iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VII **Month of publication:** July 2026

DOI: https://doi.org/10.22214/ijraset.2026.84481

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

Traditional Ecological Knowledge as an Effective Tool for Biodiversity Conservation in Ladakh: A Systematic Review

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Abstract: ***Conserving biodiversity in mountain ecosystems is becoming more difficult due to rapid climate change, habitat loss or degradation, lack of sustainable use of these landscapes, and socio-economic change. Ladakh, the Trans Himalayan region, is one of the most ecologically sensitive cold desert ecosystems with unique flora and fauna, and indigenous communities who have lived in harmony with nature for centuries. Traditional Ecological Knowledge (TEK), which has been accumulated over the years by local communities through their interaction with their natural surroundings, gives precious ecological information to manage the natural resources of the area and to conserve biodiversity in a sustainable way. This is a systematic review where various scientific and factual evidence so far generated are brought together as an effective tool for biodiversity conservation in Ladakh. Peer-reviewed articles from the years 2000 to 2025 were systematically searched from Scopus, Web of Science, and Google Scholar following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. It shows that indigenous land use systems, such as rotation of livestock grazing; collective management of water harvesting schemes; sustainable gathering of medicinal plants; protection of sacred landscapes; and participatory management of wildlife resources, have played a vital role in sustaining the resilience of these ecosystems and have conserved biological diversity. Traditional ecological practices contribute to the scientific conservation practices by incorporating ecological sustainability, cultural value, and community engagement. However, rapid climate change, the retreat of glaciers, general infrastructure development, the expansion of tourism, and the erosion of indigenous knowledge threaten the biodiversity and traditional conservation systems. It explicitly identifies the need to incorporate TEK in today's biodiversity policies, adaptive ecosystem management, and climate-resilient conservation responses. Improved scientists-policymakers-indigenous peoples relations will promote long-term conservation success and promote Ladakh's ecological and cultural values.***

Keywords: Traditional Ecological Knowledge, Indigenous Knowledge, Biodiversity Conservation, Ladakh, Trans-Himalaya, community-based conservation, climate change.

I. INTRODUCTION

Biodiversity is vital to the functioning of ecosystems, to human well-being and to the provision of ecosystem services that rely on biodiversity, such as food production, regulation of freshwater, climate regulation, pollination, soil formation, or nutrient cycling. Although it has ecological and socio-economic significance, world biodiversity is undergoing unprecedented loss because of habitat destruction, climate change, biological invasions, pollution and unsustainable exploitation of natural resources. Biodiversity loss is recognised as one of the biggest environmental issues of the twenty-first century, with an estimated one million species threatened with extinction (Díaz et al., 2019; IPBES 2019). Likewise, mountain ecosystems rank among the most climate-sensitive areas of the world to ecological changes caused by accelerating mountain temperatures, glacier retreat, changing precipitation regimes and extreme weather events (IPCC, 2023; Xu et al., 2019).

Mountain ecosystems account for almost 25% of the Earth's terrestrial surface and around 33% of all terrestrial biodiversity and make almost 50% of the world's freshwater available to more than 50% of the human population (Körner, 2004; Payne et al., 2020). The high ecological variation of these ecosystems is caused by high differences in altitude, climatic variations and rich geomorphology. Mountain regions, therefore, may have high levels of endemism but also be they are more ecologically sensitive to the effects of environmental disturbance in comparison to the lowlands (Körner, 2004; Xu et al., 2019). As a result, the conservation of mountain biodiversity is a priority for international relations, and the Convention on Biological Diversity and the United Nations Sustainable Development Goals (CBD, 2022; United Nations, 2015) focus on the protection of "Mountain biodiversity for Sustainable Conservation".

The Indian Himalayan Region (IHR) is one of the key biodiversity hotspots of the globe, encompassing a variety of ecosystems from sub-tropical forests to alpine cold deserts. Ladakh is placed at a unique and sensitive position in this region as a high-altitude Trans-Himalayan cold desert lying between the Karakoram and Greater Himalayan mountain ranges. The territory is under extreme environmental conditions such as low annual precipitation (generally below 100 mm) in the region, long winter, high solar radiation, reduced oxygen levels in the atmosphere, high altitudes, while the elevation is mostly above 7000 m above sea level (Rawat & Adhikari, 2005; Namgail et al., 2007). Yet, with these severe climatic conditions, Ladakh hosts very high biological diversity with alpine meadows, dry steppe vegetation, wetland, glaciers, rivers and rocky mountain biotic systems that is habited by attempted numbers of endemic and threatened species (Fox et al., 1991; Rawat & Adhikari, 2005).

This area is known for its iconic wildlife species such as the snow leopard (Pantera uncia), the Himalayan ibex (Capra sibirica), blue sheep (*Pseudois nayaur)*, Tibetan wild ass (Equus kiang), Tibetan argali (*Ovis ammon hodgsoni)*, black-necked crane (Grus nigricollis), and a group of endemic alpine species found in the cold deserts of this area (Fox et al., 1991; Bhatnagar et al., 2006; Angmo et al., 2024). Apart from being ecologically significant, Ladakh is also rich with its cultural diversity of indigenous population like Changpa pastoralists, Brokpa, Balti and Ladakhi farmers and their livelihood is still closely tied to the local environment. Throughout the years these communities have evolved and mastered a detailed knowledge about ecology, allowing sustainable use their natural resources with great environmental constraints (Berkes, 2018; Angmo et al., 2024).

