ISSN: 2347-4688, Vol. 13, No.(1) 2025, Pg. 62-72

Current Agriculture Research Journal

www.agriculturejournal.org

Oak Forests in Arunachal Pradesh Vs Western Himalayas of India: Ecological importance, Biodiversity, and Climate Change impacts

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Abstract

Oak forests in the Himalayan regions, particularly in Arunachal Pradesh and the Western Himalayas, represent ecologically significant landscapes that harbor a wealth of biodiversity and sustain a variety of ecosystem services essential for environmental stability and human well-being. These forests, dominated by key oak species such as *Quercus griffithii, Quercus serrata, Quercus lanata, and Quercus leucotrichophora,* play a crucial role in maintaining ecological balance by supporting diverse flora and fauna, stabilizing soil, regulating hydrological cycles, and acting as significant carbon sinks. This literature review synthesizes current knowledge on the ecological functions and significance of oak-dominated forest ecosystems in these Himalayan regions. It assesses their contributions to carbon sequestration, soil conservation, and water resource regulation, with a particular emphasis on their resilience and adaptive capacity under changing environmental conditions. The review also delves into the impacts of climate change, including alterations in temperature and precipitation patterns, which have led to observable shifts in species composition, forest structure, and overall forest health. Such changes pose significant risks to the long-term stability of these ecosystems and the services they provide. In light of these challenges, the review further evaluates the effectiveness of existing conservation and management strategies aimed at preserving oak forest ecosystems. This includes community-based forest management practices,

Article History
Received: 10 January 2025
Accepted: 22 April 2025

Keywords
Altitudinal Gradient;
Adaptive Management;
Carbon Dynamics;
Ecosystem Services;
Forest Resilience;
Forest Resilience;
Species Composition Shift.

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Doi: https://dx.doi.org/10.12944/CARJ.13.1.06

afforestation efforts, protected area networks, and climate adaptation policies. The synthesis underscores the urgent need for integrated, science-based approaches that incorporate traditional ecological knowledge, promote biodiversity conservation, and enhance the climate resilience of oak forests in the Himalayan landscape. The present review aims to compare the oak forests of Arunachal Pradesh and the Western Himalayas with respect to their ecological characteristics, biodiversity patterns, and vulnerability to climate change. The rationale for this comparison is to highlight region-specific differences and inform appropriate conservation strategies across the Eastern and Western Himalayan landscapes.

Introduction

Oak forests are essential components of the ecosystems in Arunachal Pradesh and Western Himalayas. While both forest types contribute significantly to biodiversity conservation and provide numerous ecosystem services, they face increasing challenges due to climate change. Oak forests, characterized by species like *Quercus griffithii* in Arunachal Pradesh, are highly sensitive to changing climatic conditions. As climate change alters temperature patterns and precipitation regimes, these forests undergo shifts in species distribution, structure, and function. This review examines the ecological and conservation significance of oak forests in Arunachal Pradesh and compares them with those in the Western Himalayas, particularly regarding their vulnerability to climate change.[1,2]

India is home to approximately 35 species of oaks (genus *Quercus*), with around 15 species occurring in the Eastern Himalayan region (including Arunachal Pradesh) and about 20 species in the Western Himalayas.[3] In Arunachal Pradesh, dominant species include *Q. griffithii, Q. lamellosa, Q. glauca,* and *Q. semicarpifolia,* which co-occur with genera such as Castanopsis and Lithocarpus, forming biodiverse forest assemblages that are part of the Indo-Burma biodiversity hotspot.[4,5] Some of these species, such as *Q. griffithii* and *Q. lamellosa*, are considered ecologically significant due to their restricted altitudinal ranges and their roles in supporting endemic fauna.[6]

