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Growth Rings and Climate Patterns: Evaluating the Dendrochronological Review of Central and Peninsular India

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Abstract: Dendrochronology has emerged as a vital tool for reconstructing past climates and understanding tree-climate interactions, yet its application in Peninsular India remains limited and uneven. This review synthesizes published studies from the region, covering 20 tree species across 14 families, and reveals a striking dominance of *Tectona grandis*, which accounts for more than 96% of research efforts. Teak has proven to be a robust proxy for monsoon rainfall and drought events, owing to its distinct growth periodicity and strong climatic sensitivity, but the overwhelming reliance on a single species restricts broader ecological inference. Other promising taxa such as *Toona ciliata*, *Magnolia champaca*, and *Dalbergia latifolia* remain underexplored despite demonstrated dendrochronological potential. Spatially, research is disproportionately concentrated in moist deciduous and evergreen forests, while dry deciduous ecosystems, which may capture stronger precipitation seasonality signals, are underrepresented. Methodologically, most studies emphasize dendroclimatology and ring dating, with limited integration of wood anatomy, density, and isotopic approaches that could deepen climate signal extraction. Collectively, these gaps highlight the urgent need for expanding species coverage, diversifying ecological settings, and adopting interdisciplinary methodologies to strengthen tree-ring science in India. Advancing such efforts will not only refine monsoon reconstructions but also enhance regional climate resilience strategies, water management planning, and long-term ecosystem monitoring under global climate change.

Keywords: Dendrochronology, Climate, Broadleaf trees, Precipitaion, Central and Penisular India

Dendrochronology is the branch of science that studies tree rings and gives detailed information about tree age, growth pattern, past environmental conditions, forest fire, soil distribution, insect pest outbreaks, and wood density of tree species in past ecological conditions (Schweingruber 2012). Tree ring data on environmental conditions through their growth pattern and later used as a collection of historical data in past environments. Tree ring width gives information about growth patterns and long-term environmental deal with past variation time scales yearly (George 2014). This information is critical to understand the climate change in particular vegetation areas (Babst et al., 2018, Upadhyay and Tripathi, 2019) to understand the relationship between their growth pattern and climate condition (Gaire et al., 2020). This scientific discipline leverages the annual growth increments, or tree rings, to reconstruct past environmental conditions, with dendroclimatology specifically utilizing ring-width variations to infer historical climate variability. Beyond radial growth, dendroanatomy, which involves the analysis of xylem-cell features, offers a more nuanced understanding of the complex xylogenetic processes and their responses to environmental fluctuations (Pandey 2021). The intricate relationship between tree-ring characteristics and environmental parameters, including climatic variables, forms the foundation for dendrochronological interpretations, elucidating the historical context of ecological dynamics (Gartner et al., 2002). The formation of these annual rings, encompassing both earlywood and latewood, is intrinsically linked to seasonal growth patterns and can be meticulously cross dated to specific years, thereby creating robust chronologies for various interdisciplinary applications. This precise dating technique allows for an annual, and seasonal, resolution of past events, making it an invaluable tool for archaeological and environmental reconstructions (Towner 2015). Tree-ring records provide an effective proxy method for examining paleoclimatic conditions, as the annual growth ring width reflects surrounding climatic variability, establishing a temporal record of past trends and specific events (Carroll and Jules 2005).

A greater number of dendrochronological studies on the related history of particular forest areas, as well as climatic conditions past and present, have been carried out in various geographical regions of India (Bhattacharyya and Shah 2009, Shah et al., 2014, Pandey et al., 2016). Tree ring research in India mostly focuses on forestry aspects like wood quality, wood productivity, and growth patterns. Tree ring is mainly used for the reconstruction of climate and environmental issues.