Traditional Ecological Knowledge (TEK) is the complex, cumulative ecological knowledge, practices, beliefs and social institutions that are learned by indigenous and local peoples from their local environments and develop over long periods of occupation and use. In contrast to conventional scientific knowledge, TEK is local in nature, flexible, contextual and passed down through the generations with oral history, cultural traditions, and learning through doing experiences (Berkes et al., 2000; Houde, 2007). It includes monitoring of the ecosystem, seasonal ecosystems, behaviour of species, soil properties, water availability, grazing practices and sustainable harvesting. To note is that TEK has an integral aspect of ecological knowledge with cultural values, ethics, and community governance mechanisms that instill sustainable governance of resources (Berkes, 2018; Folke, 2004).

In the last 20 years, the scientific community has paid far more attention to the recognition of TEK. Indigenous knowledge also plays a significant role in the conservation of biodiversity, adaptation to climate change, restoration of degraded ecosystems, sustainable farming practices, fishery and wildlife management in many ecological contexts (Gadgil et al., 1993; Berkes et al., 2000; Garnett et al., 2018). The Global Assessment Report of the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES, 2019; Díaz et al., 2019) also noted that, overall, the well-being of biodiversity is better on indigenous-managed lands than in other areas overseen solely through traditional conservation methods. Incorporating TEK and combining scientific knowledge has therefore become a key tenet in international biodiversity policies, such as the Convention on Biological Diversity and the Kunming–Montreal Global Biodiversity Framework (CBD, 2022).

Under the harsh climatic conditions and scarce natural resources of Ladakh, TEK has been developed through a centuries of adaptation process. Indigenous Peoples use very efficient management practices of rotation grazing, seasonal traveling, harvesting water, promoting traditional water systems (kul), taking care of water sources (ging), caring for plants with healing properties and managing wildlife in their communities. Historically, these practices have helped to ensure the ecological balance and sustainable livelihoods in one of the most harsh inhabited environment in the world (Nüsser et al., 2012; Ballabh & Chaurasia, 2007). Moreover, the religion of Tibetan Buddhism has instilled the conservation values manifested in conserving sacred sites, no hunting or prevention of wildlife harm and thereby harmonious co-existence with the wild animals (Jackson & Wangchuk, 2004; Mishra et al., 2004).

But, the ecological and cultural systems which support the TEK in Ladakh are under a severe threat. Climate warming over the Trans-Himalayan region has been rapid and this has increased the rate of glacier retreat, impacted the hydrological regime, decreased snow cover, and had changed the vegetation dynamics (Xu et al., 2019; IPCC, 2023). In parallel, infrastructure investment, tourism and market booms, military exercises, livelihood expectations, and other factors have been responsible for habitat fragmentation and loss of indigenous knowledge systems. The younger generations are shying away from traditional work, meaning there are fewer opportunities for transmission of ecological knowledge from one generation to the next (Angmo et al., 2024; Berkes, 2018). These environmental and socio-economic pressures highlight the need for documentation, preservation, and incorporation of TEK in modern-day conservation of biodiversity.

While many studies have been carried out in Ladakh on ethnobotany, pastoralism, medicinal plants, wildlife conservation and climate adaptation, knowledge is still scattered on various disciplines. There is no full synthesis yet which has assessed the potential of TEK as a tool for biodiversity conservation in the region. This knowledge gap needs to be filled to guide evidence-based conservation policies, enhance community involvement and prioritize future research.

Thus, this systematic review is set to co-join and bring together contemporary scientific evidence on the role of TEK in conservation of Ladakh's biodiversity. The review aims to: (i) discuss the ecological characteristics and biodiversity of Ladakh; (ii) discuss the indigenous knowledge systems with respect to the management of natural resources; (iii) discuss TEK contribution to biodiversity conservation and climate resilience; (iv) discuss some of the important issues related to the threats to TEK systems; and (v) suggest ways for integrating TEK in future with scientific conservation and environmental policy. This review may help to reinforce the importance of the body of available evidence on indigenous knowledge as an essential resource of sustainable biodiversity conservation in fragile mountain environments.

II. MATERIALS AND METHODS

This review has been conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 Guidelines which aim to provide information to readers regarding the methodological transparency, reproducibility and comprehensive synthesis of all the literature available here (Page et al., 2021). Three scientific databases (Scopus, Web of Science Core Collection and Google Scholar) were used to systematically search, as these databases cover environmental sciences, ecology, ethnobiology, conservation biology and Himalayan studies (Snyder, 2019; Page et al., 2021). Backward citation tracking of highly cited articles, as well as of authoritative reports, was performed to find more additional relevant publications.

Search strategy comprised of the Boolean operators followed by Keywords such as "Traditional Ecological Knowledge," "Indigenous Knowledge," "Ethnobiology," "Ethnobotany," "Biodiversity Conservation," "Ladakh," "Trans-Himalaya," "Cold Desert," "Pastoralism," "Medicinal Plants," "Community Based Conservation," and "Climate Change. Peer-reviewed journal articles, review papers, book chapters and institutional reports written in English during the period 2000-2025 were deemed acceptable. Studies were considered if they have focussed on the nature of biodiversity conservation, indigenous ecological knowledge, traditional pastoralism, natural resource management, wildlife conservation, utilization of medicinal plants, and ecosystem management conducted in Ladakh or ecologically similar Trans-Himalayan regions. Abstracts of conferences, duplications, grey literature not subject to peer-review and editorials were excluded, likewise papers that not related with the conservation of biodiversity (Moher et al., 2009; Snyder, 2019).