In contrast, the Western Himalayas are dominated by *Q. leucotrichophora*, *Q. floribunda*, and *Q. semecarpifolia*, which serve as keystone species in temperate broadleaf forests and provide critical ecosystem services such as slope stabilization and microclimate regulation.[7] Biodiversity patterns also differ markedly: the Eastern Himalayas, particularly Arunachal Pradesh, exhibit higher overall species richness and endemism, driven by complex topography, humid climate, and biogeographic overlap with Southeast Asia.[8] Oak forests in this region support rich communities of birds, epiphytes, and arthropods. By comparison, Western Himalayan oak forests support region-specific species such as the Cheer pheasant (*Catreus wallichii*), the Himalayan black bear (*Ursus thibetanus*), and a diversity of bryophytes and lichens. These differences highlight the importance of regionally tailored conservation and research priorities.

Oak forests are ecologically critical across the Himalayan region, functioning as keystone ecosystems that support biodiversity, stabilize watersheds, and mitigate climate change.[9,10] Estimates suggest that Himalayan oak forests can store between 150 to 250 Mg C ha^{-1} in above- and below-ground biomass, making them significant carbon reservoirs in montane environments.[11] The lower C storage (3.99 Mg C ha^{-1} yr^{-1}) for mixed Oak forest. In terms of hydrological regulation, oak stands have been shown to enhance infiltration rates by 30–50% compared to adjacent coniferous forests and reduce surface runoff, thereby playing a pivotal role in maintaining year-round streamflow and groundwater recharge.[12,13] Their deep-rooted systems improve soil structure, reduce erosion by up to 60%, and contribute to nutrient cycling through leaf litter decomposition. Moreover, oak forests serve as critical habitat for over 200 species of birds and mammals, many of which are endemic or threatened.[14] These quantified ecological functions

underscore the importance of oak forests as multifunctional ecosystems, which are increasingly vulnerable to anthropogenic pressures and climate change.

To ensure a structured and meaningful comparison, this review examines oak forests in Arunachal Pradesh and the Western Himalayas through four key parameters: (i) species richness and composition, highlighting differences in dominant *Quercus* species and their associated biodiversity—such as the dominance of *Q. semecarpifolia*, *Q. leucotrichophora*, and *Q. floribunda* in the Western Himalayas, in contrast to *Q. griffithii*, Q. glauca, and *Q. lamellosa* in Arunachal Pradesh; (ii) ecological functions and ecosystem services, focusing on the role of oak forests in maintaining soil fertility, regulating hydrology, supporting pollinators, and serving as critical carbon sinks in montane environments; (iii) climatic conditions and climate change impacts, examining regional differences in temperature and precipitation regimes, the vulnerability of oak species to rising temperatures, phenological shifts, and the altitudinal migration of forest types; and (iv) anthropogenic pressures and conservation strategies, analyzing patterns of forest use, grazing intensity, fuelwood extraction, shifting cultivation, and the presence or absence of formal conservation frameworks. By employing these comparative parameters, the review aims to reveal how ecological dynamics and conservation priorities differ between the two regions, while also identifying cross-regional knowledge gaps. Such an approach is essential not only for understanding the broader ecological significance of oak forests across the Indian Himalayas but also for developing region-specific strategies to enhance forest resilience in the face of climate change and anthropogenic stress.

Methodology

This review synthesizes existing knowledge on the ecological importance, biodiversity, and climate change impacts on oak (*Quercus* spp.) forests in Arunachal Pradesh and the Western Himalayan region of India. The approach taken was qualitative and integrative, relying entirely on secondary data sourced from previously published literature and official databases.[15,16] No new fieldwork or remote sensing data collection was conducted. A systematic literature review was undertaken using online academic databases such as Web of Science, Scopus, Google Scholar, and JSTOR.[17-19] The search terms included combinations of keywords such as "oak forests," "*Quercus*," "*Eastern Himalaya," "Western Himalaya," "Arunachal Pradesh," "biodiversity," "climate change impacts," "carbon sequestration,"* and *"ecosystem services*." The review focused primarily on peer-reviewed journal articles published between 1990 and 2024, but also included relevant grey literature such as government reports, biodiversity assessments, and forest working plans.[19]