Historical development of dendrochronology in India: Dendrochronological research in India began in the mid-20th century with preliminary studies focusing on tree-ring analysis in temperate forests of the Himalayas. Initial works by (Pant and Borgaonkar 1983) laid the foundation for tree-ring studies in India, emphasizing their potential for climate reconstruction. Further advancements were made by (Yadav et al., 2006), who established long-term chronologies using conifer species such as *Cedrus deodara* and *Pinus roxburghii*. These early investigations primarily focused on the Himalayan region due to the presence of long-lived conifer species, which are particularly well-suited for dendrochronological studies. However, the application of these methodologies to the tropical and subtropical forests of Central and South India presented unique challenges, primarily due to less pronounced seasonality and the presence of complex growth patterns in many deciduous and evergreen species (Muhammad et al., 2021).

The establishment of tree-ring chronologies in India has facilitated reconstructions of past climatic patterns, particularly variations in temperature and precipitation. Studies by Bhattacharyya et al. (2007) and Shah et al. (2013) have demonstrated the impact of monsoonal variability on tree growth patterns, providing valuable insights into historical drought occurrences and temperature fluctuations.

Applications of dendrochronology in India: The primary applications of dendrochronology in India can be categorized into three main areas: climatic reconstructions, hydrological studies, and archaeological research. Dendrochronological records have been instrumental in reconstructing past climatic trends. Studies by Borgaonkar et al. (2010) have linked tree-ring width variations to monsoon strength, highlighting prolonged drought periods over the past few centuries. Such reconstructions are crucial for predicting future climate scenarios and understanding long-term climate variability.

Tree-ring analysis has also been employed to study historical water availability and river discharge patterns. Studies in the Western Himalayas and Central India have revealed correlations between tree growth and river flow, aiding in water resource management and flood prediction (Shah et al., 2014).

Dendrochronology has been applied in dating ancient wooden structures and artifacts in India. Studies by Bhattacharyya et al. (2009) have successfully dated timber used in historic temples and traditional buildings, providing chronological benchmarks for architectural history. Dendrochronology has proven to be a versatile tool in India, extending its applications beyond climatic reconstructions to include ecological and hydrological studies (Khan et al., 2013).

Challenges and future prospects: Despite significant advancements, dendrochronology in India faces several challenges. The tropical climate of India, characterized by less distinct seasonal variations in tree rings, poses difficulties in accurate dating (Quesada-Roman et al., 2022). Furthermore, the limited availability of suitable tree species for dendrochronological analysis restricts the scope of research. Addressing these limitations necessitates exploring alternative proxies, such as intra-annual density fluctuations, and expanding research to understudied regions and species (Tayyab et al., 2023) (Muhammad et al., 2021).

Future research should focus on expanding tree-ring networks across diverse ecological regions. Dendrochronology and Radiocarbon dating are the investigation of sedimentary records for studies on ecology or climate (Quarta et al., 2021). Collaborative efforts between Indian and international research institutions can enhance methodological approaches and improve the precision of climate reconstructions. India's climate-specific due to being impacted by seasonal wind patterns such as the Winter Monsoon and Summer Monsoon, along with related rainfall and temperature changes. The Indian economy depends on Variations of the monsoon, but the documents of monsoon data are not satisfactory for creating accurate climate projection systems. To more effectively analyze the long-term turn data of tree rings is a very important role in climate reconstructions and providing detailed information creates data for many centuries of (Bhattacharyya and Shah 2009). Three research institutions, viz., the Birbal Sahni Instute of Palaeoscience. IISC, IITM are currently the main centers in India for pursuing various aspects of tree-ring studies(Bhattacharyya and Shah 2009).

MATERIAL AND METHODS

Study area: India is a vast subcontinent with diverse geographical and cultural regions. Central India and Peninsular India possess unique physical, climatic, and socio-cultural characteristics. Central India serves as a transitional zone between the northern and southern parts of the country, while Peninsular India forms the southernmost geographical unit, surrounded by water on three sides (Singh 2020). Central India primarily includes the states of Madhya Pradesh and Chhattisgarh**,** along with portions of Uttar Pradesh and Maharashtra. Tropical dry and moist deciduous forests dominate it (Singh et al., 2024). Central India is home to tree species such as *Tectona grandis* (teak), *Shorea robusta* (sal), and *Dendrocalamus strictus* (bamboo) (Chandrakar et al., 2021, Dixit 2022), which show potential for dendrochronological studies.