After removing all irrelevant articles from the pool after title and abstract screening, potentially relevant articles were then assessed for eligibility for the predefined inclusion criteria, which involved full-text screening. Data gathered from each study involved year of publication, geographical region, study goals, biodiversity elements examined, traditional methods of conservation, methodology and major results, and any gaps in research. Because there was significant heterogeneity across the included articles in ecological variables, methodological designs and conservation outcomes opting for a qualitative narrative synthesis instead of a quantitative meta-analysis, was employed (Page et al., 2021). The final review was structured based on key thematic areas including biodiversity characteristics, traditional pastoral systems, ethnobotanical knowledge, water resource management, wildlife conservation, socio-ecological resilience, climate adaptation, and policy integration.

III. BIODIVERSITY OF LADAKH

The region of Ladakh of roughly 59146 km² is included in the north western Indian Himalaya mountain ranges and is part of the Trans-Himalayan biogeographic region. There are rugged mountain ranges, as well as extensive glaciers, alpine meadows, dry steppe vegetations, river valleys, high-altitude lakes and wetlands, between 2700 and 7600 m FMSL. The region has an extremely arid climate with an average annual precipitation below 100 mm, long winters, high solar radiation, low atmospheric oxygen concentration and high day to night temperature fluctuation because of rain shadow effect of the Himalayas (Rawat & Adhikari, 2005, Namgail et al., 2007, Xu et al., 2019). Yet, under such harsh environmental conditions, Ladakh is home to extraordinary biological diversity, which can withstand extreme environmental pressures thanks to special adaptations.

Ladakh has not only high species richness, its ecological importance lies in being one of the biggest continuous cold-desert ecosystem units in the world. A high diversity of ecological niches sustained by altitudinal gradients, glacial hydrology, the processes associated with permafrost, and a heterogeneous geomorphology are found, which support a large variety of endemic and threatened species (Rawat & Adhikari, 2005; Mishra et al., 2004). Higher altitudes have an abundance of alpine grasslands which support an important grazing habitat for wild ungulates and domesticated animals while riparian corridors and wetlands maintain relatively high primary production in otherwise dry areas (Namgail et al., 2007; Nüsser et al., 2012). Therefore, ecological processes occurring within the Ladakh region are of significant interest in terms of regional hydrological regulation, nutrient cycling, carbon storage, and in maintaining ecosystem resilience in the face of future climate change (Xu et al., 2019; IPCC, 2023).

The flora diversity of Ladakh is a particularly special one, as the plants have to withstand freezing temperatures, lack of water, high UV radiation and lack of nutrients. Over 1200 vascular plant species have been reported with several plant species of medicinal, aromatic and economically important of the region, some of them are endemic (Kala, 2005; Rawat & Adhikari, 2005). Sea buckthorn (*Hippophae rhamnoides*), *Rhodiola imbricata, Ephedra gerardiana, Arnebia euchroma, Juniperus indica, Aconitum heterophyllum* and some other species of *Saussurea, Potentilla and Astragalus* are prominent species. These species play crucial roles in soil stabilization, erosion control, nutrient cycling, pollinator support and preservation of the productivity of alpine ecosystems; as well as for the food, fodder, fuelwood, medicines and livelihoods of indigenous communities (Ballabh et al. Chaurasia, 2007; Kala, 2005; Angmo et al., 2024). According to ethnobotanical studies, certain medicinal plants are used sustainably due to traditional harvesting practices based on ecological understanding, which includes selective harvesting and taking care of reproductive plants (Ballabh et al., 2008; Angmo et al., 2024).

Ladakh hosts one of the most unique groups of high-altitude wildlife of Asia, many of which are acclimated to despicable hypoxic and cold-desert environment. The region is internationally known to hosts viable populations of the endangered snow leopard (Panthera uncia), considered as the top predators of the Trans-Himalayan ecosystems (Fox et al., 1991; McCarthy & Mallon, 2016). Other significant mammals are Himalayan ibex *Capra sibirica*, blue sheep *Pseudois nayaur*, Tibetan argali *Ovis ammon hodgsoni*, Tibetan wild ass *Equus kiang*, Tibetan gazelle *Procapra picticaudata*, Tibetan wolf *Canis lupus chanco* and Eurasian Lynx Lynx lynx, Himalayan marmot Marmota himalayana and red fox Vulpes vulpes (Bhatnagar et al., 2006; Namgail et al., 2007). Herbivores like blue sheep, ibex are of critical importance ecologically, as they affect vegetation dynamics and are the main preys of snow leopard thus maintaining trophic interaction critical for the stability of the ecosystem (Bagchi et al., 2004; Mishra et al., 2004).

Avian diversity is also important, especially in the wetlands and freshwater habitats of high altitudes in the region where they are located.

