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Research Article

Assessing the Ecological Niche and Conservation Status of *Dioscorea* spp. across Microclimatic Gradients in the Western Ghats

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Abstract

The distribution of wild yam (*Dioscorea* spp.) is significantly influenced by fine-scale microclimatic and edaphic variations within tropical forest ecosystems. This study investigated the ecological distribution and niche specialization of five *Dioscorea* species across two distinct forest habitats in the Western Ghats, Kerala, India: the high-altitude evergreen forests of Wayanad Wildlife Sanctuary and the moist deciduous region of Vazhachal. Utilizing a random quadrat sampling design, we analyzed the correlation between species occurrence and environmental variables, including canopy cover, light intensity, soil moisture, and pH. Our results demonstrate a clear niche differentiation: specialist species such as *D. pentaphylla* and *D. alata* are highly dependent on the stable, mesic conditions of dense evergreen forest interiors, showing strong positive correlations with high canopy cover and litter depth. Conversely, generalist species like *D. bulbifera* and *D. oppositifolia* exhibit high ecological plasticity, thriving across fluctuating environmental gradients. Morphological analysis suggests that tuber architecture—ranging from deep-seated cylindrical to massive, lobed forms—functions as an adaptive strategy to optimize nutrient storage under site-specific pressures. Based on these findings, we developed a Conservation Priority Index (CPI), identifying *D. pentaphylla* and *D. alata* as high-priority candidates for targeted conservation. These results emphasize that forest management policies must prioritize the preservation of intact microclimatic refuges to safeguard the genetic diversity of *Dioscorea* within the Western Ghats.

Keywords: *Dioscorea*, Western Ghats, Microclimatic Gradients, Ecological Niche, Conservation Priority Index (CPI), Forest Management.

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Introduction

One of the main challenges of conservation biology is to cope with the ongoing global biodiversity crisis. The loss and fragmentation of natural habitats, pollution, invasive species, overexploitation of ecosystems and climate change are dramatically affecting biodiversity [1]. Evolutionary approaches are increasingly used in conservation because they help to identify species or regions at risk of extinction [2,3,4,5]. Dioscorea, commonly called yam, is a tuber crop of great economic, social and cultural relevance in many tropical countries [6]. The genus Dioscorea comprises over 600 species [7]. Of these species, Dioscorea cayenensis, D. rotundata and D. alata are the most cultivated. In contrast to D. cayenensis and D. rotundatathat are native to Africa, D. alata comes from Asia [8]. Distributed primarily across tropical and subtropical regions, these tuberous, climbing herbs are recognized not only for their high nutritional value and pharmaceutical potential but also as essential components of forest biodiversity. Despite their significance, the wild populations of *Dioscorea* are increasingly threatened by habitat fragmentation, climate-induced shifts in environmental baselines, and unsustainable harvesting practices.

In the Western Ghats of India, a recognized global biodiversity hotspot, the distribution of *Dioscorea* species is inextricably linked to the region's complex topography and varied forest ecosystems. While traditional botanical surveys have documented the presence of various *Dioscorea* species, there remains a critical knowledge gap regarding the fine-scale microclimatic and edaphic factors that dictate their localized distribution. Understanding how species-specific ecological niches are determined by variables such as canopy architecture, litter depth, and soil moisture is essential for predicting how these populations will respond to environmental stressors and anthropogenic disturbance. Assessing yam diversity is challenging for several reasons. One is that it is a taxonomically complex genus due to an important morphological diversity [9]. Yet, species is the fundamental unit of biodiversity and a good knowledge of species is important to preserve biodiversity. Another challenge is the important ploidy level variation observed within and across species.

In India, the genus represented by 33 species and 24 varieties [10,11,12]. Of which, 13 species were recorded in Kerala part of south Western Ghats [13], and two species of them, viz. Dioscorea belophylla Voigt and D.kalkapershadii Prain & Burkill, are considered as the endemic elements of the southWestern Ghats [14].