Central India, encompassing states such as Madhya Pradesh, Chhattisgarh, and parts of Maharashtra, experiences a tropical climate with three seasons: summer, monsoon, and winter (Singh et al., 2025). The summer season (March to June) is characterized by high temperatures, often exceeding 40°C, particularly in May (IMD 2021). Peninsular India consists of Maharashtra, Karnataka, Andhra Pradesh, Telangana, Tamil Nadu, Kerala, and Goa. The Arabian Sea bounds it to the west, the Bay of Bengal to the east, and the Indian Ocean to the south (Majumdar, 2022). It lies between 18° N and 26° N latitude and 75° E and 85° E longitude. This region encompasses diverse geographical features, including the Maikal and Satpura Ranges, Vindhya Hills, and river valleys of the Narmada, Mahanadi, and Godavari. The forests of Peninsular India fall under Moist and Dry Deciduous, Evergreen, and Mangrove Forests (ISFR 2021, Agrawal et al., 2010).

The forest types are Moist Deciduous and Tropical Dry Deciduous, with some patches of Thorn and Mixed Forests (Champion and Seth 1968). Peninsular India has a tropical monsoon climate with moderate seasonal variations. The region is influenced by both the southwest and northeast monsoons, with the latter providing significant rainfall to the eastern coast, particularly in Tamil Nadu (Sreekala et al., 2022). Unlike Central India, Peninsular India experiences relatively stable temperatures throughout the year, ranging from 20°C to 35°C, with coastal regions maintaining higher humidity levels (IMD 2021). The Western Ghats play a crucial role in orographic rainfall, making Kerala and coastal Karnataka among the wettest regions in India, with annual rainfall exceeding 2500 mm (Chandrashekar et al., 2018).

Central India and Peninsular India exhibit distinct climatic patterns due to their geographical locations, topographical features, and proximity to water bodies. This paper examines the climatic conditions of these two regions, highlighting seasonal variations, temperature ranges, and monsoonal influences. A major distinction between the two regions is the absence of a severe winter in Peninsular India, attributed to its proximity to the equator and moderating influence of the surrounding seas. In contrast, Central India experiences greater temperature variability due to its continental location. The climatic differences between these regions significantly impact agriculture, water availability, and overall ecosystem dynamics.

The methodology for reviewing the dendrochronological potential of Central India and peninsular India was designed to systematically collect and analyze data from existing studies. This review not only focuses on tree-ring research within Central India and peninsular India but also compares findings from other Indian regions where similar species have been studied, providing a broader perspective on dendrochronology's applicability.

Data collection: A comprehensive literature search was conducted using academic databases such as Google Scholar, Web of Science, Scopus, Science Direct, Wiley Online Library, ResearchGate, and Springer Link. Additional sources, including books, government reports, theses, and dissertations, were reviewed to ensure an exhaustive dataset (Acosta-Hernandez et al, 2017).

Search terms included combinations of keywords such as "Dendrochronology," "tree-ring analysis," "Central India," “Peninsular India”, "Western Ghats," "tropical deciduous forests," "climate reconstruction," and "tree growth-climate relationship." The review covered literature published between 1992 and 2024 to incorporate recent advancements in dendrochronological research.

Inclusion and exclusion criteria: Studies were included if they: Focused on dendrochronological research in Central India or peninsular India regions with similar tree species (e.g., Western Ghats, Eastern Ghats). Provided detailed methodologies for tree-ring sampling and analysis. Examined relationships between tree-ring growth and climatic parameters such as rainfall, temperature, or drought indices. Studies were excluded if they did not involve dendrochronology, lacked clear methodological details, or focused solely on other ecological aspects, such as biodiversity. Duplicate studies and those with overlapping datasets were also excluded.

