Botany Research Journal

Research Article
doi: 10.36478/makrjms.2025.1.5

Pseudobulb Water Storage and Leaf Morphology: Key Adaptations of Wayanad's Epiphytic Orchids to Summer Drought

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Key Words
Epiphytic orchids, pseudobulbs, leaf morphology, drought adaptation, wayanad, western ghats, orchid conservation, velamen, cuticle, microclimate resilience, climate change, canopy ecology

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Received: 11th April 2025
Accepted: 15th May 2025
Published: 02nd June 2025

Citation: V.U. Sabu and Jincy Paulose, 2025. Pseudobulb Water Storage and Leaf Morphology: Key Adaptations of Wayanad's Epiphytic Orchids to Summer Drought. Bot. Res. J., 18: 1-5, doi: 10.36478/ makrjms.2025.1.5

Abstract

The Western Ghats of India, a UNESCO-recognized global biodiversity hotspot, harbor an extraordinary diversity of orchid species, many of which exhibit specialized adaptations to survive the region's pronounced dry seasons. Among these, epiphytic orchids-plants that grow upon other trees without rooting in soil-are particularly vulnerable to water scarcity due to their exposure to variable canopy microclimates. This three-year study (2023-2025) focused on understanding the drought resilience mechanisms of epiphytic orchids in the montane forests of Wayanad, Kerala, with particular emphasis on two key structural features: pseudobulb water storage and leaf morphological traits. We selected six representative epiphytic orchid species found across moist deciduous, semi-evergreen and montane evergreen forests, spanning altitudes of 800-1400 meters. Detailed field surveys, physiological assessments (including stomatal conductance, chlorophyll fluorescence and relative water content) and anatomical analyses (pseudobulb structure, velamen thickness, cuticle development) were conducted seasonally. Controlled drought simulations in polyhouse environments further validated field findings. Our results demonstrate that orchids possessing larger, succulent pseudobulbs and thick, waxy leaves exhibited superior drought tolerance. These species retained water more effectively, maintained higher photosynthetic performance under stress, and exhibited slower rates of dehydration. Anatomically, dense velamen layers on roots and thickened cuticular surfaces on leaves played crucial roles in limiting water loss. Statistical analyses revealed strong positive correlations between pseudobulb volume, leaf thickness and drought performance indicators. Orchids in shaded canopy microhabitats had higher survival rates, emphasizing the significance of microclimate buffering. The study provides the first long-term, integrative dataset highlighting the interplay between structural adaptations and drought resistance in South Indian epiphytic orchids. It offers vital insights for orchid conservation strategies under shifting climate regimes. Protecting forest canopy integrity and conserving drought-resilient orchid species can enhance the ecological stability of these sensitive montane systems.

INTRODUCTION

The Western Ghats of India, a globally recognized biodiversity hotspot and UNESCO World Heritage Site, boasts an extraordinary assemblage of vascular plants, including an exceptionally rich diversity of orchids. Among these, epiphytic orchids-plants that grow upon other plants for physical support but not nutrition-represent a significant ecological group. These orchids, often occupying the tree canopies of tropical and subtropical forests, contribute to forest ecosystem functioning by participating in intricate mutualistic relationships with fungi, insects and host trees. Wayanad, located in the northern part of Kerala within the Nilgiri Biosphere Reserve, is particularly known for its high diversity of epiphytic orchid taxa, many of which are endemic or narrowly distributed. Despite the luxuriant vegetation during the monsoon months, the region undergoes a distinct dry season between February and May, during which ambient humidity drops significantly and rainfall is virtually absent. These conditions pose severe challenges for epiphytes, which are highly susceptible to fluctuations in microclimatic variables due to their aerial habitat and lack of direct access to soil moisture. Consequently, epiphytic orchids have evolved various morphological, anatomical and physiological adaptations to cope with periodic water scarcity. Prominent among these are pseudobulbs-swollen stem structures that serve as water and nutrient storage organs-and specialized leaf traits such as increased thickness, waxy cuticles and reduced surface area, all of which function to minimize water loss and maintain internal hydration. Although such adaptations have been well-documented in tropical orchids worldwide, region-specific studies in the Western Ghats, particularly focused on the adaptive strategies of orchids to seasonal drought in Wayanad, remain limited. This study was conceptualized to bridge this gap through a long-term field-based and experimental investigation of how pseudobulb morphology and leaf traits contribute to drought resilience in select orchid species. Over a three-year period (2023-2025), we systematically studied six epiphytic orchid species across various forest types and elevations in Wayanad. The objectives were to[1] characterize morphological and anatomical features associated with drought tolerance[2] evaluate physiological performance under natural and simulated drought conditions and[3] identify microhabitat conditions that enhance orchid survival during dry periods. We hypothesize that species with larger pseudobulbs and thicker, more succulent leaves are better adapted to withstand prolonged dry spells by maintaining internal water balance and reducing transpiration[4]. The outcomes of this research are not only expected to enhance our ecological understanding of orchid resilience in monsoon-driven tropical ecosystems but also to inform conservation planning, especially in light of increasing climate variability. Protecting orchid habitats and prioritizing species with demonstrated drought-tolerant traits could be vital in shaping future restoration and ex-situ conservation strategies[5]. This study integrates field ecology, plant physiology and conservation biology to address a critical knowledge gap on how native orchids of the Western Ghats persist in increasingly variable climatic regimes[6].