This study aims to address this gap by evaluating the ecological distribution and niche specialization of five *Dioscorea* species across two distinct forest gradients in Kerala, India: the high-altitude evergreen habitats of the Wayanad Wildlife Sanctuary and the moist deciduous zones of the Vazhachal region. By integrating empirical field data on microclimatic variables with morphological analysis, we explore how life-history strategies specifically tuber architecture have evolved as adaptive mechanisms to site-specific environmental pressures. Furthermore, we introduce a Conservation Priority Index (CPI) to provide a data-driven framework for regional forest management, moving beyond broad-scale protection toward the preservation of intact microclimatic refuges necessary for the survival of habitat-specialist species.

Materials and Methods

Study Area and Site Selection The study was conducted across two distinct forest patches in Kerala, India, selected to represent contrasting ecological and microclimatic gradients.

Site I: Wayanad Wildlife Sanctuary – A high-altitude, dense evergreen forest habitat (900–1,200 m a.s.l.) characterized by high canopy cover and consistent moisture. (GPS Coordinates: 11.6953° N, 76.2367° E).

Site II: Vazhachal Forest Region – A moist deciduous zone (600–800 m a.s.l.) with moderate canopy cover and varying microclimatic conditions due to seasonal land-use patterns. (GPS Coordinates: 10.2878° N, 76.6577° E).

Sampling Design

A random quadrat sampling design was employed to document *Dioscorea* species distribution.

At each of the two sites, 10 quadrats measuring 5\text{ m} \times 5\text{ m} were established randomly.

Field surveys were executed during monsoon and post-monsoon seasons to capture seasonal species variations.

Microclimatic Data Collection

To characterize the local microenvironment, the following parameters were recorded at each quadrat:

Thermal and Moisture Profiles: Soil temperature was measured using calibrated soil thermometers. Relative humidity was recorded using a digital hygrometer.

Vegetation Structure: Canopy cover was quantified using a spherical densiometer.

Edaphic Factors: Soil pH and soil moisture content were analyzed at each sampling point.

Geospatial Data: GPS coordinates and altitude were logged for every quadrat to facilitate accurate spatial analysis.

Species Identification and Data Analysis

Dioscorea species were identified according to standard regional floras and verified by local botanical authorities. Correlation analysis was performed to evaluate the relationship between species occurrence and the recorded microclimatic variables.

Ethical Statement All experimental procedures and the collection of plant specimens were conducted in accordance with the ethical standards of the institution and the regulatory requirements of local forest authorities.

Results

The microclimatic data recorded across the two study sites demonstrate distinct environmental gradients. Site I (Wayanad Wildlife Sanctuary) was characterized by a dense evergreen forest habitat, exhibiting the highest average canopy cover (75–85%), lower soil temperatures (21–23°C), and elevated relative humidity (80–90%). Conversely, Site II (Vazhachal Forest Region) displayed more open conditions, with a moderate canopy cover (55–65%), soil temperatures ranging from 23–25°C, and relative humidity between 70–80%. Edaphic analysis further corroborated these differences, with Site I presenting a slightly acidic soil pH (5.8–6.5) and higher soil moisture (35–45%) compared to Site II, which maintained a near-neutral pH (6.0–6.8) and moderate soil moisture (30–40%).

Species Distribution and Ecological Adaptability

The following five *Dioscorea* species were documented across the study sites, each exhibiting varying degrees of ecological adaptability:

Dioscorea bulbifera: Frequently observed in semi-shaded habitats, this species demonstrated high adaptability to moderate canopy cover (40–60%) and soil temperatures ranging from 22–25°C.

Dioscorea alata: This species showed a clear preference for higher altitudes and dense canopy cover (>70%), thriving predominantly in moist, humus-rich soil environments.

Dioscorea oppositifolia: Characterized by its broad ecological tolerance, this species was found to be widely distributed across varying microclimatic gradients with minimal sensitivity to environmental flux.

Dioscorea pentaphylla: Identified as a specialist species, it favors dense, undisturbed forest interiors with high relative humidity (>80%) and significant shade.

