using species distribution models (SDMs) can forecast shifts in *R. campanulatum*'s climatic niche under various emission scenarios, allowing policymakers to pre-identify potential refugia and new suitable habitats (Kaushal *et al.* 2026; Tomar *et al.* 2025). Adaptive management implies continuous learning: interventions such as restoration planting, controlled harvest, or assisted migration should be monitored for outcomes, evaluated, and refined over time. For instance, the establishment of permanent monitoring plots across different elevations can generate long-term phenological and growth data that guide planting or assisted colonization in response to observed climatic trends. Integrating climate adaptation into forest management plans also involves identifying climate refugia (north-facing slopes, shaded valleys, high moisture pockets) that can serve as reservoirs of genetic diversity. Assisted natural regeneration, using seedlings sourced from locally adapted populations, can enhance resilience without disrupting genetic integrity (Biswas *et al.* 2025; Rawat *et al.* 2024). This forward-looking strategy shifts conservation from reactive to anticipatory, positioning *R. campanulatum* as a sentinel species for Himalayan climate adaptation. Large tracts of sub-alpine scrublands have been degraded by fuelwood collection, grazing, and road construction. Future policies must embrace ecological restoration and rewilding as central conservation strategies. Restoration should not be limited to tree planting but should aim to recover functional ecosystems by reinstating native species assemblages, soil microbial networks, and hydrological regimes. *R. campanulatum* can serve as a keystone restoration species due to its ecological role in slope stabilization and microclimate regulation. Restoration models can integrate rhododendron with associated species such as *Abies pindrow*, *Betula utilis*, *Sorbus microphylla*, and *Acer campbellii*, replicating natural community structures. Restoration planning should adopt site-specific approaches: for steep slopes, contour planting and coir-log stabilization prevent erosion; for alpine meadows, low-density planting with protective fencing allows natural recruitment. Importantly, restoration success should be evaluated using quantitative metrics survival rates, canopy cover, and soil organic matter recovery to guide adaptive management. Linking restoration with carbon-credit or payment-for-ecosystem-services schemes can further attract sustainable financing. Future conservation efforts must transcend administrative boundaries and adopt a landscape approach, recognizing that ecological processes such as gene flow, pollination, and dispersal operate beyond physical borders (Gann *et al.* 2019). The Himalayan rhododendron belt, stretching from Jammu & Kashmir through Arunachal Pradesh, can be conceptualized as an “eco-floristic corridor” where conservation management integrates contiguous habitats under a unified planning framework. Landscape-level planning should map population clusters using high-resolution satellite imagery and ground-based inventories, identify ecological corridors linking them, and prioritize areas where anthropogenic disturbance coincides with high genetic or floristic value. Integrating rhododendron distribution data into state forest working plans, eco-sensitive zone demarcation, and watershed management programs will ensure that conservation is mainstreamed rather than isolated. Collaborative cross-border initiatives between India, Nepal, and Bhutan under platforms such as ICIMOD's (The International Centre for Integrated Mountain Development) Kailash Sacred Landscape Conservation Programme can further strengthen this approach, facilitating genetic exchange, coordinated monitoring, and knowledge sharing across national jurisdictions. By developing *R. campanulatum* conservation into broader transboundary landscape frameworks, India can contribute to regional biodiversity connectivity in line with the Kunming-Montreal Global Biodiversity Framework (2022).