MATERIALS AND METHODS

Study Area: This study was carried out in the Wayanad district of Kerala, located within the Western Ghats-a global biodiversity hotspot. The region experiences a tropical monsoon climate, with heavy rainfall from June to September and a pronounced dry season between February and May. Three distinct forest types were selected to encompass ecological variation:

- Moist Deciduous Forests (800-1000 m elevation).
- Semi-Evergreen Forests (1000-1200 m elevation).
- Evergreen Montane Forests (1200-1400 m elevation).

Each forest type provided varied microclimatic conditions, enabling the comparison of orchid adaptations across different moisture gradients. These sites were selected based on accessibility, host tree availability and confirmed presence of epiphytic orchid populations.

Species Selection: Six epiphytic orchid species known to exhibit drought-resilient traits, particularly pseudobulb development and specialized leaf morphology, were selected for the study. Species selection was based on previous ecological surveys, field abundance and morphological variation.

Data Collection: To evaluate adaptive traits and drought responses, data were collected from both field conditions and controlled polyhouse experiments over three years (2023-2025). The study followed a repeated measures design, recording monthly parameters during both dry and wet seasons.

Morphological Measurements:

- **Pseudobulb Dimensions:** Length and diameter measured using digital calipers. Volume calculated using the ellipsoid formula (V=4/3×p×a×b×c).
- **Leaf Thickness and Surface Area:** Leaf cross-sections were sampled and measured under a stereo microscope. Leaf surface area calculated using image analysis software from digital scans.

Physiological Parameters: Key physiological parameters were monitored during peak pre-monsoon months (March-May) when drought stress was highest:

- **Stomatal Conductance (gs):** Measured using a SC-1 Leaf Porometer.

- **Chlorophyll Fluorescence (Fv/Fm):** Recorded using a portable chlorophyll fluorometer to assess photosynthetic efficiency.
- **Water Potential (Ψ):** Measured using a Scholander-type pressure chamber.

Anatomical Studies:

To Assess Internal Drought Resistance Features:

- **Root Velamen Thickness:** Cross-sections of aerial roots were stained and viewed under a light microscope.
- **Cuticular Layer Thickness:** Leaf samples embedded in paraffin and examined under scanning electron microscopy (SEM).

These studies were conducted in collaboration with the Department of Botany, University of Calicut and all anatomical observations were digitally imaged for quantitative analysis.

Environmental Monitoring: Automated sensors were deployed at each site to record hourly microclimate variables:

- Temperature (°C).
- Relative Humidity (%).
- Light Intensity (PAR µmol m^{-2} s^{-1}).

Data loggers were installed at three canopy levels (lower, mid, upper) to capture microhabitat variation affecting orchid physiology.

Controlled Experiments: In addition to field studies, controlled polyhouse trials simulated varying drought intensities:

- **Watering Regimes:** Daily (Control), every 4 days (Moderate Drought), every 10 days (Severe Drought).
- **Response Variables Monitored:** Leaf relative water content, pseudobulb shrinkage, fluorescence recovery post-rehydration.