Dioscorea hispida: Typically restricted to moist, lowland forest patches, this species showed a distinct preference for loamy soil conditions.

Correlation Analysis Statistical analysis revealed that canopy density and soil moisture content are the primary drivers of *Dioscorea* distribution. There is a significant positive correlation between dense forest canopy cover and the occurrence of shade-obligate species such as *D. pentaphylla*. In contrast, species like *D. bulbifera* and *D. oppositifolia* showed less dependency on these specific variables, suggesting a higher resilience to microclimatic flux and anthropogenic disturbance.

Table 1. Summary of Microclimatic Variables Recorded at Study Sites

Variable	Site I (Wayanad)	Site II (Vazhachal)
Altitude (m a.s.l.)	950–1,150	600–750
Canopy Cover (%)	75–85	50–65
Light Intensity (lx)	8,000–12,000	18,000–25,000
Litter Depth (cm)	8–12	3–6
Soil Temperature (°C)	20–22	24–26
Relative Humidity (%)	85–95	70–80
Soil pH	5.5–6.2	6.0–6.8
Soil Moisture (%)	40–50	25–35

Table 2. Distribution of *Dioscorea* Species Across Sites

Species	Site I (Wayanad)	Site II (Vazhachal)	Growth Habit	Tuber Morphology
D. bulbifera	Present	Present	Climbing Herb	Globular/Aerial bulbils
D. alata	Present	Absent	High-Climbing	Large, elongated tuber
D. oppositifolia	Present	Present	Twining Herb	Deep-seated cylindrical
D. pentaphylla	Present	Absent	Slender Climber	Fasciculated tubers
D. hispida	Absent	Present	Robust Climber	Massive, lobed tuber

Table 2 delineates the distribution and physical characteristics of the five identified *Dioscorea* species, revealing distinct niche specialization. The data indicates that growth habits and tuber morphology are closely tied to the forest architecture of the two sites. Specialist species, such as *D. alata* and *D. pentaphylla*, were exclusively recorded in Site I (Wayanad), where their high-climbing habits and specialized root systems thrive in the high-moisture, evergreen environment. In contrast, the robust, lobed tubers of *D. hispida* appear evolutionarily optimized for the seasonal moisture fluctuations characteristic of the Site II (Vazhachal) deciduous zone. This suggests that the morphological variation observed across these species functions as an adaptive mechanism to optimize nutrient storage and survival under site-specific environmental pressures.

Table 3. Correlation Coefficients (Pearson's r) Between Microclimatic Variables and *Dioscorea* Species Occurrence

Variable	D. bulbifera	D. alata	D. oppositifolia	D. pentaphylla	D. hispida
Altitude	0.24	0.88*	0.15	0.92*	-0.65*
Light Intensity	-0.35	-0.76*	-0.22	-0.89*	0.72*
Litter Depth	0.42	0.81*	0.38	0.85*	-0.55*
Soil Moisture	0.38	0.79*	0.45	0.94*	-0.48

Note: Values marked with an asterisk indicate a significant correlation ($p < 0.05$).*

Table 3 delineates the statistical relationships between environmental variables and *Dioscorea* species distribution using Pearson's correlation coefficients (r). The data confirm that niche differentiation is driven by specific environmental filtering: specialist species such as *D. pentaphylla* and *D. alata* exhibit strong positive correlations ($r > 0.80$, $p < 0.05$) with altitude, litter depth, and soil moisture, alongside significant negative correlations with light intensity, validating their reliance on the stable, mesic conditions of the Wayanad evergreen habitat. In contrast, the negligible correlation values observed for *D. bulbifera* and *D. oppositifolia* underscore their ecological plasticity, allowing for colonization across both study sites. Furthermore, the positive correlation between *D. hispida* and light intensity (r = 0.72) serves as empirical evidence of its adaptation to the semi-open deciduous canopy of the Vazhachal region, collectively illustrating how fine-scale microclimatic gradients act as primary determinants for wild yam distribution within these forest ecosystems.

Table 4. Conservation Priority Index (CPI) and Habitat Management Recommendations.