In total, over 100 documents were initially screened. After applying inclusion criteria based on relevance, data quality, and geographic focus, 52 key studies were selected for in-depth review and comparative analysis. These included taxonomic checklists, ecological assessments, species inventories, and studies documenting climate-related changes in forest structure, phenology, or species distributions. For biodiversity comparison, the number of *Quercus* species, associated flora and fauna, and endemic or threatened species were compiled and contrasted across the two regions. Climate change impacts were assessed based on observed trends (e.g., altitudinal species migration, phenological shifts) and modeled projections available from regional climate studies and forest ecology reports. Where possible, cross-regional comparisons were made using parameters such as species richness, endemism, forest composition, elevation range, and reported ecosystem services (e.g., carbon storage, water regulation). Findings are presented thematically to highlight similarities, differences, and region-specific conservation challenges.

Ecological Importance of Oak Forests in Arunachal Pradesh vs. Western Himalayas

Forest Composition and Structure

In Arunachal Pradesh, the oak forests are highly diverse, comprising of species such as *Quercus lanata*, *Quercus serrata*, and *Quercus griffithii* at elevations ranging from 1,500 to 3,500 meters.[20,21] *Quercus griffithii*, in particular, is found in subtropical regions of Arunachal Pradesh and contributes significantly to the richness of these ecosystems. This species exhibits adaptations that enable it to thrive in extreme conditions, making it a crucial part of the forest structure. However, climate change is

affecting these regions, as rising temperatures and shifting precipitation patterns could potentially alter the distribution of *Quercus griffithii* and other oak species, pushing them to higher altitudes or reducing their survival in current ranges.[22]

In the Western Himalayas, oak forests, primarily dominated by *Quercus* leucotrichophora, *Quercus* floribunda, and *Quercus* semecarpifolia, are found at slightly lower altitudes. These forests also face threats from climate-induced changes but experience different climatic pressures due to their location. Rising temperatures and changing precipitation patterns have begun pushing oak species upwards, leading to changes in vegetation composition.[23,24] In both regions, *Quercus* species are at risk of being outcompeted by more drought-tolerant or temperature-resistant species.

Ecological Roles

Oak forests in both regions provide essential ecological functions, including carbon sequestration, water retention, and soil stabilization (Table 1). In Arunachal, where these forests are located in ecologically sensitive areas, their role in watershed management is particularly critical.[25] Climate change is anticipated to exacerbate water availability issues, especially during dry seasons, as shifting rainfall patterns affect forest health and productivity. Similarly, in the Western Himalayas, oak forests play a vital role in regulating soil erosion and preventing landslides, particularly amid increasingly erratic monsoons driven by climate change.[26] However, these ecological services are under threat, as rising temperatures and changing rainfall patterns continue to stress the forest health.

Table 1: Ecological Importance of Oak Forests in Arunachal Pradesh vs. Western Himalayas

Ecological Parameter	Arunachal Pradesh (Eastern Himalayas)	Western Himalayas (e.g., Uttarakhand, Himachal Pradesh)
Dominant Oak species	*Quercus griffithii, Q. lanata, Q. serrata* High rainfall,	*Quercus leucotrichophora, Q. floribunda, Q. semecarpifolia*
Climate influence	humid subtropical to temperate climate	Drier temperate climate with distinct seasonality
Soil stabilization role	High slope gradients—oak root systems prevent erosion and landslides	Crucial for preventing soil loss in degraded mountainous terrains
Carbon sequestration potential	Dense canopy and fast litter turnover enhance carbon storage	Moderate to high carbon stock in older stands with slower decomposition
Water regulation function	Maintains perennial springs and moist microclimates	Regulates streamflow, recharges aquifers, supports water availability
Biodiversity support	High endemism; supports subtropical-temperate transitional species	Supports Himalayan fauna and montane flora with migratory species habitat
Cultural-ecological link	Sacred groves, local tribal practices of conservation (e.g., Monpa, Sherdukpen, Nyishi, Apatani)	Strong cultural ties with traditional agroforestry and village commons