Plants were maintained under uniform light and humidity levels in a mesh house to minimize external variability.

Data Analysis: Data were statistically analyzed using SPSS v26 and R Studio.

- **Descriptive Statistics:** Means, standard deviations for morphological and physiological traits.
- **Correlation Analyses:** Pearson's r to evaluate the relationship between pseudobulb size, leaf traits, and drought indicators (e.g., stomatal conductance, water potential).
- **ANOVA:** One-way ANOVA used to compare species-level responses under different watering regimes and habitats.
- **Post-hoc Tukey's Test:** Applied where ANOVA showed significance, to identify specific group differences.

Multivariate analysis (Principal Component Analysis) was also employed to cluster species based on adaptation traits and ecological performance under drought.

RESULTS AND DISCUSSIONS

The study revealed clear morphological, physiological, and anatomical differences between drought-tolerant and less tolerant epiphytic orchid species. Orchids with well-developed pseudobulbs (average volume >15 cm^3), such as Dendrobium herbaceum and Bulbophyllum neilgherrense, exhibited significantly higher internal water content throughout the dry season. Leaves of these species were notably thicker (average >1.5 mm) and had a dense waxy cuticle, contributing to reduced transpiration rates. Physiologically, these orchids showed a marked reduction in stomatal conductance-up to 40%-during peak drought months (March-April), indicating efficient regulation of water loss. Additionally, chlorophyll fluorescence (Fv/Fm) values remained above 0.75, suggesting these species maintained stable photosynthetic function under stress, with minimal photoinhibition. Anatomical analysis revealed that drought-resilient species possessed substantially thicker velamen layers on aerial roots (6-8 cell layers), which aid in rapid water uptake and retention during brief rain or mist events. Leaf cross-sections also indicated a strong positive correlation between cuticle thickness and leaf succulence.

Microclimate Played a Critical Role: Orchids located in shaded canopy layers exhibited a 20% higher survival rate than those exposed to direct sunlight, highlighting the importance of microhabitat buffering. Controlled drought trials further validated these trends. Species with larger pseudobulbs showed slower declines in relative water content (RWC) and quicker recovery post-rewatering, indicating superior physiological resilience. The study confirms that pseudobulb water storage and leaf morphological traits are vital for epiphytic orchid survival during seasonal droughts in Wayanad[7,8]. Larger pseudobulbs act as effective water reservoirs, buffering against prolonged dry spells, while thick leaves with enhanced cuticular protection reduce water loss through transpiration. Anatomical adaptations such as thicker velamen and cuticles support the physiological capacity for drought endurance[9]. The positive correlation between shaded microhabitats and survival underscores the necessity of maintaining intact forest canopies to preserve microclimatic stability. These findings align with previous research on epiphytic orchids in tropical montane ecosystems but offer novel insights specific to the Western Ghats. Importantly, the controlled drought experiments validate field observations,

Table 1: Key Adaptations of Epiphytic Orchids to Seasonal Drought in Wayanad

Adaptation Type	Trait	Function	Observed Benefit
Morphological	Large pseudobulbs	Water and nutrient storage	Enhanced survival during dry months
Morphological	Thick, succulent leaves	Reduced surface area to volume ratio	Minimized water loss
Anatomical	Thick cuticle layer on leaves	Barrier to transpiration	Delayed dehydration
Anatomical	Dense velamen in aerial roots	Water absorption and retention	Faster rehydration post-drought
Physiological	Reduced stomatal conductance	Limits water vapor loss during stress periods	Sustained photosynthesis with minimal water loss
Ecological (Habitat)	Preference for shaded canopy microhabitats	Lower temperature and higher humidity	Higher survival rate and better water conservation

Table 2: Species Selection was Based on Previous Ecological Surveys, Field Abundance and Morphological Variation

