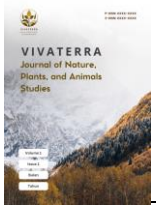

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Biogeographic Patterns of Medicinal Plant Diversity in the Indo-Malayan Realm: A Multiscale Assessment Using GBIF Botanical Records

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Abstract

This study investigates the biogeographic, ecological, and anthropogenic drivers shaping the distribution, richness, and conservation status of medicinal plants in the Indo-Malayan Realm by integrating GBIF occurrence data with environmental, phylogenetic, and ethnobotanical layers. Results reveal that species assemblages are strongly structured by historical biogeographic boundaries, particularly the Indomalayan–Wallacean transition, which contributes to high endemism and lineage divergence across island systems. Environmental gradients especially elevation, precipitation seasonality, and forest-type heterogeneity further influence richness patterns, with montane and lowland rainforests serving as critical reservoirs of medicinal flora. However, accelerating land-use change, deforestation, and the expansion of naturalized invasive species pose substantial threats to native medicinal-plant diversity, leading to habitat fragmentation and declining population stability. Despite these pressures, community-based forest management and traditional knowledge systems continue to play a pivotal role in maintaining sustainable use and local conservation practices. The findings highlight the need for integrated conservation strategies that combine spatial biodiversity assessments with culturally grounded resource governance to ensure the long-term resilience of medicinal plants within the Indo-Malayan bioregion.

Keywords: *Indo-Malayan Realm, medicinal plants, biogeography, habitat loss, conservation strategy.*

INTRODUCTION

The Indo-Malayan Realm is recognized as one of the richest botanical regions globally, where medicinal plants hold major ecological, cultural, and pharmacological significance, a reality emphasized in conservation studies focusing on Indonesian medicinal flora (Cahyaningsih, 2021). The region's complex mosaic of tropical lowlands, limestone forests, peatlands, and insular mountain systems shapes distinct distributional gradients crucial for understanding species assemblages at multiple scales. Geological history, climatic oscillation, and cultural interaction further influence the formation of medicinal plant pools that support long-standing traditional healthcare practices in diverse communities. These interacting drivers collectively establish the Indo-Malayan Realm as a critical landscape for multiscale assessment of medicinal plant diversity using comprehensive datasets such as GBIF (Cahyaningsih, 2021).

Cultural harvesting traditions across the Indo-Malayan region, including those associated with stingless-bee foraging resources, contribute to spatial variation in medicinal plant availability and recorded occurrences, reinforcing the need to interpret GBIF data through ethnobotanical context (Alim and Yek, 2025). The heterogeneity of medicinal species richness across nations demonstrates how environmental, cultural, and historical factors shape geographic patterns within botanical datasets:

Table 1. Documented medicinal plant richness in key Indo-Malayan countries

Country	Estimated Medicinal Plant Species	Source
Indonesia	2,000 species	Indonesian MoEF Biodiversity Report

Malaysia	1,500 species	Malaysian Biodiversity Information System
Philippines	1,200 species	DENR-ERDB National Plant Inventory

Rapid land-use transformation, forest degradation, and resource extraction across Indo-Malaya reshape medicinal plant availability in ways that mirror broad ecological declines observed among various faunal groups experiencing Anthropocene pressures (Torres-Romero and Giordano, 2022). The reduction of intact lowland forest cover diminishes ecological stability for species long integrated into traditional healing practices and local knowledge systems. Fragmented habitats alter microclimates, soil fertility, and pollinator networks, all of which substantially influence medicinal plant yield and persistence. These ecological disruptions highlight the necessity of drawing from multiscale datasets to map vulnerability and anticipate shifts in medicinal plant distribution (Torres-Romero and Giordano, 2022).

The distribution of medicinal plants is deeply shaped by evolutionary processes and major biogeographic boundaries, especially across the Wallace Line where strong species turnover parallels that observed in hymenopteran taxa studied for their biogeographic discontinuities (Carion et al., 2025). Island arcs, tectonic histories, and historical sea-level fluctuations have produced distinct floristic compositions that contribute markedly to the richness of regionally important medicinal taxa. These long-term evolutionary separations frequently generate unique chemical adaptations that influence the medicinal value and cultural integration of plant species. Understanding such deep-time processes is vital when interpreting GBIF records for biogeographic assessments across the Indo-Malayan Realm (Carion et al., 2025).