Biodiversity in Oak Forests: Arunachal Pradesh vs. Western Himalayas

Floral Diversity

The oak forests of Arunachal Pradesh exhibit remarkable floral diversity, featuring species such as *Bauhinia variegata, Chrysopogon* spp., *Arundinella* spp., and *Quercus griffithii*[27] (Table 2 & Figure 1). However, this rich diversity is increasingly threatened by the dual pressures of climate change and habitat disturbance resulting from human activities. Increased temperatures are expected to shift plant communities toward higher elevations or regions

with favourable microclimates, leaving certain species at heightened risk of extinction.[28] Similarly, the oak forest of the Western Himalayas dominated by species such as *Aconitum and Berberis* spp., face vulnerabilities due to the shifting of climatic zones (Table 2 & Figure 1). Both regions are predicted to experience a decline in species richness at lower elevations, accompanied by shifts in dominant species that may alter the overall biodiversity landscape.

Table 2: Biodiversity in Oak Forests: Arunachal Pradesh vs. Western Himalayas

Biodiversity aspect	Arunachal Pradesh (Eastern Himalayas)	Western Himalayas
Floral diversity	High floristic richness with tropical, subtropical, and temperate species mix	Rich in temperate and sub-alpine flora, fewer tropical species
Associated tree species	*Castanopsis spp., Rhododendron spp., Schima wallichii*	*Rhododendron arboreum, Myrica esculenta, Cedrus deodara* (at higher altitudes)
Understory vegetation	Dense shrubs (*Ardisia, Maesa*, ferns), medicinal herbs	Grasses, mosses, lichens, and alpine herbs like *Valeriana, Picrorhiza*
Epiphytic diversity	High: orchids, ferns, mosses due to humid microclimate	Moderate: lichens and mosses dominate in cooler, drier environments
Faunal richness	Mammals: red panda, clouded leopard, flying squirrels; Birds: hornbills, barbets	Mammals: Himalayan black bear, leopard, barking deer; Birds: monal, cheer pheasant
Endemic and Rare Species	Several endemic orchids, amphibians, and butterflies	Endemism lower; important for endan -gered montane bird and mammal species
Ecosystem interactions	Complex due to varied altitudinal zones and tribal forest use	Well-studied predator-prey and pollinator dynamics in montane zones
Conservation status	High biodiversity but less documented; vulnerable to shifting cultivation	Moderately documented; threatened by land use change and overgrazing

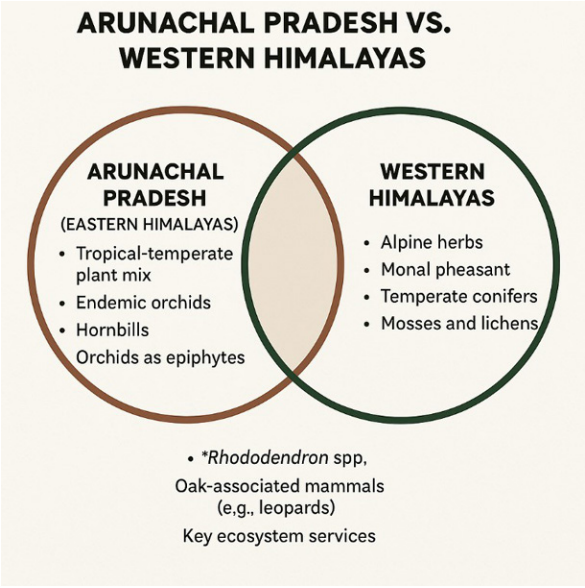

Fig. 1: Venn diagram illustrating the biodiversity of oak forests in Arunachal Pradesh (Eastern Himalayas) and the Western Himalayas.

