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Climate Change and Orchid Adaptation: Evaluating the Ecophysiological Responses of Wayanad's Endemic Orchids

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Abstract

The montane ecosystems of Wayanad, nestled within the Western Ghats-a recognized UNESCO World Heritage site and biodiversity hotspot-support a remarkable array of endemic orchid species. These orchids, particularly epiphytic and lithophytic types, are highly sensitive to changes in microclimatic conditions, making them valuable biological indicators of ecological stress under changing climate regimes. This study presents the results of a four-year ecophysiological investigation (2021–2025) into the adaptive responses of selected endemic orchids to climate variability, focusing on the impacts of increased temperature, irregular rainfall, and prolonged summer drought. Four representative species-*Rhynchostylis retusa*, *Bulbophyllum neilgherrense*, *Coelogyne nervosa*, and *Dendrobium aqueum*-were selected based on their ecological prominence and distinct growth forms. A combination of in-situ fieldwork and controlled-environment experiments was employed to evaluate physiological and morphological responses. Sampling was conducted across varied elevations (800–1500 m) and habitat types (evergreen, semi-evergreen, and moist deciduous forests). Physiological measurements included stomatal conductance, leaf relative water content, leaf water potential, chlorophyll fluorescence (Fv/Fm), and phenological behavior. Anatomical assessments of root velamen, leaf cuticle thickness, and pseudobulb structure were performed using light and electron microscopy. Species such as *B. neilgherrense* and *C. nervosa* showed significant drought tolerance attributed to pseudobulb water storage and thick velamen layers, while *D. aqueum* exhibited facultative CAM photosynthesis during peak dry months, confirmed via $\delta^{13}C$ isotope analysis. Multivariate regression analysis revealed that orchid survival and physiological performance were strongly influenced by canopy density ($R^2 = 0.72$), relative humidity ($R^2 = 0.68$), and elevation ($R^2 = 0.64$). Species located in higher-elevation, closed-canopy microhabitats maintained stable water potentials and photosynthetic efficiency even under extreme drought. Phenological records indicated delayed flowering and pseudobulb initiation in years with early summer onset, suggesting climate-driven shifts in developmental timing. These findings emphasize the importance of microhabitat conditions and morphological adaptations in buffering orchids against climate-induced stress. Conservation strategies must prioritize the preservation of shaded forest canopies, host tree diversity, and hydrological stability to maintain orchid-rich habitats. This study contributes a foundational understanding of orchid ecophysiology in the Western Ghats and offers critical insights for formulating climate-resilient conservation policies in tropical montane ecosystems.

INTRODUCTION

Orchids are one of the most diverse and evolutionarily advanced families of flowering plants, comprising more than 28,000 species globally. Their high degree of ecological specialization, particularly among epiphytic and lithophytic types, renders them excellent indicators of environmental change. These plants often maintain delicate dependencies on host trees, specific light and humidity regimes, and mycorrhizal associations. Nowhere is this complexity more pronounced than in biodiversity hotspots like the Western Ghats of India, a UNESCO World Heritage Site and one of the eight "hottest hotspots" of global biodiversity.

Within the Western Ghats, the Wayanad region in northern Kerala is a key ecological zone characterized by mid- to high-elevation moist forests, shola-grassland mosaics, and dense semi-evergreen cover. These habitats host numerous orchid species, many of which are endemic, rare, or poorly studied. Historically, Wayanad's montane microclimates-characterized by consistent humidity, filtered sunlight, and seasonal rainfall-have supported rich orchid diversity. However, this ecological equilibrium is now under stress due to shifting climatic patterns, anthropogenic pressures, and land-use transformations.

Recent decades have seen a rise in the frequency and duration of summer droughts, erratic rainfall, and rising ambient temperatures in Wayanad. These changes disrupt microclimatic conditions crucial for orchid survival-particularly for epiphytes that depend on canopy cover for humidity regulation and protection from direct solar radiation. Such climatic anomalies, compounded by habitat fragmentation and deforestation, pose severe threats to orchid populations, often pushing species to the edge of local extinction.

While global literature has documented adaptive traits in orchids across Southeast Asia and Neotropical ecosystems, there remains a significant gap in understanding how endemic South Indian orchids physiologically and morphologically respond to prolonged climate stress. Most studies have focused on short-term phenological trends or generalized floristic surveys, failing to capture longitudinal, species-specific ecophysiological data.

This three-year study aims to address that gap by evaluating the adaptive strategies of select endemic epiphytic orchids of Wayanad under increasing climatic variability. Specifically, the research focuses on drought resilience mechanisms such as pseudobulb water storage capacity, variations in leaf morphology (thickness, cuticle, succulence), root structure modifications, and photosynthetic adjustments like CAM metabolism. The study integrates continuous microclimatic monitoring, in situ phenological observations, and physiological measurements across multiple elevations and habitat types.

By identifying patterns of survival and stress resilience over time, this research not only enhances our understanding of plant adaptation under climate change but also supports evidence-based conservation planning. The findings will be crucial for species recovery efforts, microhabitat-based restoration, and climate-smart orchid horticulture in the Western Ghats. Ultimately, this work contributes to a broader ecological discourse on how climate change reshapes montane biodiversity dynamics in tropical forest ecosystems.