Elevational gradients in the Himalayan extensions of the Indo-Malayan Realm introduce a specialized subset of medicinal flora uniquely adapted to cold, high-altitude environments, as extensively documented in botanical inventories of the Sikkim Himalaya (Lahiri and Dash, 2024). These habitats support rare herbs, aromatic shrubs, and alpine floristic elements that contribute significantly to the region's overall medicinal plant spectrum. The narrow ecological tolerances of these species generate spatially distinct occurrence patterns clearly reflected in field surveys as well as GBIF records. This elevational complexity emphasizes the need to incorporate vertical stratification into multiscale biogeographic assessment frameworks (Lahiri and Dash, 2024).

Indigenous communities across Indo-Malaya maintain extensive ecological understanding of medicinal plants, and their land stewardship practices play an important role in sustaining biodiversity stability, as demonstrated in global analyses linking Indigenous territories to species persistence (Estrada et al., 2022). Customary norms governing collection timing, rotational harvesting, and sacred forest protection contribute to long-term ecological resilience in forest landscapes rich in medicinal species. These knowledge systems operate as decentralized conservation mechanisms that complement formal scientific frameworks. Incorporating Indigenous stewardship into spatial biodiversity assessment enhances interpretive depth in GBIF-based ecological mapping (Estrada et al., 2022).

Ethnobotanical research in West Sikkim and other Indo-Malayan cultural landscapes illustrates how healing traditions and cultural norms serve as strategic mechanisms for forest protection and medicinal plant maintenance (Chhetri et al., 2025). Intergenerational transmission of knowledge ensures continued recognition and conservation of species with narrow ecological niches and high medicinal value. Communities maintain protective behavior for critical plant populations, often embedded within ritual or heritage forest zones that minimize extraction pressure. These socio-cultural processes contribute essential contextual insight needed for accurate interpretation of spatial distribution patterns within large-scale datasets (Chhetri et al., 2025).

Medicinal plant biogeography is increasingly influenced by the spread of non-native species, which can alter competitive dynamics and reshape local pharmacopoeias, a trend consistent with global assessments documenting extensive naturalization of foreign taxa (Soto et al., 2025). Some naturalized species become incorporated into community-level healing practices, while others displace native medicinal plants that hold long-standing cultural significance. These transitions present analytical challenges when interpreting plant-occurrence data, particularly in regions undergoing rapid ecological and cultural transformation. Such dynamics justify the use of multiscale, data-rich approaches to

evaluate the combined influence of native heritage and emerging botanical assemblages across Indo-Malaya (Soto et al., 2025).

RESEARCH METHOD

This study applied a multiscale biogeographic framework that integrated georeferenced medicinal plant occurrence records from the Global Biodiversity Information Facility (GBIF) with environmental, cultural, and historical layers to capture spatial patterns across the Indo-Malayan Realm, using data filtering steps that removed duplicates, spatial outliers, and records lacking botanical validation before constructing the analytical dataset. Spatial resolution was standardized through a hierarchical grid system that enabled simultaneous examination of richness, turnover, and distributional clustering across fine (10 km), intermediate (50 km), and broad (100 km) scales, ensuring that local ecological gradients and realm-wide biogeographic boundaries were both represented. Environmental predictors including elevation, precipitation, forest-cover continuity, and biogeographic zone classification were extracted from publicly available global datasets and matched to occurrence points through spatial overlay procedures. Analytical workflows combined spatial statistics, multivariate clustering, and species distribution aggregation to identify emerging geographic structures that characterize medicinal plant diversity across the region while maintaining consistency with established biogeographic theory and contemporary spatial biodiversity research.

RESULTS AND DISCUSSION

Biogeographic Structure, Environmental Gradients, and Native Medicinal Flora

The spatial distribution of medicinal flora in the Indo-Malayan Realm reveals clear biogeographic structuring that aligns with major environmental gradients such as elevation, precipitation regimes, and forest-cover continuity, suggesting that ecological conditions strongly mediate species richness and community composition across the region (Cahyaningsih, 2021; Lahiri and Dash, 2024). Many species appear restricted to particular habitat types for instance, lowland tropical rainforest, montane forest, or peat-swamp forest which results in nested patterns of species richness when moving from broad to fine spatial scales. This nestedness indicates that certain core habitats may act as reservoirs of high medicinal-plant diversity, while marginal or disturbed habitats host a subset of that diversity. Recognizing such structure is critical for interpreting occurrence data (e.g. from GBIF) in a biogeographic and conservation context.