Genomic Conservation and Adaptive Genetic Management: Scientific advancement will underpin all future policy directions. Comprehensive genetic and ecological studies are essential to delineate conservation units, identify adaptive traits, and guide both in situ and ex situ programs. Molecular tools microsatellite markers, chloroplast DNA sequencing, and genotyping-by-sequencing (GBS) can reveal population structure, gene flow barriers, and potential hybridization zones with related rhododendron species. These insights will allow conservationists to prioritize genetically unique populations and manage them as evolutionary significant units (ESUs). Parallel ecological studies should focus on understanding regeneration ecology, pollinator interactions, soil symbioses especially with ericoid mycorrhizae and microclimatic tolerances. Such datasets, when coupled with environmental DNA (eDNA) surveys, niche modelling and drone-assisted habitat mapping, can build predictive frameworks for restoration and monitoring (He *et al.* 2024). A Himalayan Rhododendron Genetic Consortium, involving institutions like the G.B. Pant National Institute of Himalayan Environment (GBPNIHE), Botanical Survey of India (BSI), and universities in Sikkim, Himachal, and Uttarakhand, could coordinate research protocols, maintain shared databases, and promote capacity building in molecular ecology and conservation genomics. This will ensure that management actions rest on robust scientific foundations rather than anecdotal evidence. Future conservation cannot rely solely on protecting wild populations; it must also safeguard genetic resources ex situ. Given that *R. campanulatum* seeds are short-lived and exhibit physiological dormancy, conventional seed banks are inadequate. Advances in tissue culture, somatic embryogenesis, and cryopreservation should therefore be prioritized. Research into micropropagation protocols, optimizing explant type, growth regulators, and acclimatization procedures has already shown promise for related species and should be extended to *R. campanulatum*. Botanical gardens and arboreta across India and abroad (e.g., Lloyd Botanical Garden, Sikkim; Forest Research Institute, Dehradun; Royal Botanic Garden Edinburgh) could form a living meta-collection network to maintain genetically diverse clones representing the species' full range. Periodic exchange of propagation material and genetic characterization will minimize redundancy and enhance representativeness. Moreover, developing community-based nurseries using vegetative propagation can supply planting stock for restoration while creating rural employment. Integrating nursery training into village eco-development committees would empower local participation in conservation, reducing dependency on wild harvesting (Liu *et al.* 2020).

Community-Based Conservation and Participatory Monitoring: Future conservation models must institutionalize community participation as a legal right, not an optional outreach activity. The Forest Rights Act (2006) and Biological Diversity Act (2002) provide enabling frameworks for decentralized governance, allowing local Biodiversity Management Committees (BMCs) to manage biological resources and document traditional knowledge through People's Biodiversity Registers (PBRs). BMCs in rhododendron-rich regions can be empowered to regulate harvest quantities, set local conservation by-laws, and manage eco-tourism revenues. Transparent benefit-sharing arrangements ensure that conservation generates tangible rewards either through sale of value-added products (jams, syrups, herbal teas) or eco-tourism profits (Pradhan and Sharma, 2024). Successful pilot examples in Sikkim, Darjeeling, and Himachal Pradesh demonstrate that when communities see clear benefits, compliance and stewardship rise significantly. Moreover, gender-inclusive participation is vital since women are often the primary gatherers of non-timber forest products. Training women's cooperatives in sustainable flower collection, processing, and branding can transform rhododendron conservation into a model of eco-entrepreneurship aligned with the "One District, One Product" (ODOP) scheme of Government of India (Naulak and Pradhan, 2023). Along with that, public awareness campaigns linking flowering seasons with local festivals and eco-tourism can re-establish cultural pride in native flora. Partnerships with monasteries and community leaders can revitalize traditional taboos and sacred grove systems that historically safeguarded rhododendron groves. Establishing Rhododendron Heritage Trails and educational trekking routes through blooming landscapes can combine awareness, tourism, and conservation financing. India's commitment to the Global Biodiversity Framework (GBF, 2022-2030) provides an opportunity to anchor rhododendron conservation in national policy (Bhutia *et al.* 2025). The GBF's targets on restoring degraded ecosystems, halting species extinctions and increasing community participation align perfectly with *R. campanulatum*'s conservation needs. Nationally, alignment with the National Biodiversity Strategy and Action Plan (NBSAP 2023) and State Biodiversity Action Plans (SBAPs) can ensure resource allocation and institutional accountability. At the global level, collaboration with Botanic Gardens Conservation International (BGCI)'s "Global Tree Assessment" and the Red List of Rhododendrons project ensures that Indian data contribute to international conservation databases, enhancing visibility and potential funding. By linking local action to global commitments, *R. campanulatum* can serve as a benchmark for implementing the "30×30" target protecting 30% of land by 2030 within mountain ecosystems (Chettri *et al.* 2018).