Data extraction and verification: A standardized Excel format was used to systematically extract data. Key data points included the tree species studied, sampling locations, core extraction methods, tree-ring measurement techniques, climatic variables analyzed, and primary findings. Comparative fields captured similarities and differences in tree growth-climate relationships between Central India to peninsular India

Scientific names and tree species classifications were verified using authoritative botanical databases such as Plants of the World Online (https://powo.science.kew.org/). This step ensured consistency in species identification, especially for species studied across different regions of India.

Data analysis and reporting: Descriptive statistics were calculated to summarize the spatial and temporal coverage of studies, species diversity, and the range of climatic variables examined. Comparative analyses were conducted to evaluate how similar tree species in different regions (e.g., *Tectona grandis* in Central India versus the *Western Ghats*) respond to climatic factors.

The findings were synthesized into an inventory highlighting the dendrochronological Studies of Central India and peninsular India its. This inventory included details on tree species, study locations, methodologies, and key results. The comparative analysis provided insights into regional differences and commonalities in tree-ring growth responses.

RESULTS AND DISCUSSION

State-wise analysis of dendrochronological research in the Indian peninsular region reveals distinct patterns in both publication frequency and species focus (Fig. 1). Kerala accounts for the highest number of publications (13 articles), though only two species have been studied, reflecting repeated work on a narrow taxonomic base. Karnataka, with seven published articles, demonstrates the widest species coverage (17 species), indicating greater exploration of taxonomic diversity (Fig. 1). Maharashtra has an equal number of publications (7) but concentrated exclusively on a single species, primarily teak. Andhra Pradesh (5 articles), Tamil Nadu (1 article), and Madhya Pradesh (1 article) have relatively fewer studies, each limited to one species (Fig. 1). This distribution suggests a geographic and taxonomic imbalance, with research clustered in a few states and often restricted to teak or other widely distributed hardwoods, underscoring the need to diversify both regional and species coverage in future dendrochronological investigations.

Dendrochronological research has been conducted across three distinct vegetation types (Fig. 2). Notably, 48.28% of these studies have focused on Tropical Moist Deciduous, making them the predominant subject of investigation. This is followed by Tropical Evergreen Forests, which account for 34.48% of the studies (Fig. 2). Conversely, Tropical Dry Deciduous Forests have received considerably less attention, comprising only 31.03% of the total research conducted in the Indian peninsular region (Fig. 2).

A total of 20 tree species, belonging to 14 different families, were used in dendrochronological studies conducted across the Indian Peninsula (Fig. 3). Among these, the family Fabaceae had the highest species richness, contributing 3 species (14.3%), suggesting its notable presence in dendrochronological research (Fig. 3). Families such as Lamiaceae, Magnoliaceae, Meliaceae, and Myristicaceae each contributed 2 species (9.5%), reflecting moderate species-level representation. The remaining nine families, Anacardiaceae, Bignoniaceae, Combretaceae, Euphorbiaceae, Lythraceae, Malvaceae, Moraceae, Sapindaceae, and Ulmaceae, were each represented by a single species (4.8%) (Fig. 3). However, despite this taxonomic diversity, the dominance of Lamiaceae was overwhelming when analyzed in terms of article representation (Fig. 4).