MATERIALS AND METHODS

Study Area: This three-year ecophysiological study (2023–2025) was conducted in Wayanad district of Kerala, a biodiversity-rich region in the southern Western Ghats. The district exhibits remarkable topographical and ecological diversity, with elevation gradients ranging from 700 m to over 2100 m. The climate is characterized by a pronounced monsoonal rhythm with distinct wet (June–October), dry (December–April), and transitional (May and November) periods. To assess orchid responses under different ecological and microclimatic conditions, three distinct forest zones were selected across an elevational transect:

Site A-Moist Deciduous Forest (800–1000 m): Dominated by tree species such as Terminalia paniculata, Lagerstroemia microcarpa, and Careya arborea, this zone experiences high solar exposure during the dry season due to deciduous canopy loss. Relative humidity (RH) drops below 60% during peak summer.

Site B-Semi-Evergreen Forest (1000–1200 m): Characterized by partial canopy closure and presence of evergreen elements, this zone retains relatively stable microclimates. Common associates include Myristica, Persea, and Syzygium species.

Site C-Shola-Grassland Ecotone (>1200 m): This high-elevation habitat includes fragmented shola patches interspersed with montane grasslands. It is marked by cool temperatures, frequent mists, and rock-dominated terrain.

Each site was equipped with environmental sensors and monitored regularly throughout the study period to capture seasonal fluctuations.

Target Species Selection: Four orchid species were selected based on their ecological representativeness, conservation status, and distinct water-use strategies (Table 1). Species were chosen to include a range of

Table 1: Selected Orchid Species and Targeted Ecophysiological Parameters (2023–2025)

Species Name	Growth Habit	Adaptive Traits Studied	Habitat Type	Conservation Status
Rhynchostylis retusa	Epiphytic	Leaf thickness, waxy cuticle, pseudobulb absence	Moist deciduous forest	Near Threatened (IUCN)
Dendrobium aqueum	Epiphytic	Water-retentive stems, seasonal dormancy	Evergreen mid-elevation	Endemic to Western Ghats
Bulbophyllum neilgherrense	Lithophytic	CAM metabolism, root anchorage in crevices	Rocky hill slopes	Rare
Vanda tessellata	Epiphytic	Leaf surface reduction, exposed canopy survival	Dry semi-evergreen	Data Deficient
Coelogyne nervosa	Epiphytic	Pseudobulb swelling, stomatal regulation	Humid ravines	Vulnerable

Table 2: Target Orchid Species and Habitat Preferences

Species Name	Growth Habit	Habitat Preference
Rhynchostylis retusa	Epiphytic	Moist deciduous forest (Site A)
Dendrobium aqueum	Epiphytic	Semi-evergreen upper canopy (Site B)
Bulbophyllum neilgherrense	Lithophytic	Rocky slopes, shola edge (Site C)
Coelogyne nervosa	Epiphytic	Shaded ravines, mid-canopy (Site B)

Table 3: Summary of Physiological Parameters and Survival Rates (2021–2025)

Species	Mean Stomatal Conductance (mmol m?²s?¹)	?leaf (MPa)	Pseudobulb Water Storage (%)	Survival Rate (%)
Rhynchostylis retusa	92 ± 5	-1.3	15	78
Dendrobium aqueum	65 ± 4	-1.8	33	85
Bulbophyllum neilgherrense	58 ± 6	-2.1	41	91
Coelogyne nervosa	49 ± 3	-2.0	46	93

Table 4: Summary of Key Adaptive Features and Conservation Implications

Adaptive Feature	Function	Conservation Implication
Pseudobulb Water Storage	Maintains water during dry periods	Retain moisture-buffered canopy zones
Thick Leaf Cuticle & Succulence	Minimizes transpiration	Avoid exposure during rewilding; plant in shaded microsites
Velamen in Roots	Enhances water absorption & retention	Maintain host tree species with optimal bark textures
Stomatal Regulation	Reduces water loss during stress	Monitor physiological health during translocation efforts
Host-Specific Mycorrhizal Symbiosis	Facilitates nutrient and water uptake	Investigate fungal partners during propagation and reintroduction

growth habits (epiphytic and lithophytic) and microhabitat preferences.

Thirty healthy individuals per species were tagged across their natural habitats. Each individual was georeferenced, photographed, and monitored consistently throughout the study.

Parameters Measured: A combination of physiological, anatomical, and environmental parameters was monitored to assess water relations, stress responses, and phenology under changing microclimatic conditions.

Physiological Parameters:

Stomatal Conductance (gs): Measured biweekly using a portable porometer (SC-1, Decagon Devices) on mature leaves during early morning (08:00–09:30) to minimize diurnal fluctuations.

Leaf Water Potential (Ψ_leaf): Measured monthly using a Scholander-type pressure chamber. Midday values (12:00–13:00) were prioritized to assess peak drought stress.

Chlorophyll Fluorescence (Fv/Fm): Assessed monthly using a portable fluorometer (OS30p+, Opti-Sciences) on dark-adapted leaves to evaluate photosystem II efficiency and photoinhibition during dry spells.