Wetlands like Tso Moriri, Tso Kar and Pangong Tso are internationally significance breeding and migratory grounds of vulnerable black-necked crane (*Grus nigricollis*), bar-headed goose (*Anser indicus*), ruddy shelduck (*Tadorna ferruginea*), brown-headed gull (*Chroicocephalus brunnicephalus*) and many migratory waterbirds (Fox et al. 1991; Bhojak et al. 2024). They serve important roles such as groundwater recharge (Tockar et al., 2014), water purification and purification, sediment removal, nutrient cycling and sustaining the regional hydrological balance, besides support of the traditional pastoral and agriculture-based livelihoods (Rawat & Adhikari, 2005; Nüsser et al., 2012).

Keeping its unique ecological importance in mind, a number of Protected Areas are located in the region of Ladakh such as the Hemis National Park, Changthang Wildlife Sanctuary, Karakoram Wildlife Sanctuary and Tso Moriri Wetland Conservation Reserve. The Huangstang and Hemis (approx 4,400 km2) national parks are among the most critical strongholds for the conservation of the snow leopard population, and Changthang Wildlife Sanctuary conserves vast alpine pasture, shared by wildlife and nomadic pastoralists (Fox et al., 1991; Namgail et al., 2007). However, in many protected areas elsewhere, wildlife and indigenous communities have to coexist and community participation is an essential ingredient to good conservation outcomes and traditional resource management mechanisms are therefore central to conservation success in Ladakh (Jackson & Wangchuk, 2004; Mishra et al., 2004).

Ladakh has strong ecological value, yet faces various anthropogenic and climatic pressures that are threatening its biodiversity. Glaciers are retreating and snow melt patterns are shifting, along with drought events and extreme climate conditions that have become more common, in the Trans-Himalayan region (IPCC, 2023; Xu et al., 2019). At the same time, the expansion of tourism, road construction, urbanisation, military infrastructure, mining, and shifting the use of land have led to habitat fragmentation and ecological disturbance being more intense (Namgail et al. 2007; Angmo et al., 2024). These pressures have led to a loss of connectivity, escalations of human-wildlife conflict, and the risk of many alpine species needing fragile cold-desert type habitat (McCarthy & Mallon, 2016; IPCC, 2023).

Approaches that go beyond the Protected Areas management to integrated Socio-Ecological conservation is thus needed for the long-term conservation of Ladakh's biodiversity. The scientific literature has been building up on the significance of indigenous knowledge and practices in promoting ecological resilience far removed from expectations, as they have supported the use of resilient grazing systems, community-controlled water resources, culturally preserved landscapes, and traditional harvesting methods that limit environmental harm (Berkes et al., 2000; Berkes, 2018; Angmo et al., 2024). Insights into these knowledge systems lay the groundwork for the next section, where TEK is discussed in the context of its value for biodiversity conservation.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

IV. TRADITIONAL ECOLOGICAL KNOWLEDGE AS AN EFFECTIVE TOOL FOR BIODIVERSITY CONSERVATION IN LADAKH

Traditional Ecological Knowledge (TEK) is coming into the spotlight as a valid, culturally rich and scientifically valuable knowledge framework that can complement modern biodiversity conservation. According to the Convention on Biological Diversity (CBD) (2022), the traditional knowledge is considered as the accumulated knowledge, innovation and practices of indigenous and local communities developed over long periods of time in their interaction with a particular environment. In a similar vein, Berkes (2018) views TEK as an adaptive knowledge system that involves an ongoing system of cultural values, customary institutions, ecological observations and resource management practices that change in response to changes in environmental conditions. Whereas traditional science tends to focus on manipulating variables within experiments and conducting relatively short-term observations, TEK is derived from many centuries of observation from long-term user interactions with ecosystems, offering fine-scale ecological data that is often not available from formal science-based monitoring efforts (Berkes et al., 2000; Folke, 2004; IPBES, 2019).

Globally, a number of studies have shown that indigenous peoples are stewards of almost 25% of the landmass on Earth, and protect about 80% of the remaining biodiversity – an essential contribution to global conservation efforts (Garnett et al., 2018; IPBES, 2019). Incorporating ecological sustainability into cultural norms and customary governance, indigenous-managed landscapes are often characterized by lower rates of habitat degradation, higher ecological integrity and species persistence than neighbouring landscapes managed conventionally (Díaz et al., 2019; Garnett et al., 2018). In response, recent global biodiversity frameworks have increasingly called for linking TEK to the creation of conservation plans, restoration of ecosystems, and climate change adaptation plans (CBD, 2022; IPBES, 2019).

In the case of Ladakh, their Traditional Ecological Knowledge is the result of a long process of adaptation to the harshest of all mountain environments on the planet. The indigenous community of Changpa, Brokpa, Balti and traditional farmers of the Ladakh region have developed detailed ecological knowledge on climate variability, snow dynamics, pasture productivity, behaviour of wild animals including traditional livestock, availability of water, medicinal plants etc. (Angmo et al., 2024; Berkes, 2018). Over the years these communities have developed an historically similar outlook on nature, where humans are part of a greater ecological whole, and where the sustainable use of natural resources helps to sustain the ecosystem and livelihood over time. Due to severe climatic constraints, this holistic ecological world view has helped coexistence between the conservation of biodiversity and the survival of humanity (Folke, 2004; Berkes et al., 2000).