Lamiaceae alone accounted for 96.55% of the total studies (Fig. 4), reflecting a concentrated research focus on this family, largely attributable to the frequent selection of *Tectona grandis*, which was utilized in 96.55% of the reviewed studies (Fig. 5). In contrast, other families such as Meliaceae (10.34%) and Magnoliaceae (6.90%) were only marginally represented (Fig. 5). All other families, including Fabaceae, despite higher species richness, appeared in only 3.45% of the articles each (Fig. 5). *Toona ciliata* and *Magnolia champaca* were the second most frequently studied species, each appearing in 6.90% of the articles (Fig. 5). All other species, including *Terminalia alata*, *Dalbergia latifolia*, *Gmelina arborea*, and *Mangifera indica*, were each reported in only 3.45% of the studies (Fig. 5). These results

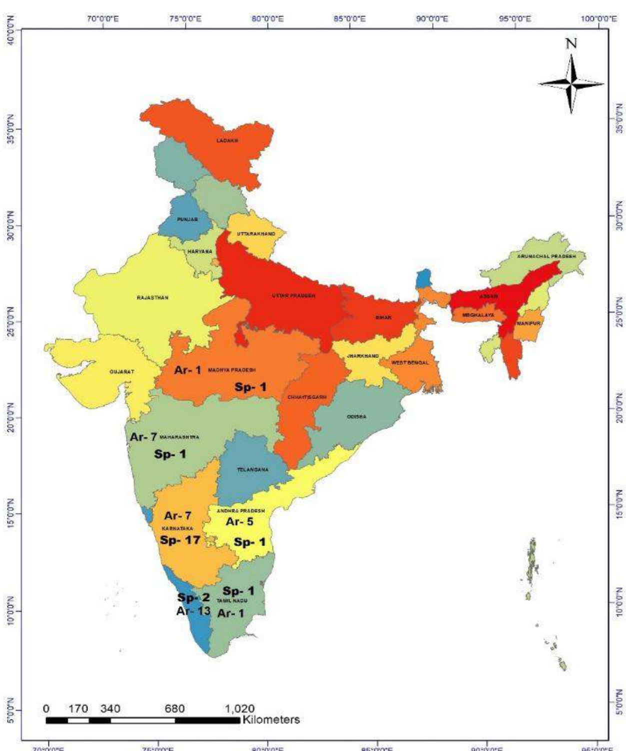

Fig. 1. State-wise analysis of Dendrochronological studies performed in the Central and peninsular region of India. AR -articles, SP- species

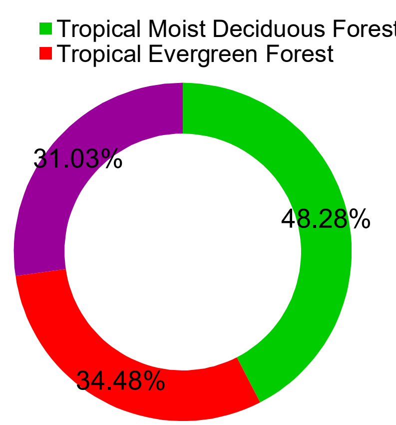

Fig. 2. Percentages of studies classified according to the type of forest ecosystem following Champion and Seth's forest classification system

reveal a clear research preference for specific species, especially teak, based on dendrochronological suitability, while also highlighting the underutilization of several other ecologically important taxa in growth ring analysis.

The reviewed studies were categorized based on their primary area of application within dendrochronological research across the Indian peninsular region (Fig. 6). A majority of the studies (65.52%) focused on dendroclimatology, reflecting a strong emphasis on climate-growth relationships in tree-ring research (Fig. 6). Dendrochronology as a core dating method accounted for 27.59% of the studies, while more specialized applications such as dendroanatomy and studies involving growth ring and specific gravity were each represented by only 3.45% of the literature (Fig. 6). This distribution highlights a notable research inclination toward climate-focused dendrochronological analysis, with limited exploration into wood anatomical and density-related investigations (Fig. 6).