Pseudobulb Water Content: Periodic gravimetric analysis was conducted by harvesting fallen pseudobulbs (post-senescence), measuring fresh and dry weights to estimate water retention capacity.

Anatomical and Structural Features:

Root Anatomy: Root sections were hand-cut or microtomed, stained (safranin-fast green), and observed under a compound microscope. Velamen thickness, cortical cell dimensions, and xylem architecture were documented.

Leaf Thickness and Cuticle: Leaf cross-sections were examined for cuticle integrity, palisade thickness, and mesophyll cell density.

Microclimatic and Environmental Variables:

Canopy Cover: Quantified using hemispherical photography and analyzed using Gap Light Analyzer software to calculate leaf area index (LAI) and light transmission.

Relative Humidity and Temperature: HOBO data loggers installed at each site recorded hourly RH and temperature values, enabling the generation of species-specific microclimatic profiles.

Soil and Bark Moisture Content: Measured monthly using gravimetric methods and moisture probes to assess the substrate's water availability for lithophytic and epiphytic orchids respectively.

Phenological Observations: Monthly monitoring of phenophases-leaf flush, leaf senescence, pseudobulb initiation, budding, flowering, and fruiting—was conducted to correlate seasonal shifts with physiological stress.

Experimental Design: In addition to in-situ observations, controlled polyhouse experiments were established at the Kerala Agricultural University Research Station, Ambalavayal (approx. 950 m asl). The experiment simulated seasonal drought by regulating irrigation frequency and ambient humidity.

- Plants from each species were acclimatized in uniform pots for one month.
- Drought treatments were applied in three levels: Mild (75% field capacity), Moderate (50%), and Severe (25%), sustained for four weeks.
- Physiological stress indicators (?_leaf, gs, Fv/Fm) were monitored weekly.
- Recovery was evaluated 10 days post re-watering.

Statistical Analysis:
Descriptive Statistics: Mean, standard deviation, and coefficient of variation were calculated for all parameters across time and treatments.

ANOVA and Tukey's HSD Test: Used to test significant differences in physiological traits across species, sites, and seasons.

Pearson's Correlation Coefficient®: Evaluated relationships between environmental variables (RH, canopy cover) and orchid responses (Ψ_{leaf}, gs, Fv/Fm).

Principal Component Analysis (PCA): Conducted to reduce dimensionality and identify key variables driving drought tolerance.

Multiple Regression Models: Developed to predict survival likelihood based on integrated morpho-physiological traits and microclimatic data.

RESULTS AND DISCUSSIONS

- Species with prominent pseudobulbs (Bulbophyllum, Coelogyne) retained water more effectively.
- CAM photosynthesis indicators were observed in Bulbophyllum neilgherrense.
- Orchids in shaded microhabitats showed higher chlorophyll fluorescence and lower transpiration loss.
- Polyhouse-stressed individuals exhibited temporary stomatal closure and delayed phenology but showed >80% recovery.

The data confirm that Wayanad's endemic orchids have evolved specific traits to cope with dry-season stress. Pseudobulb water storage emerged as a major adaptation, complemented by leaf cuticular thickening and reduced stomatal aperture. Orchids in higher elevation zones, such as Coelogyne nervosa, displayed superior drought tolerance, likely due to prolonged cloud cover and stable humidity.

Physiological plasticity was evident across species, especially in root morpho-anatomical traits that facilitated efficient water uptake. Microhabitat features (canopy cover, slope orientation, host tree bark moisture) played a decisive role in plant performance.

Climate simulations in polyhouse conditions highlighted the critical thresholds beyond which recovery was impaired, underscoring the risk of climate extremes surpassing adaptive limits.

CONCLUSION

This comprehensive three-year study underscores the remarkable yet fragile resilience of endemic orchids in the Wayanad region of the Western Ghats, where seasonal droughts and emerging climate anomalies threaten delicate epiphytic communities. Our research demonstrates that these orchids exhibit a range of ecophysiological adaptations—including pseudobulb water storage, thickened cuticles, velamen-rich roots, and stomatal regulation—that enable survival during seasonal dry spells. However, these adaptations are contingent upon stable microclimatic conditions, particularly shaded canopy environments, consistent humidity, and host tree integrity. The continuity of these microhabitats is now at risk due to forest fragmentation, canopy loss, and erratic weather patterns, emphasizing the urgent need for conservation strategies that reinforce ecological buffers. Therefore, we recommend the following conservation priorities: (1) **Microclimate-sensitive rewilding protocols** that mimic natural canopy and substrate conditions; (2) **Community-assisted restoration** to promote native tree cover and orchid reintroduction; and (3) **Integration of endemic orchid species into climate-smart agroforestry systems**, allowing for co-conservation in agricultural landscapes. Future research should delve into **molecular markers of stress tolerance**, as well as **orchid–mycorrhizal symbioses**, which are likely crucial for seed germination and drought survival but remain underexplored. A multidisciplinary approach combining field ecology, genomics, and restoration science will be essential to protect and sustain orchid biodiversity in the face of accelerating climate change.

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