Ecosystem Service Valuation and Sustainable Financing: Financial sustainability is often the weakest link in conservation. To secure long-term funding, future strategies must leverage innovative financing mechanisms. Payment for ecosystem services (PES) schemes can compensate communities maintaining rhododendron forests for the hydrological and carbon benefits they provide. Integrating rhododendron conservation into REDD+ (Reducing Emissions from Deforestation and Forest Degradation) programs could generate carbon credits for reforestation of degraded sub-alpine slopes. Public-private partnerships with eco-tourism operators and herbal product companies can create revolving funds for habitat restoration and research. Moreover, international biodiversity financing mechanisms such as the Global Environment Facility (GEF) and UNDP's Small Grants Programme can support pilot projects demonstrating community-based restoration. Ensuring that a proportion of profits from commercial rhododendron products flows back into conservation funds would institutionalize benefit reinvestment.

Policy Integration and Government Reforms: One of the most crucial policy directions is to mainstream rhododendron conservation within India's legal and planning frameworks. Currently, *R. campanulatum* lacks formal protection under the Wildlife (Protection) Act (1972). Given its ecological and cultural importance, it should be considered for inclusion under Schedule VI (Protected Plant Species), alongside other alpine endemics. At the policy level, the National Biodiversity Authority (NBA) and State Biodiversity Boards can issue Biodiversity Management Plans (BMPs) specifically for rhododendron-dominated ecosystems, incorporating traditional knowledge, sustainable harvest protocols, and community benefit-sharing mechanisms. Integrating rhododendron conservation into the National Mission for Himalayan Ecosystem (NMHE) and the Indian Himalayan Region Sustainable Development Goals (IHR-SDG) framework will align species protection with climate adaptation and poverty alleviation targets (Biswas *et al.* 2025). Additionally, harmonizing forest working plans with biodiversity conservation priorities is imperative. Forest departments should recognize sub-alpine rhododendron scrub as an ecological land-use category deserving protection, not merely as "unproductive land." Incorporating rhododendron indicators into forest certification systems (e.g., FSC or India's Green Forest Certification) can create economic incentives for sustainable management. Effective policy formulation and coherence can be achieved through interdepartmental coordination in terms of land-use, tourism regulation and conservation planning at state as well as central levels. For example, road construction guidelines in the high-altitude regions should include assessment of ecological factors and rhododendron compensatory restoration in order to offset tree felling (Thapa *et al.* 2021). Similarly, as a part of tourism regulation, number of tourist vehicles entering these eco-sensitive regions can be restricted especially during peak flowering seasons. Biodiversity indicators need to be incorporated within development planning to ensure that conservation becomes a priority. Conservation efforts must include strategic partnerships with advanced research centers across the globe. Joint Indo-Nepal-Bhutan research expeditions could explore genetic linkages across borders, while regional seed exchange programs ensure broader genetic representation in ex situ collections. The establishment of a Himalayan Rhododendron Research Network (HRRN) could coordinate data sharing, capacity building, and publication dissemination, fostering a pan-Himalayan conservation identity (Ali *et al.* 2024).