One of the prominent traditional practices relating to TEK to support biodiversity conservation in Ladakh is traditional pastoralism. The Changpa nomadic pastoralists traditionally have been practicing adaptive stocking rates and rotation grazing as well as seasonal movement within the vast range of high, broad alpine pastoral lands in Changthang Plateau based on their ecological understanding. Decision making for grazing is also based on the snow cover, vegetation growth, soil moisture and animal movement, with objective to avoid overstocking the fragile alpine vegetation (Namgail et al., 2007; Bhatnagar et al., 2006). Seasonal shifting of livestock can provide grazed lands enough recuperation period as well as maintain the diversity of vegetation, soil fertility, and productivity of forage, and reduce degradation of habitat and erosion (Mishra et al., 2004; Bagchi et al., 2004). With the emphasis moving more and more towards contemporary ecological research, the conclusions are that rotational grazing based on indigenous knowledge is more beneficial to ecosystem resilience, recuperation of vegetation and sustainability of biodiversity than continuous grazing systems (Briske et al., 2008; Berkes, 2018).

Cultural practices promoting livestock/wild herbivore co-existence are also traditional practices. Grazing landscapes that are shared with livestock are often used by blue sheep (*Pseudois nayaur*), Himalayan ibex (*Capra sibirica*), Tibetan argali (*Ovis ammon hodgsoni*) and kiang (*Equus kiang*). Throughout the year, indigenous herders are aware of wildlife movement and adjust the amount of grazing utilized to reduce direct competition for forage during this time. This kind of adaptive management can conserve populations of prey species that are vital for the survival of apex species like the snow leopard (*Panthera uncia*) (Bagchi et al., 2004; Namgail et al., 2007) and minimize ecological conflict. Scientific studies have shown that areas with high indigenous herbivorous use tend to contribute to a higher volume of herbivores and better quality of the landscape than those areas intensively grazed by commercial herbivores (Bhatnagar et al., 2006; Mishra et al., 2004).

Another impressive case of TEK in the service of biodiversity conservation in Ladakh is that of water resource management. Water scarcity has traditionally been the biggest environmental challenge in the cold-desert ecosystem due to its reliance on seasonal snowmelt and glacial runoff for agriculture. The indigenous people invented an elaborate irrigation network, called “kul”, that consists of gravity-fed channels for redistributing glacial melt water over long distances to fields. (Nüsser et al., 2012; Dame & Nüsser, 2011).

These constitute irrigation systems which are complemented by zing, traditional storage reservoirs which temporarily hold meltwater for irrigation in times of low stream discharge. The distribution of irrigation water is managed by customary community institutions, which work out the need and come up with fair distribution timetables, but which also avoid overusing the limited water sources (Nüsser et al., 2012). At the same time, these locally developed governance systems foster productive agriculture, preserve wetland ecosystems, mitigate soil erosion, and retain biodiversity reliant on seasonal water (Dame & Nüsser, 2011; Berkes, 2018).

TEK also proves to be very significant in protecting its abundance of medicinal plant resources in Ladakh. Identification, ecology, harvesting, processing and therapeutic application of alpine medicinal plant species requires rich knowledge, on which indigenous medicine Sowa-Rigpa (Amchi) relies. Some of these plants like *Rhodiola imbricata, Arnebia euchroma, Ephedra gerardiana, Aconitum heterophyllum and Hippophae rhamnoides* have been long used in the treatment of respiratory disorders, cardiovascular diseases, digestive ailments, inflammation and high-altitude sickness (Ballabh & Chaurasia, 2007; Ballabh et al., 2008). More importantly, the traditional practice of medicinal plant collection relies on the principles of ecologies involving harvesting mature specimens, avoiding reproductive plants, limiting intensity of harvesting and collection at certain phenological stages to maintain natural regeneration (Kala, 2005; Angmo et al., 2024). This has traditionally helped to take the strain on sensitive alpine plants and helped to preserve medicinal sources for the future.

The latter is further illustrated by recent ethnobotanical studies that show that indigenous knowledge can play a useful role in conserving genetic diversity, promoting the cultivation of Local Medicinal Plants in agroecosystems and household gardens, thus reducing pressure on harvesting indigenous plants and creating an extra source for medicines (Angmo et al., 2024; Kala, 2005). The integration of conservation and healthcare provides an example of the multifunctionality of TEK--conservation, cultural identity, and community wellbeing.

Religious beliefs and cultural institutions are other important mediums for the contribution of TEK in providing biodiversity conservation. Living in Ladakh, most people are practising Tibetan Buddhism, which encourages the people to treat every living being with compassion and not kill the wildlife unnecessarily. Other traditional landscape areas, such as sacred mountains, monasteries, lakes and forests are considered to hold spiritually important landscapes, where extraction and hunting are, or are socially discouraged to be permitted (Berkes, 2018; Jackson & Wangchuk, 2004). The diverse nature of these culturally protected landscapes often also provides informally protected space for biodiversity activities, areas that may incur more anthropogenic pressure on biodiversity if not protected. These same connections between sacred natural areas and biodiversity protection are observed among many indigenous peoples and the ecological value of cultural forms of conservation is illustrated (Berkes et al., 2000; Folke, 2004).