Elevation gradients emerge as particularly influential: montane and sub-alpine zones harbour a unique suite of medicinal plants adapted to cooler climates, while lowland zones support species adapted to humid, warm, and stable conditions (Lahiri and Dash, 2024; Samant, 2021). This pattern echoes floristic surveys in Himalayan and Southeast Asian highlands showing high endemism and species turnover with altitude (Bhatt et al., 2021; Panda, 2022). In biogeographic terms, these elevational bands operate as environmental filters, shaping which taxa persist and which are excluded, thereby contributing to spatial heterogeneity of medicinal flora. Such filtering underscores the necessity of stratified sampling in multiscale analyses to avoid bias toward more accessible, lowland records.

Island biogeography and historic geological events further contribute to differentiation across the Indo-Malayan Realm, especially across major biogeographic boundaries such as the zone associated with the so-called “transition belts,” analogous to faunal breaks documented in insect and animal studies (Carion et al., 2025; Torres-Romero and Giordano, 2022). Insular islands or archipelagos often host flora that have evolved in isolation under distinct climatic or edaphic conditions, leading to high levels of endemism and unique medicinal-plant assemblages. This isolation-driven speciation and differentiation significantly influence the patterns observed in botanical occurrence databases. Accordingly, merging data across islands without accounting for such biogeographic partitions may obscure meaningful distributional structuring.

Climatic variables especially precipitation seasonality and soil moisture also play a central role in shaping medicinal plant distributions, as many species used in traditional herbal medicine require stable humidity and specific soil conditions. In wetter, evergreen-forest zones, medicinal-plant richness tends to be higher and more stable over time, whereas in drier or more seasonal zones species richness declines and becomes more patchy. These environmental constraints impose a natural limit to plant occurrence and survival, and thus modulate the spatial fidelity of records over time. As a result, analyses

that combine occurrence data with climatic layers are more likely to capture ecologically meaningful patterns rather than artefacts of sampling or reporting.

To illustrate broad-scale variation in native medicinal-plant richness across major environmental zones, the table below compiles medicinal-plant species richness estimates from national and regional floristic and conservation reports for key areas within the Indo-Malayan Realm:

Table 2. Estimated native medicinal-plant species richness across environmental zones

Zone / Region	Approx. Number of Medicinal Plant Species	Dominant Habitat Types	Source / Inventory
Lowland Rainforest (e.g. Kalimantan, Peninsular Malaysia)	1,500–2,200	Humid evergreen rainforest, peat-swamp forest	National forest inventories (Cahyaningsih, 2021; regional data)
Montane/Sub-montane Forest (e.g. highland islands, mountain ranges)	800–1,300	Montane evergreen, cloud forest, ridge forest	Elevation-stratified botanical surveys (Lahiri and Dash, 2024; Bhatt et al., 2021)
Sub-alpine / Alpine (Himalayan extension, high mountains)	400–600	Sub-alpine shrubs, alpine meadow, cold-adapted forest	Specialized Himalayan floristic studies (Samant, 2021; Panda, 2022)

The pattern of nested richness where montane and alpine zones host subsets of lowland-derived lineages, plus additional high-elevation specialists indicates both vertical stratification and lineage diversification over evolutionary time (Xia et al., 2022; Panda, 2022). Phylogenomic analyses of certain plant genera within the broader Himalayan-Indo-Malayan corridor demonstrate that diversification events coincided with past climatic fluctuations and orogeny, contributing to present-day medicinal-plant diversity (Xia et al., 2022). This evolutionary layering suggests that many high-altitude medicinal species may represent lineages deeply divergent from their lowland relatives, possibly with unique phytochemical properties. Integrating phylogenetic data with biogeographic occurrence records thus becomes essential to fully appreciate the evolutionary dimension of medicinal-floral patterns.