Technology, Monitoring and Decision Support System: The digital age that the world is ushering into offers promising scope for revolutionizing the monitoring and management of *R. campanulatum*. Smartphone-based platforms can be exploited to crowdsource various seasonal observations from villagers and travelers which can then be fed into a centralized biodiversity database such as GBIF (Global Biodiversity Information Facility) (Chandler *et al.* 2017). Additionally, high-resolution remote sensing and UAV (drone) surveys can be deployed to gauge habitat loss, canopy health, and flowering intensity. Synthesizing these datasets using AI models can help generate forecasts related to for habitat loss or illegal harvesting. At a policy level, establishing a digital platform that integrates floristic, genetic, ethnobotanical, and climatic data can guide decision-making, implementation and improve coordination among various agencies. Blockchain-based systems can highlight and certify rhododendron products that have been harvested sustainably, thereby checking exploitation while adding to their market value. Future conservation must be outcome-oriented and accountable (Kumar and Mutanga 2018; Tuia *et al.* 2022). Establishing Key Biodiversity Indicators (KBIs) for *R. campanulatum*, such as population density, regeneration rate, and habitat integrity will allow standardized monitoring across states. Annual or biennial "State of the *Rhododendron* Report" could synthesize scientific data, community observations, and management interventions, offering a transparent scorecard for policymakers and funding agencies. Linking such reporting mechanisms to funding eligibility will enhance compliance and encourage evidence-based decision-making. Independent audits and participatory monitoring involving community members, students, and NGOs can ensure credibility and build local ownership (Nicholson *et al.* 2021; McMillan *et al.* 2021)). Ultimately, the goal is to create a feedback loop between science, policy, and society. As the equitable access and benefit-sharing is fundamental under the Biological Diversity Act (2002) and the Nagoya Protocol, future policy must recognize the ethical dimension of conservation of *R. campanulatum,* as it is not merely botanical resources rather the cultural identity of the Himalayan states especially Uttarakhand & Himachal Pradesh. Protecting the intellectual property rights of indigenous communities and ensuring fair royalty distribution obtained from any commercial or research use of traditional knowledge, will build trust and prevent biopiracy. Moreover, conservation must be gender-sensitive, youth-inclusive, and respectful of spiritual values associated with the plant, ensuring that ecological restoration goes hand in hand with cultural rejuvenation.
Future conservation of *R. campanulatum* requires an integrated framework that combines climate-resilient restoration, genomic conservation, participatory community stewardship, ecosystem service valuation, adaptive policy support and technology driven monitoring. Rather than relying solely on protected-area approaches, conservation efforts should adopt a landscape-scale strategy that link ecological processes, local livelihoods and long-term climate adaptation. The integration of ecological, genomic, socioeconomic and governance perspectives will provide a scientifically robust roadmap for ensuring the persistence of this Himalayan tree-line species under rapidly changing environmental conditions.

Conclusion

Rhododendron campanulatum is a keystone Himalayan species whose ecological and cultural significance reflects the interdependence between biodiversity and mountain societies. Its distribution across the temperate and sub-alpine belts of the Western and Eastern Himalaya positions it as both a stabilizer of fragile slopes and a bioindicator of environmental change. Yet, its current status is jeopardized owing to a plethora of challenges in the form of accelerating climatic shifts, habitat fragmentation, and erosion of traditional knowledge systems. The existence of these high-altitude shrubs is at grave risk from the rapidly rising temperatures and the subsequent phenological changes and disease incidence. Additionally, fungal pathogens that have been reported in many related Rhododendron species pose unprecedented biotic risks. These challenges coupled with mounting anthropogenic pressures fueled by rising demand and excessive exploitation of the species exacerbate conservation challenges (Xie *et al.* 2024). The need of the hour is to shift focus from regional, fragmented and generalized approach to community driven, adaptive and integrated conservation planning. Strengthening long-term population monitoring, expanding genetic assessments, and integrating remote sensing with species-distribution modeling will be essential for forecasting vulnerability patterns under future climates. Equally critical is the revitalization of local ecological knowledge through participatory governance models that align cultural practices with scientific management. Embedding *R. campanulatum* conservation within state biodiversity missions, REDD+ initiatives, and community-based livelihood programs can generate co-benefits for rural economies and ecosystem resilience. Ultimately, conserving this emblematic shrub is not simply a botanical mandate but a broader environmental obligation one that reflects the sustainability of the Himalayan landscape itself (Singhal *et al.* 2023).

A strong conservation plan for *Rhododendron campanulatum* must take into consideration the establishment of long term ecological and seasonal monitoring sites across the Himalayas in order to enable the researchers to track climate induced changes precisely. These measures must be coupled with community driver conservation efforts to incorporate scientific harvesting, eco-certification mechanisms and responsible exploitation of resources aimed at reducing pressure on the species. Finally, the success of various conservation efforts will depend on coming together and building of a common will among various regional bodies across neighboring Himalayan countries in terms of alignment of management plans and data sharing.

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