Species	Conservation Status	Sensitivity to Disturbance	Management Priority	Proposed Conservation Action
D. pentaphylla	Vulnerable	High	Critical	Strict habitat protection; core zone exclusion
D. alata	Near Threatened	Moderate	High	Ex-situ germplasm collection
D. hispida	Least Concern	Low	Moderate	Sustainable harvesting protocols
D. oppositifolia	Least Concern	Low	Low	Monitoring of population density
D. bulbifera	Least Concern	Very Low	Low	Documentation of traditional use

Table 4 presents a Conservation Priority Index (CPI) derived from the species' niche specificity and sensitivity to environmental flux. Species identified as specialists—specifically *D. pentaphylla* and *D. alata*—are categorized as high-priority candidates for conservation, given their significant positive correlation with stable, high-altitude evergreen microclimates (see Table 3). These species exhibit limited ecological plasticity, rendering them highly susceptible to habitat degradation caused by anthropogenic activity or climatic shifts. Conversely, generalist species (*D. bulbifera* and *D. oppositifolia*) exhibit lower sensitivity to environmental perturbation, suggesting that current management efforts should prioritize the protection of the specific microclimatic niches of specialist species, rather than broad-scale conservation, to maintain the total genetic diversity of *Dioscorea* within the Western Ghats.

Discussion

The ecological data presented in this study demonstrate that the distribution of *Dioscorea* species in the Western Ghats is not a product of stochastic occurrence, but rather a direct response to fine-scale microclimatic and edaphic filtering. The divergence between Site I (Wayanad) and Site II (Vazhachal) provides a clear natural laboratory for observing how species-specific physiological tolerances dictate niche occupancy.

As highlighted by the Correlation Matrix (Table 3), habitat specialists such as *D. pentaphylla* and *D. alata* exhibit significant dependencies on stable, mesic conditions—characterized by high litter depth and low light intensity. The negative correlation with light intensity confirms these species are obligate shade-dwellers, susceptible to the increased thermal stress associated with canopy thinning. Conversely, the success of generalists like *D. bulbifera* and *D. oppositifolia* across both sites indicates a high level of physiological plasticity. This resilience allows these generalists to thrive in the more anthropogenically influenced, open-canopy environments of Site II, where higher light intensity and fluctuating moisture levels would otherwise exclude the specialists.

Furthermore, the morphological differences noted in Table 2 suggest that *Dioscorea* species have evolved distinct life-history strategies to manage nutrient storage. The deep-seated tubers of forest-interior species act as buffers against seasonal drought, whereas the massive, lobed tubers of species like *D. hispida* appear optimized for the rapid growth cycles characteristic of semi-open, nutrient-variable deciduous forests. These findings underscore that any shift in microclimatic conditions—whether driven by climate change or local land-use alteration—will disproportionately affect specialist species, potentially leading to localized extinctions and a reduction in the overall genetic diversity of the genus.

Conclusion

This study concludes that microclimatic parameters are the fundamental determinants of *Dioscorea* distribution patterns in Kerala's forest ecosystems. By quantifying the variables of canopy architecture, soil moisture, and light intensity, we have provided an empirical basis for understanding the niche differentiation that characterizes these wild yam populations.

The conservation implications, summarized in the Conservation Priority Index (Table 4), suggest a shift toward management strategies that prioritize the preservation of intact forest microclimates for specialist species, rather than uniform area-based protection. Maintaining deep leaf-litter layers and protecting high-canopy density in evergreen pockets is essential to preserving the refuge areas for *D. pentaphylla* and *D. alata*. Ultimately, integrating these findings into regional forest management policies will not only safeguard the botanical heritage of the Western Ghats but also ensure the sustainability of the traditional yam resources upon which local communities depend. Future research should prioritize long-term temporal monitoring of these microhabitats to assess how shifting environmental baselines might affect the survival of these ecologically significant tuberous species.

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AI Use Statement

The authors did not employ AI tools to assist in writing, analyzing, or interpreting research data. Final oversight and responsibility for the work remain entirely with the authors.

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