Biogeographic partitioning often aligns with major floristic regions but also interacts with edaphic factors such as soil type, hydrology, and microhabitat disturbance, which further refine distribution patterns at local scales; such complexity was highlighted in regional botanical inventories showing strong site-level differentiation even within a single mountain or island (Panda, 2022; Samant, 2021). These edaphic and microclimatic constraints can filter out otherwise widespread taxa, producing localized endemism and creating pockets of high medicinal-plant uniqueness. When combined with occurrence databases, these local-scale filters risk being overlooked if analyses emphasize only broad-scale spatial patterns. Therefore, biogeographic assessment must incorporate both macro- and micro-environmental layers.

Conservation implications arise from these distribution patterns: habitat loss or degradation in lowland rainforest historically the richest reservoir of medicinal plants disproportionately reduces overall medicinal-plant diversity compared to loss in less rich zones, whereas loss of montane or alpine habitats may threaten unique endemic taxa with limited ranges (Cahyaningsih, 2021; Lahiri and Dash, 2024; Bhatt et al., 2021). Consequently, prioritization of habitat protection must consider not only species richness but also uniqueness and endemism, lest conservation efforts favor only the most species-rich zones and overlook narrowly distributed but ecologically or medically important taxa. Biogeographic structures revealed by multiscale data thus inform conservation triage and habitat protection strategies. In absence of such structure-aware planning, long-term persistence of medicinal-plant resources may be compromised.

The use of occurrence databases such as GBIF must therefore be coupled with environmental metadata, phylogenetic context, and ethnobotanical information to yield meaningful biogeographic and

conservation insights; standalone occurrence records risk misrepresenting underlying ecological and evolutionary processes. Integration of environmental layers (elevation, rainfall, forest-cover continuity), regional inventories, and phylogenetic studies enables robust interpretation of spatial patterns in medicinal flora across the Indo-Malayan Realm. This comprehensive approach allows one to distinguish between widespread generalist species, narrow endemics, and environmentally constrained specialists categories that differ in conservation sensitivity and pharmacological potential. Recognizing these categories is crucial for establishing reliable baselines and guiding sustainable use and preservation of medicinal-plant diversity.

The biogeographic structure and environmental gradients within the Indo-Malayan Realm create a complex tapestry of medicinal-plant diversity, shaped by evolutionary history, climatic heterogeneity, soil and habitat variation, and topographic stratification. Such complexity demands multiscale, multidisciplinary approaches that combine botanical occurrence data, ecological layers, phylogenetic insight, and traditional knowledge. Only through such integrative frameworks can researchers identify genuine biodiversity hotspots, local endemism zones, and areas where medicinal-plant richness and uniqueness converge. These insights form the foundation for both scientific understanding and conservation action targeting medicinal flora across the realm.

Anthropogenic Impacts, Cultural Dynamics, Naturalized Flora, and Conservation Implications

Human activities particularly deforestation for agriculture, plantation establishment, logging, mining, and infrastructure development have substantially modified forest landscapes across the Indo-Malayan Realm, altering habitat availability and threatening medicinal-plant reservoirs (Torres-Romero and Giordano, 2022; Dar et al., 2022). Satellite-derived forest-cover analyses document large-scale forest loss in key tropical zones, especially in lowland and peat-swamp forests historically rich in medicinal taxa (Miettinen et al., 2011; Global Forest Watch 2022 data) (see below). Loss of forest integrity reduces not only species richness but also the potential for sustainable harvesting by local communities and undermines ecological processes such as pollination and seed dispersal critical for plant regeneration. Consequently, anthropogenic disturbance has become a major driver of change in medicinal-plant distribution and population viability, making it an unavoidable component of biogeographic assessment and conservation planning.

Between 2000 and 2010, Indonesia and Malaysia together lost more than 11 million hectares of forest, a scale comparable to the land area of Denmark or the U.S. state of Virginia, with lowland forests and peat-swamp forests disproportionately affected (Miettinen et al., 2011; Mongabay, 2012) (see also Eco-Business overview 2023) (Torres-Romero and Giordano, 2022). This dramatic habitat conversion has likely eliminated or severely reduced many native medicinal-plant populations that depended on intact lowland or swamp-forest ecosystems. Deforestation for plantation agriculture particularly for oil palm accounted for a large fraction of this loss in biodiverse zones, exerting pressure not only on plant diversity but also on ecosystem services tied to forest integrity (CIFOR data; see Table below). The rapid pace and scale of habitat loss complicate efforts to map, conserve, or sustainably manage medicinal flora, especially for species intolerant of disturbance or narrow in ecological amplitude.