Faunal Diversity

In both Arunachal Pradesh and the Western Himalayas' oak forests provide critical habitat for numerous wildlife species (Table 2 & Figure 1). In Arunachal, species such as the Red Pandas, Himalayan Black Bears, Sambars, and various pheasants depend on oak habitats.[29] Similarly, the oak forest of the Western Himalayas support species like the Kashmir Markhor and Barking Deer. However, climate change poses a significant threat to these faunal populations by reducing the availability of suitable habitats. As temperatures increase, many species will be compelled to migrate to higher elevations or may face population decline due to the loss of food sources and habitat fragmentation.[30]

Climate Change Impacts on Oak Forests

Temperature and Precipitation Shifts

In both Arunachal Pradesh and the Western Himalayas, climate models predict significant temperature increases, with projections suggesting a rise of 2-4°C by mid-century.[31-36] This increase in temperature will directly affect the oak forests of both regions, which depend on cooler, temperate conditions at specific altitudes (Figure 2). The combing effects of rising temperature and altered rainfall patterns are expected to trigger a range shift, pushing certain oak species to higher altitudes, which could further fragment the forests. Species that ae unable to migrate upwards may face the risk of extinction.[37]

In Arunachal Pradesh, shifting rainfall patterns and changes in monsoon intensity pose significant risks, particularly affecting the delicate balance of soil moisture levels, which are crucial for the forest ecosystem's stability.[38] Increased rainfall during certain periods can lead to waterlogging, which affects root systems and promotes fungal diseases, both of which are expected to increase with rising temperatures[39] (Figure 2). The Western Himalayas will experience similar risks, however, warmer temperatures may create drought-like conditions during dry seasons, intensifying stress on oak species.

Forest Health and Vulnerability to Pests and Diseases

Warmer and more erratic climates create favourable condition for the spread of invasive species and pathogens (Figure 2). Oak forests in both regions are already showing signs of increased pest pressure. For instance, the oak moth (*Operophtera brumata*), which affects *Quercus* species, could expand its range with rising temperatures, further impacting the health of the forests' in both the Eastern and Western Himalayas. The spread of fungal infections such as Phytophthora spp. also poses a significant threat. This increasing vulnerability can lead to decreased oak regeneration rates, with long-term implications for forest stability.[40]

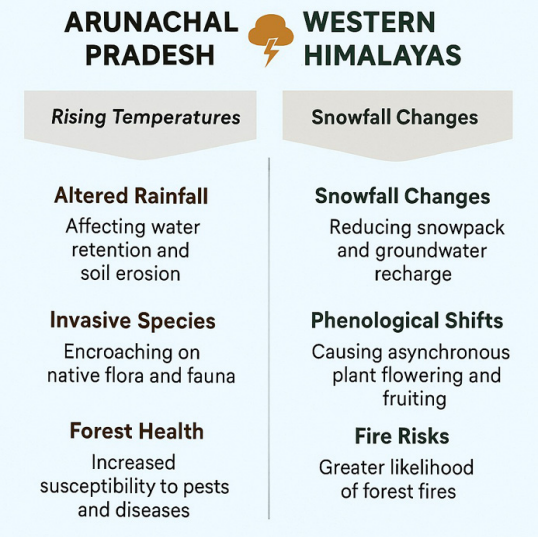

Fig. 2: Comparative impacts of climate change on oak forests in Arunachal Pradesh and the Western Himalayas.

Conservation Strategies in the Face of Climate Change

Integrated Conservation Approaches

Arunachal Pradesh utilizes community-based conservation models, including Joint Forest Management (JFM) and Village Forest Development Committees (VFDCs). These models encourage local participation in forest management and enhance sustainability against climate-related disruptions (Figure 3). In these models, community engagement plays a vital role in addressing to climate change impacts, such as changing water cycles and forest health.[41]

In the Western Himalayas, large-scale protected areas and wildlife corridors, like the Great Himalayan National Park help reduce the impacts of climate change by preserving large, contiguous tracts of