The temporal distribution of dendrochronological studies in the Indian Peninsula (Fig. 7) reveals a sporadic publication

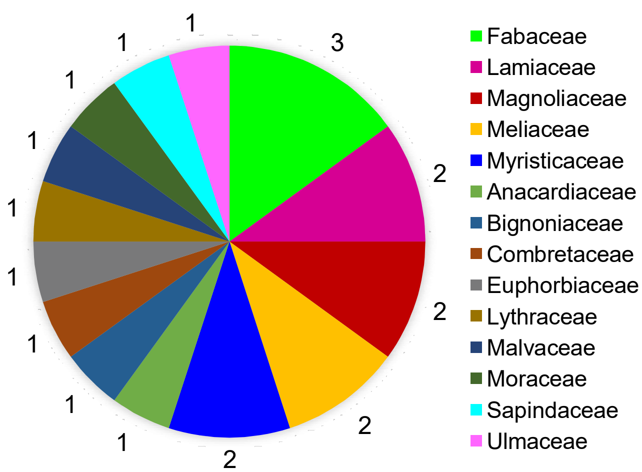

Fig. 3. Family-wise distribution of tree species selected for dendrochronological study in the Indian peninsular region

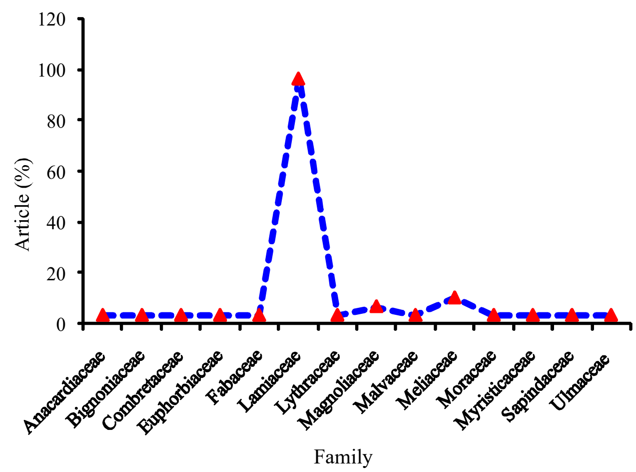

Fig. 4. Dendrochronological studies performed in the Indian peninsular region, categorized by taxonomic family

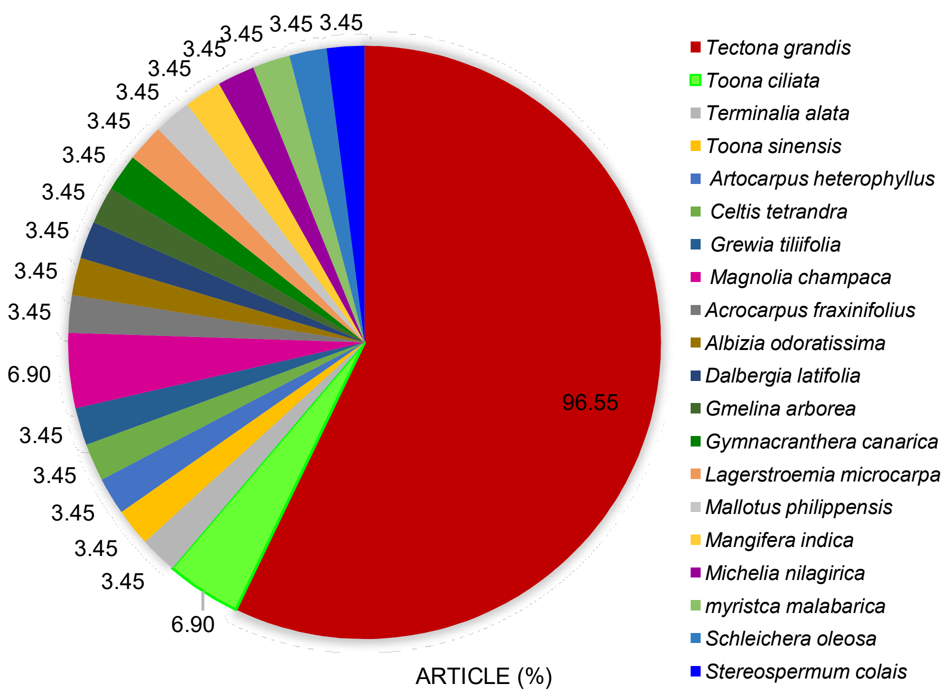

Fig. 5. Dendrochronological studies performed in the Indian peninsular region, categorized by tree species