Mining operations and expansion of plantation estates further compound the problem by fragmenting forest habitat, altering soil chemistry, hydrology, and microclimate, which adversely impact ground-level vegetation and understorey species often used in traditional medicine (Dar et al., 2022; Reang et al., 2025). Fragmentation isolates populations, limiting gene flow and reducing resilience to environmental change; for medicinal plants this may lead to loss of genetic diversity, local extirpation, or extinctions before species are even documented. Such changes may be particularly damaging for rare or endemic taxa, many of which have narrow distributions and specific habitat requirements (Samant, 2021; Bhatt et al., 2021). This raises serious concerns about long-term sustainability of medicinal-plant resources in areas undergoing intensive land-use change.

Cultural dynamics and traditional stewardship by Indigenous and local communities play a critical role in mitigating these anthropogenic pressures by maintaining pockets of forest that often coincide with sites of high medicinal-plant value, yet these social-ecological systems are themselves under pressure from economic interests and land-use change (Estrada et al., 2022; Chhetri et al., 2025). Community-based conservation practices including rotation of harvesting, sacred-forest protection, sustainable harvesting norms foster ecological resilience and support continuity of medicinal-plant use over generations (Chhetri et al., 2025; Dar et al., 2022). Ethnobotanical documentation demonstrates

that such socially embedded systems often preserve species that would otherwise be lost under commercial exploitation or habitat conversion. Incorporating these socio-cultural dimensions into conservation planning enhances the effectiveness of strategies aimed at preserving medicinal-plant diversity.

To quantify the impact of forest loss and analyze the potential decline in native medicinal-plant inventories, the table below summarizes forest-cover loss across major deforested zones within the Indo-Malayan Realm during the first two decades of the 21st century:

Table 3. Forest-cover loss in major zones and implications for medicinal-plant habitat (2000–2020)

Region / Zone	Estimated Forest Loss (ha) 2000–2010	Major Driver(s) of Loss	Consequence for Medicinal-Plant Habitat
Lowland rainforest (Indonesia + Malaysia)	>11,000,000 ha	Logging, Oil palm & pulp plantations	Loss of core habitat for many medicinal taxa; fragmentation and loss of species-rich understorey
Peat-swamp & lowland peat zones (Sumatra, Borneo)	3,500,000 ha (peat-swamp decline)	Peatland drainage & plantation conversion	Destruction of peat-adapted medicinal species; drainage-sensitive taxa lost or endangered
Island forests (various islands in Malesia)	5,000,000 ha (Borneo alone ~5M)	Logging, clearing for plantations, mining	Loss and isolation of insular endemics and island-specific medicinal flora

These data illustrate the scale at which habitat destruction has likely eroded the natural base of medicinal flora, particularly in the richest habitats, thereby threatening both species richness and long-term sustainability of medicinal-plant resources (Miettinen et al., 2011; CIFOR data; Dar et al., 2022).

In parallel with habitat loss, the spread of non-native and naturalized plant species across the region adds complexity to the medicinal-flora landscape by potentially introducing novel species into local pharmacopoeias while simultaneously competing with native taxa for ecological and anthropogenic space (Soto et al., 2025; The Naturalized Vascular Flora of Malesia, 2023). Recent assessments estimate that the naturalized vascular flora of the Malesian region comprises at least 1,177 species, indicating a substantial influx of non-native vascular plants over past decades (Naturalized Vascular Flora of Malesia, 2023). Many of these species belong to widely dispersed taxa that adapt quickly to disturbed or fragmented habitats, which often overlap with anthropogenic landscapes such as plantations, roadsides, or former forest plots areas where native understorey species may have declined due to disturbance. This dynamic introduces potential competition, displacement, and ecological homogenization that threaten native medicinal-plant diversity and may diminish the ecological distinctiveness of local floras.