In the present days, the importance of such community participation has grown in the entire region of Ladakh in relation to wildlife conservation programmes. In the past, snow leopards caused economic damages and sometimes human life losses to livestock raising households with their predations, leading retaliatory killing of predators. But conservation programs that combine the use of traditional knowledge and incorporate scientific management have made significant contributions to the ability of local people to coexist with wildlife. The implementation of predator-proof livestock compounds, community-based livestock insurance programs, eco-tourism initiatives, conservation education, and participatory management of wildlife monitoring, have helped to minimize human-wildlife conflict and engender local support for conservation of the snow leopard (Jackson & Wangchuk, 2004; Maheshwari & Sathyakumar, 2020). Indigenous herders share valuable ecological data on seasonality wildlife movement, the abundance of wildlife, their distribution, denning sites and predator presence which can be used to complement the scientific field surveys and camera-trap monitoring (McCarthy & Mallon, 2016; Maheshwari & Sathyakumar, 2020). These joint conservation initiatives are often effective at showcasing the benefits of combining TEK and science for more effective conservation, and community management of biodiversity.

The adaptive value of TEK is also more traditional ecological knowledge helps indigenous communities react proactively to the changing environment. Consistent monitoring of other variables (such as snowfall, glacier melt, flowering phenology, animal migration, and water availability) allows communities to adjust agricultural activities, livestock tending and pastoral movement, and harvest to changing climate conditions (Berkes, 2018; IPCC, 2023). The local perception and knowledge of climatic phenomena and conditions have been shown to often align very closely with that recorded by instrumental measurements and thus can be of great value as a scientific source of data on climatic events and changes (Xu et al., 2019; Angmo et al., 2024). These observations, when part of a regional conservation planning process, can assist in better adaptive management by decision makers to conserved biodiversity in more and more uncertain climate regimes.

The evidence available together, shows that the TEK provides a feasible and effective path for conservation, incorporating problems of ecological sustainability, adaptive resource management, cultural stewardship and community governance. TEK is not an alternative measure to scientific conservation; it should be seen as augmenting modern ecological practices offering long-term observations of the environment, local solutions that can be applied to conservation, and culturally and socially viable conservation options. Thus, it is increasingly concluded that collaborative governance models, which see indigenous communities as more than stakeholders, but as partners in the planning and management of biodiverse conservation areas, is essential for successful conservation efforts in Ladakh (IPBES, 2019; CBD, 2022; Berkes, 2018).

V. CHALLENGES, RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the demonstrated contribution of Traditional Ecological Knowledge (TEK) to biodiversity conservation, several ecological, socio-economic, institutional, and policy-related challenges threaten its continued application in Ladakh. Continuous indigenous institutions, culture, and ecosystems are essential in order to ensure the efficacy of TEK. But with the fast-changing environment and socio-economic transformation, these interdependent systems have been disturbed, and put both the indigenous knowledge and biodiversity at risk. As such, there is a need for an increased emphasis on synergy between TEK and science in the design of conservation strategies in the Trans Himalayan region and a need for addressing the changing and new environmental and development challenges (Berkes, 2018; IPBES, 2019; CBD, 2022).

Climate change is considered to be the biggest long-term threat to the Ladakhi biodiversity and TEK. Climate change in the Himalayan region is warming faster than the global average, as well as warming faster than the local area (IPCC, 2023; Xu et al., 2019), which has caused quick deterioration of glaciers, decline in snow cover, a change in precipitation patterns, and an increase in extreme climatic events. Glacial melt and seasonal snowfall are crucial for agriculture, pastoralism, and access to water; therefore, even a small climate change can significantly reduce the functioning of these ecosystems, and people's way of life. Climate-induced changes in alpine vegetation have manifested in changes in species composition, flowering phenology and productivity, and the effects on pasture quality have had a direct effect on livestock management and wildlife distribution (Xu et al., 2019; Angmo et al., 2024). Changes in these environments pressure the ability of indigenous knowledge systems to predict, developed over a number of centuries in stable climatic conditions.

Traditional Ecological Knowledge is further being degraded by changing socio-economic situations. Due to expansion of road infrastructure, increase in market integration, modern educational system, the development of tourism and urbanisation, livelihoods are diversified other than in the agriculture and pastoralism sector. Traditionally, intergenerational transfer of ecological knowledge was common, but with the increasing perceptions from younger generations, opportunities for such knowledge transfer are challenged, as they in turn migrate towards urban centres or take jobs that are disconnected with the field of resource management (Berkes, 2018; Angmo et al., 2024). With fewer and fewer youth engaging in traditional jobs, the knowledge and skills of oral history related to wildlife behaviour, medicines, weather prediction, grazing and water allocation are fading out. The same trend of loss of indigenous knowledge has been noted all over the world, where cultural change is a major problem in conserving biodiversity (Gadgil et al., 1993; Díaz et al., 2019).

Tourism has become an opportunity as well as challenge for conservation of biodiversity, in Ladakh. The area has seen a massive rise in domestic and international tourists in the last 20 years after which it became easier to get there and infrastructure was improved. Tourism creates jobs, fosters eco-tourism projects and raises the public awareness about conservancy. But at the same time, unchecked tourism has also increased the pressure on the fragile ecological communities by generating wastes, extracting water, fragmenting the habitats and driving off-road activities and/or disturbing the wildlife, especially at the high mountain wetlands and alpine habitats (Namgail et al., 2007; McCarthy & Mallon, 2016). In other areas, rise in tourism have also changed the traditional land-use pattern as commercial development processes override indigenous land-use systems.