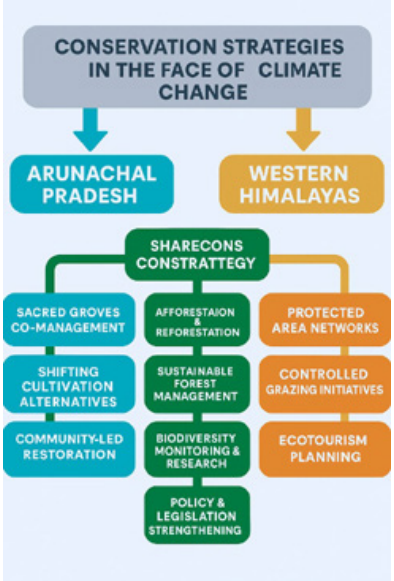

Fig. 3: Conservation strategies for oak forests in Arunachal Pradesh and the Western Himalayas in response to climate change.

forest habitat that can support shifting species ranges (Figure 3). However, habitat connectivity remains a challenge due to increasing human settlements and agricultural activities.[42] Both regions require more adaptive management strategies to address climate change related disturbances by emphasizing climate adaptation through forest restoration, habitat protection, and collaborative approaches (Figure 3).

Policy and Research Needs

There is an urgent need in both regions to implement climate adaptation strategies for the future management of oak forests (Figure 3). In order to implement effective policies, it is significant to improve monitoring of oak health, track changes in species distribution, and assess the vulnerability of forests to climate change (Table 3). Local climate action plans must be developed that specifically target the integration of climate change considerations into forest policy, with focus on ecosystem-based adaptation measures[42] (Figure 4).

Table 3: Policy-driven interventions for Oak Forest conservation: A strategic framework

Policy	Strategic action	Arunachal Pradesh focus	Western Himalayas focus
Forest governance & regulation	Strengthen enforcement of forest protection laws	Integrate community forest rights under FRA, 2006; Align with Pakke 2047 Declaration for climate-resilient forest management	Enhance patrolling and monitoring via forest departments
Climate-responsive zoning	Define eco-sensitive and climate-resilient zones	Delineate zones integrating indigenous land-use systems; Integrate with Pakke Declaration zoning guidelines	Expand buffer zones around protected areas
Afforestation & restoration policies	Promote native species reforestation	Focus on *Quercus griffithii, Q. serrata* regeneration under climate-smart reforestation; guided by Pakke Declaration goals	Encourage natural oak regeneration over pine monoculture
Community participation & incentives	Policy frameworks to support community-led conservation	Institutionalize Van Panchayats & JointForest Management (JFM) with tribal councils; promote community forest initiatives under Pakke 2047 vision	Strengthen JFM through Panchayati Raj institutions

Data, monitoring & early warning systems	Create open-access forest vulnerability maps and data tools	Encourage community-driven biodiversity monitoring under Pakke- inked citizen science programs	Implement remote-sensing and AI tools for phenological shifts
Policy-education integration	Climate curriculum in forestry training institutes	Incorporate TEK (Traditional Ecological Knowledge) in policy training; Pakke as a model site for environmental education	Link research outputs to field-level policy implementation
Incentives & green finance	Payments for Ecosystem Services (PES) and REDD+ models	Pilot PES in community forests & watersheds around Pakke Landscape	Integrate oak conservation into CAMPA funds & CSR projects