trend from 1992 to 2023, characterized by notable fluctuations in research output. Early contributions were sparse, with only one article each in 1992, 1996, 1997, 2000, and 2005. A gradual increase is observed from 2007 onwards, with two studies published each in 2007, 2008, and 2010 (Fig. 7). The peak research activity occurred in 2011, with four publications, followed by a slight decline in subsequent years. Secondary peaks were noted in 2012 and 2016 (three articles each), indicating intermittent surges in interest. The period after 2018 has reflected a moderate and consistent output, with one to two publications per year (Fig. 7). Overall, the data suggest that dendrochronological research in the Indian peninsula has expanded over the past two decades, albeit with irregular intervals of heightened activity.

This review reveals that dendrochronological research in Peninsular India remains heavily skewed in terms of species selection, forest type coverage, and research applications.

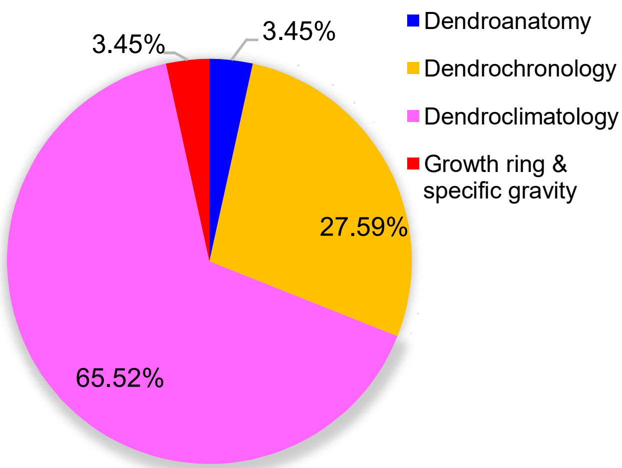

Fig. 6. Dendrochronological studies conducted in the Indian peninsular region, categorized by area of application

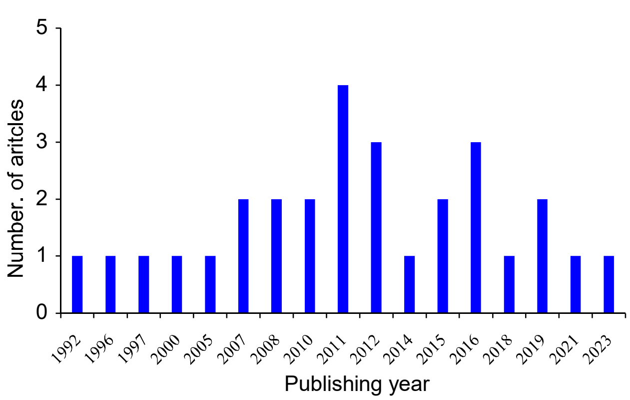

Fig. 7. Dendrochronological studies published in Indian peninsula, grouped by year of publication

Despite sampling 20 species across 14 families, the vast majority of studies (>96%) rely on *Tectona grandis*. Analyses conducted in Central India have demonstrated strong positive correlations between teak tree-ring widths and both monsoonal rainfall and soil moisture indices, establishing teak as a highly reliable proxy for past precipitation (Ram et al., 2008). Similarly, investigations in the Western Ghats confirmed ability of teak to reliably reflect drought years based on ring-width chronologies (Deepak et al., 2017). Further, Sinha (2012) provided empirical evidence linking teak ring-width variations to local rainfall and temperature, reinforcing teak's strong monsoon sensitivity. This focus is understandable given teak's pronounced annual layering, cambial dormancy from October–December, reactivation by pre-monsoon rains, and maximal growth during June–July (Priya and Bhat, 1999). In addition, a study by Upadhyay et al. (2019) evaluated the dendrochronological potential of teak and developed short tree-ring chronologies, which further substantiates its reliability as a climate-sensitive species for dendroclimatic reconstructions.