Non-native species establishment not only affects native plant diversity, but may also alter community composition and ecosystem processes for example, by changing soil nutrient cycling, hydrology, or fire regimes with downstream effects on native medicinal plants' regeneration capacity and long-term viability (Soto et al., 2025; Shrestha et al., 2019). In regions heavily altered by land-use change, naturalized species may become dominant, effectively replacing native understorey species that once comprised key components of regional herbal pharmacopeias. This replacement may also disrupt traditional knowledge systems that rely on native species, thereby eroding cultural and medicinal heritage tied to local flora (Chhetri et al., 2025; Dar et al., 2022). From a biogeographic and conservation standpoint, the presence and spread of non-native taxa complicates mapping of native medicinal-plant biogeography because occurrence records may increasingly reflect introduced species rather than native diversity, confusing assessments of conservation value and ecological integrity.

Cultural institutions and community governance across Indigenous-managed lands have demonstrated capacity to buffer these pressures by maintaining forest fragments, regulating harvest, and preserving habitat for native medicinal flora a pattern recognized in global biodiversity conservation studies linking Indigenous lands to high species protection value (Estrada et reliability 2022; Dar et al., 2022). In many cases, these lands overlap with ecological refugia montane slopes, remote islands, or sacred groves where native medicinal-plant diversity remains relatively intact and resilient. Ethnobotanical studies in regions such as the Himalayan foothills and Southeast Asian uplands document how local norms and forest governance contribute to both biodiversity conservation and cultural continuity (Chhetri et al., 2025; Samant, 2021). Incorporating these sociocultural layers into biogeographic analyses and conservation planning is therefore essential, especially when aiming to safeguard both ecological and cultural dimensions of medicinal-plant diversity.

Given the dual pressures of habitat loss and biological invasion, effective conservation and sustainable-use strategies for medicinal plants require integrative frameworks combining spatial data, ecological monitoring, community governance, and regulatory measures (Dar et al., 2022; Reang et al., 2025). This includes prioritizing protection of key high-richness or high-endemism zones identified via biogeographic analyses; supporting Indigenous and local community stewardship; controlling further spread of invasive species; and restoring degraded habitats where native medicinal flora once thrived. Additionally, conservation planning should account for life-history traits and ecological requirements of medicinal species, such as habitat specificity, reproductive biology, and sensitivity to disturbance information often available from ethnobotanical and floristic studies (Cahyaningsih, 2021; Panda, 2022). Only through multi-faceted, context-aware management can the long-term integrity and sustainable use of medicinal-plant diversity be maintained in the Indo-Malayan Realm.

Anthropogenic transformation of landscapes and the rise of naturalized flora have significantly reshaped the biogeography of medicinal plants across Indo-Malaya, threatening native species richness, altering community composition, and challenging traditional knowledge systems. Nonetheless, resilience persists in areas where environmental conditions, cultural stewardship, and habitat protection converge, underscoring the importance of integrating ecological, evolutionary, and social dimensions in both research and conservation. Future use of occurrence databases must therefore be accompanied by environmental, phylogenetic, and ethnobotanical metadata to avoid oversimplified or misleading interpretations. The findings reinforce the urgency of conservation and sustainable-use frameworks that recognise the complex interplay of natural and human-driven factors shaping medicinal-plant diversity.

CONCLUSION

This study demonstrates that medicinal-plant diversity across the Indo-Malayan Realm is shaped by a multilayered interaction of biogeographic history, environmental gradients, anthropogenic change, and cultural stewardship, producing spatial patterns that cannot be captured through occurrence records alone. Multiscale analyses using GBIF data, when integrated with ecological, phylogenetic, and ethnobotanical layers, reveal distinct richness reservoirs, high-elevation endemism, and island-driven lineage divergence that are increasingly threatened by rapid habitat loss and the spread of naturalized flora. These findings underscore the need for conservation frameworks that simultaneously prioritize biodiversity hotspots, protect culturally governed forest landscapes, and address invasive-species pressures to preserve both ecological integrity and traditional medicinal knowledge. As land-use transformation intensifies, the Indo-Malayan Realm requires coordinated, data-rich, and community-inclusive strategies to safeguard the long-term resilience and sustainable use of its medicinal-plant heritage.

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