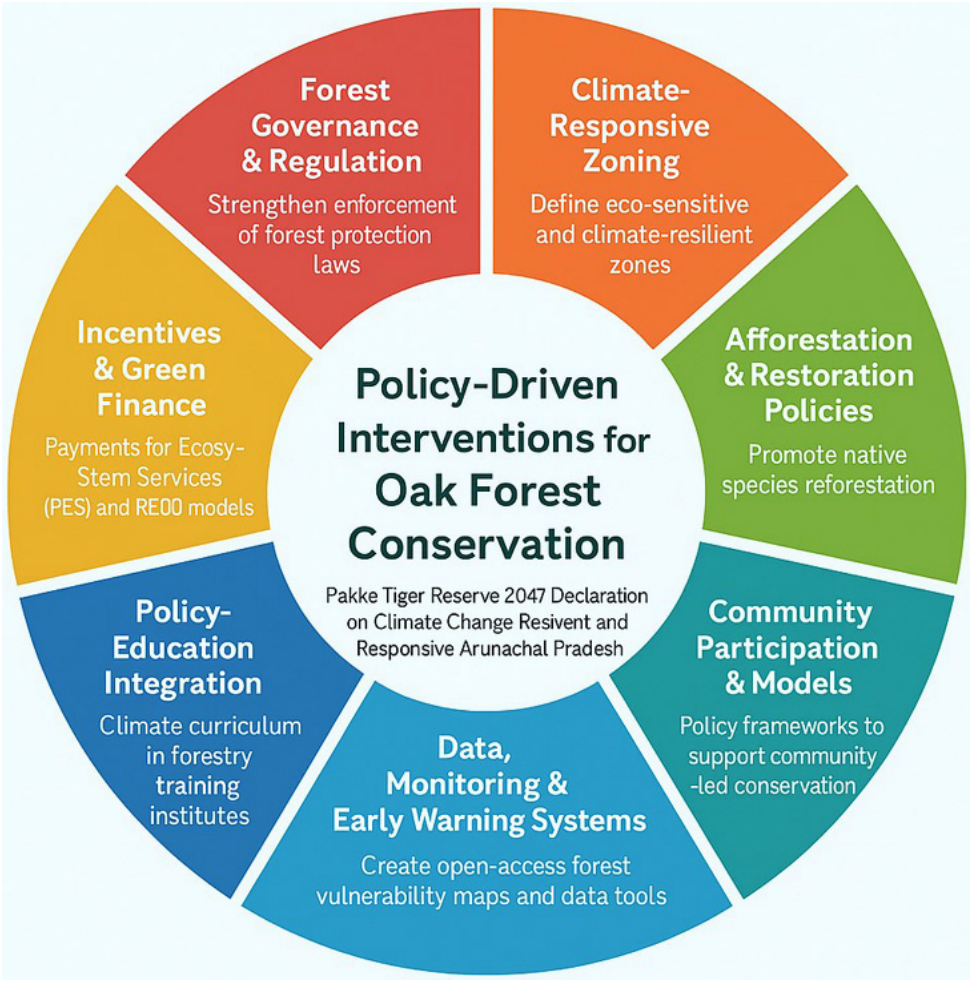

Fig. 4: Seven strategic policy pillars guiding adaptive Oak Forest management and conservation efforts in Arunachal Pradesh.

Conclusion

Oak forests play a crucial role in maintaining biodiversity and delivering ecosystem services in both Arunachal Pradesh and the Western Himalayas. However, with the changes in growing climatic conditions, it is necessary for conservation strategies to adapt in managing these forests. The responses of both regions are distinguishable from each other, but the challenges they face are quite similar, including rising temperatures, changes in rainfall patterns, and altered forest health. A combination of community-based management, scientific research, and robust climate change adaptation plans is essential to ensure the long-term conservation and health of these oak forests.

Acknowledgement

The authors acknowledge the contributions of authors and the information shared through various publications for preparing the article. Authors also thenkful to the two anonyous reviewers for their insightful comments and suggestions that greatly imporved the manuscript.

Funding Sources

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

Conflict of Interests

The authors do not have any conflict of interest.

Ethics statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Author contributions

- **Y. Johnson Singh:** Conceptualization, Methodology, Data Collection, Writing – Original Draft.
- **L.S. Lodhiyal:** Visualization, Supervision, Reviewing.
- **K.S. Kanwal:** Supervision, Reviewing.
- **D. Balasubramanian:** Data Collection, Analysis, Writing – Review & Editing.
- **Avinash Sharma:** Data Collection, Analysis, Writing – Review & Editing.

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