Despite significant progress in community based conservation programmes, human wildlife conflict is still a key conservation issue. Extremely high encounters between pastoralists and large carnivores (such as snow leopards and Tibetan wolves) are being reported due to the expansion of livestock grazing in their habitats, the dwindling of natural wildlife prey in some situations and the alteration of climatic conditions (Jackson & Wangchuk, 2004; Mishra et al., 2004). Livestock insurance, predator-proof corrals, and ecotourism projects have helped to greatly decrease retaliatory killings of carnivores, but conflict continues to arise due to economic losses suffered at the hands of pastoral households. Maintaining local support for the conservation of biodiversity will thus be necessary to continue investment into participatory conservation programmes involving indigenous knowledge and scientific management of wildlife.

There are institutional obstacles as well that make the integration of TEK in biodiversity policy to be highly ineffective. Traditional ecological knowledge and practices (TEKP) have not received much consideration in the context of conservation planning in India, where the process has been largely scientific and administrative in nature (Berkes et al., 2000; IPBES, 2019). Past international pledges such as the Kunming-Montreal Global Biodiversity Framework, stress the need to include Indigenous people in decision making and governance for biodiversity, whereas there is not yet a consistent rate of implementation. In many instances, indigenous knowledge is considered to be 'background information' and not an as valuable source of ecological evidence. Thus, bolstering formal community based Landscape Management, customary institutions and participative governance systems will also be critical to achieve long-term conservation goals in Ladakh.

A major issue is also that of the inadequate formalisation of TEK. Many areas of indigenous ecological knowledge are not well documented and are passed on orally. As a result, potentially important traditional knowledge on weather prediction, wildlife ecology, managing medicinal plants, sustainable grazing and restoration of ecosystems are at risk of being lost forever when the custodians of this knowledge—the elders—start to disappear (Houde, 2007; Berkes, 2018). Documentation should be conducted using ethical, participatory research methods, that do not infringed on IP rights, ensure prior informed consent and provide equitable benefit sharing with indigenous communities (IPBES, 2019; CBD, 2022). The neglect of these moral issues could lead to loss of trust by the community and lead to less participation in conservation projects.

Biodiversity conservation strategies in the future in Ladakh should therefore be integrated socio-ecological solutions which integrate TEK as well as modern ecological science. Recent technological development in Geographic Information Systems (GIS), remote sensing, unmanned aerial vehicles (UAVs) and camera trapping as well as environmental DNA (eDNA) and artificial intelligence opens up exciting new possibilities for monitoring biodiversity, particularly in inaccessible mountain landscapes (Pettorelli et al., 2014; Allan et al., 2022). Incorporating indigenous ecological knowledge about species behaviour, the nature of their habitat, seasonal migration and climatic variability can make a significant contribution to the interpretation of the environmental information obtained from remote sensors, and can deliver fine scale ecological information that can only be provided by technological monitoring (Berkes, 2018; IPBES, 2019). This way of co-creating knowledge has been more and more acknowledged as one of the most effective modes of adaptive conservation in times of climate change.

Future studies should focus on interdisciplinary studies that connect ecology, ethnobiology, hydrology and climate studies, geography and social sciences. It is essential to judge the impact of climate change on alpine biodiversity, traditional grazing systems, distribution of medicinal plants and availability of water by long-term monitoring programmes. Additionally, more focus should be on quantifying the conservation outcome of TEK, such as how biodiversity metrics, recovery of vegetation, ecosystem services, and social-economic resilience can be quantified. Comparative studies of landscapes that are managed by communities and formally managed landscapes would also help to better understand the ecological effectiveness of indigenous conservation systems (Garnett et al., 2018; Díaz et al., 2019).

Policy strategies should involve enhanced community involvement, indigenous education programmes, ecotourism and the sustainability of tourism practices, strengthening customary governance institutions and integrating TEK in SEAPs. Capacity-building activities can be carried out with scientists, local communities and government agencies, and also conservation organizations to enable knowledge sharing and ensure that conservation projects are culturally relevant and scientifically sound. These methods of collaboration are in line with the principles of ecosystem-based management promoted by the IPBES, CBD and the United Nations Sustainable Development Goals (United Nations, 2015; CBD, 2022).

VI. CONCLUSION

One of the biggest underutilized resources available in the fields of conservation of Biodiversity in Ladakh is the Traditional Ecological Knowledge. Through centuries of engagements among indigenous communities and the precarious environment of the Trans-Himalaya, indigenous peoples have developed TEK that includes high level understanding of wildlife, vegetation, water resources, climate variability and sustainable resource management. Furthermore, evidence synthesised in this systematic review highlights how traditional practices such as community-managed irrigation systems, sustainable harvesting of medicinal plants, sacred landscape protection, a participatory stewardship approach to wildlife, and rotation farming have been integral to the sustainability of ecosystems in addition to sustaining livelihoods. These practices demonstrate the ability to balance biodiversity conservation and sustainable resource use in an adaptive community-based approach. This review also reflects that TEK is not a replacement for, but rather a supplement to formal science-based conservation. The two opposing viewpoints suggested by indigenous observations and modern ecological techniques, can provide information that is both long term and at spatial and temporal levels that are rarely recorded at landscape scale through conventional monitoring programmes.