In contrast, *Toona ciliata* and *Magnolia champaca* appear in only 7.14% of studies, and many species, such as *Terminalia alata*, *Dalbergia latifolia*, *Mangifera indica*, and *Gmelina arborea* are each featured in just 3.57% of articles. While *T. ciliata* has shown dendrochronological potential, local chronologies in northeast India spanning several decades have been constructed and used for climate-growth interpretation (Shah and Mehrotra 2017), its adoption remains limited. This narrow taxonomic focus may limit the ecological and physiological modulation of growth responses captured in current chronologies.

The geographic distribution of studies reveals a clear imbalance, with the majority of research concentrated in Tropical Moist Deciduous (41%) and Evergreen Forests (31%), while Dry Deciduous Forests are noticeably underrepresented at 28%. This uneven pattern may reflect ease of access to wetter forests or the perception that tree rings in moist environments exhibit clearer annual boundaries. However, such spatial skew carries the risk of omitting critical climate signals inherent to drier biomes, forests characterized by stronger precipitation seasonality, which can result in distinct cambial dormancy and annual ring formation (Rozendaal and Zuidema 2011). Broader reviews of tropical dendrochronology emphasize that while many tropical tree species form annual rings, the strength and clarity of these rings are heavily influenced by local climate patterns, particularly the presence and duration of a dry season (Quesada-Roman et al., 2022). Consequently, focusing predominantly on moist and evergreen zones may limit the capture of growth responses tied to moisture-stress dynamics and seasonal drought common in dry deciduous regions.

The majority (64.29%) of studies focus on dendroclimatology, with ring dating alone accounting for 28.57% and anatomical or specific gravity investigations each at 3.57%. This reflects Indian dendrochronology's historical prioritization of monsoon reconstruction over exploring internal wood structure. Yet recent evidence from Indian teak trees shows wood density and latewood content vary significantly with age and climate, particularly in mature wood, indicating potential for richer signal interpretation through density and anatomical approaches (Sinha et al., 2014, Bhat 1995).

CONCLUSION

This review underscores that dendrochronological research in Peninsular India, though promising, remains narrowly focused in terms of species, forest types, and methodological scope. The dominance of teak-centered studies has advanced monsoon reconstructions but limits understanding of diverse climate-growth relationships across other ecologically and economically important tree species. Similarly, the underrepresentation of dry deciduous forests restricts insights into growth responses linked to seasonal water stress, which are highly relevant in the context of intensifying climate variability. Moving forward, expanding research beyond teak to include multipurpose and endemic taxa, broadening geographic coverage to neglected forest types, and integrating anatomical, density, and isotopic analyses are crucial steps to strengthen the reliability and applicability of dendrochronological findings. Such advancements would position Peninsular India as a key contributor to global tropical dendrochronology, enhance our ability to interpret past climate variability with greater confidence, and support adaptive strategies for forest management, water security, and biodiversity conservation. The future of dendrochronology in India thus lies in fostering interdisciplinary approaches and building robust, multi-species, multi-ecosystem chronologies that truly capture the climatic and ecological complexity of the region.

AUTHOR'S CONTRIBUTIONS

V. B.: Conceptualized the review framework and contributed to data collection. S.S.: led the literature compilation, data analysis, and synthesis of results, drafted and revised the manuscript, and provided overall supervision and guidance throughout the study. A.K.S.: contributed to the study design, critically reviewed the manuscript for scientific accuracy, and provided expert input. S.R.C.: prepared the map, assisted in data organization, and reference management. All authors read and approved the final version of the manuscript.

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