The synergy of complementary knowledge systems holds great promise to better preserve and manage biodiversity and nature-based solutions for climate adaptation and the restoration of ecosystems and livelihoods in the Trans-Himalayan region.

However, Traditional Ecological Knowledge and its continuation is now being increasingly threatened by the effects of the climate change, meltwater from glaciers, socio-economic changes, growing tourism, construction of infrastructure and the fading of customs and ways of life among the indigenous people. Unless active conservation of biological and cultural diversity is taken up to preserve the knowledge of the ecology gained through years of Evolution, it may get lost forever. Thus, the policy measures like recognition of community as equal partners, strengthening of customary institutions, ethical documentation of TEK and facilitation of collaborative research combining ecological sciences and indigenous knowledge are necessary for effective biodiversity conservation efforts in the region.

Finally, TEK can no longer be considered as a cultural heritage resource; it is a scientifically relevant and useful conservation tool that can contribute to increased ecosystem resilience in an environment where change is increasingly a reality. The integration of indigenous knowledge in the fields of biodiversity sector policy, protected-area management, climate adaptation and sustainable development planning provides significant potential to secure conservation of the unique biological and cultural heritage of Ladakh, as well as to meet country and global conservation goals.

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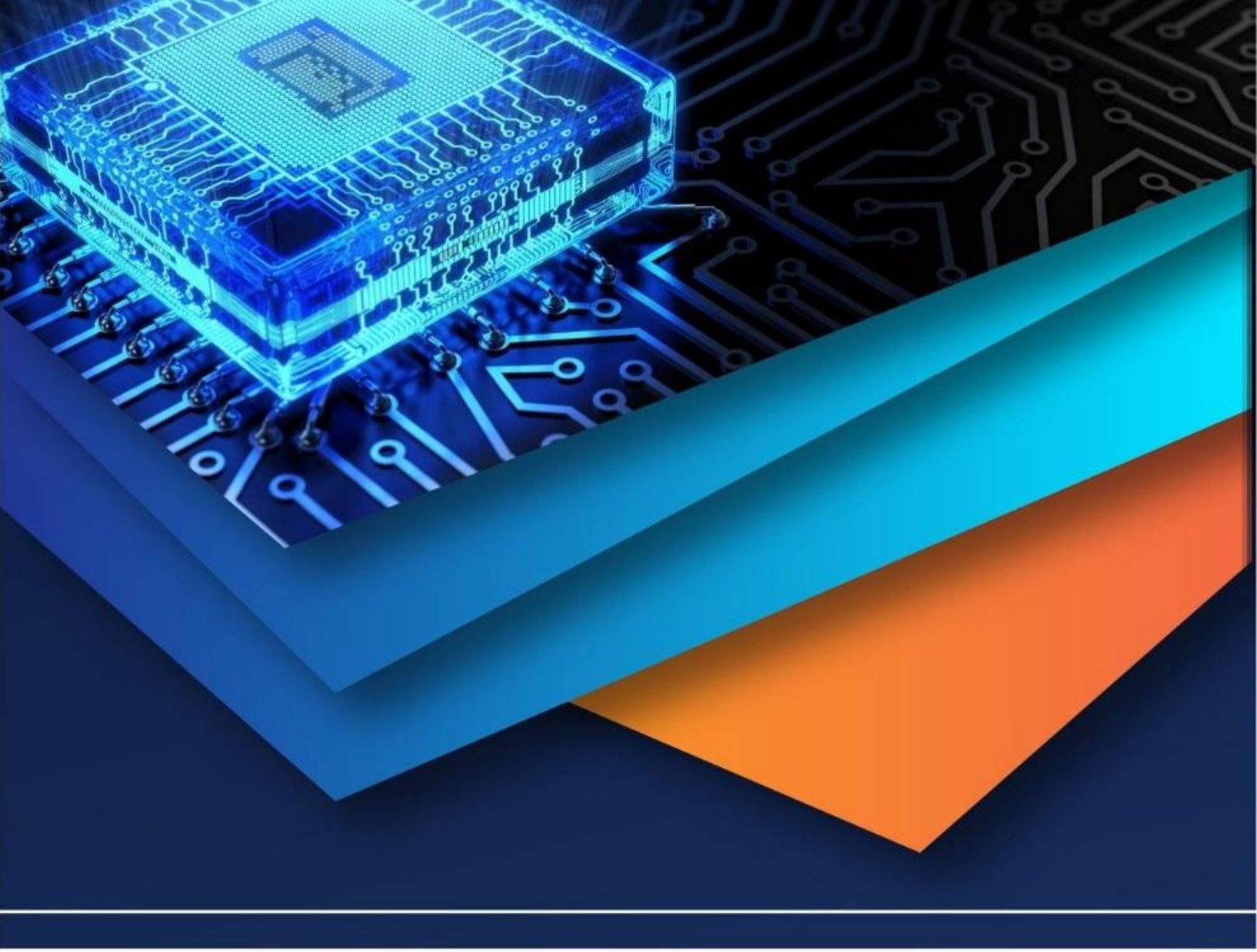

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