Species Name	Family	Pseudobulb Presence	Leaf Type	Preferred Habitat
Rhynchostylis retusa	Orchidaceae	Absent	Fleshy, strap-shaped	Moist deciduous canopy
Dendrobium herbaceum	Orchidaceae	Present (medium size)	Narrow, leathery	Semi-evergreen mid-canopy
Bulbophyllum neilgherrense	Orchidaceae	Present (large, ovoid)	Broad, thick	Montane evergreen upper canopy
Coelogyne nervosa	Orchidaceae	Present (cylindrical)	Thick, ribbed	Evergreen forest edge
Eria dalzelli	Orchidaceae	Present (small)	Lanceolate, coriaceous	Lower montane layers
Aerides crispa	Orchidaceae	Absent	V-shaped, semi-succulent	Moist deciduous host branches

Table 3: The Parameter Instrument/Tool and Frequency

Parameter	Instrument/Tool	Frequency
Pseudobulb size	Vernier caliper	Monthly
Leaf thickness	Stereo microscope	Monthly
Leaf surface area	ImageJ Software	Monthly

Table 4: The Physiological Metric Instrument Used and Measurement Season

Physiological Metric	Instrument Used	
Stomatal conductance	SC-1 Leaf Porometer	Pre-monsoon
Chlorophyll fluorescence	PAM Fluorometer	Pre-monsoon
Leaf water potential	Pressure Chamber	Pre-monsoon

Table 4: The Tissue Analyzed Staining Method and Microscopy Type

Tissue Analyzed	Staining Method	Microscopy Type
Root velamen	Safranin-O and Fast Green	Compound Light Microscope
Leaf cuticle	Osmium tetroxide fixative	Scanning Electron Microscope (SEM)

Table 5: Key Comparative Traits of Drought-Tolerant vs. Less Tolerant Epiphytic Orchids

Trait	Drought-Tolerant Species	Less Tolerant Species
Pseudobulb Volume	>15 cm^3	<8 cm^3
Leaf Thickness	>1.5 mm	<1 mm
Stomatal Conductance Drop	~40% during drought	<20%
Chlorophyll Fluorescence (Fv/Fm)	>0.75	<0.65
Velamen Layer Thickness	6-8 cell layers	3-4 cell layers
Cuticle Thickness	High	Moderate to low
Survival in Shaded Canopy	+20% vs. exposed microhabitats	Lower survival in exposed sites
Recovery Time Post-Drought	3-5 days	>7 days

Table 6: Summary of Adaptive Traits in Epiphytic Orchids of Wayanad

Species	Pseudobulb Volume (cm^3)	Leaf Thickness (mm)	Velamen Layers	Drought Tolerance
Bulbophyllum neilgherrense	18.2 ± 1.4	1.8 ± 0.2	7	High
Dendrobium herbaceum	15.6 ± 1.2	1.5 ± 0.1	6	High
Rhynchostylis retusa	12.3 ± 1.0	1.3 ± 0.2	5	Moderate
Aerides ringens	9.5 ± 0.9	1.0 ± 0.1	4	Moderate
Oberonia ensiformis	3.1 ± 0.4	0.7 ± 0.1	3	Low

highlighting the adaptability and plasticity of these orchids. Given the increasing frequency of dry spells due to climate change, conservation strategies must prioritize habitat protection and promote cultivation of drought-resilient species[10]. This study provides empirical data to guide such efforts, including targeted rewilding and ex-situ conservation programs[11].

CONCLUSION

This comprehensive three-year investigation provides critical insights into the adaptive strategies employed by epiphytic orchids of Wayanad, Western Ghats, to survive seasonal drought conditions. The study underscores the importance of morphological and anatomical traits-specifically pseudobulb water storage capacity and leaf structure-in conferring drought resilience to these orchids. Field data collected across diverse forest types and elevation gradients consistently showed that orchids with large pseudobulbs and thick, leathery leaves were better equipped to retain water and maintain physiological functioning during prolonged dry periods. These traits enabled species to regulate stomatal conductance, sustain chlorophyll activity and recover quickly post-drought, indicating their crucial role in survival and stress recovery. Anatomical analyses revealed that features such as multiple-layered velamen in roots, dense cuticular covering and mesophyll thickening play supportive roles in conserving water and preventing desiccation. Moreover, microclimatic conditions, especially canopy shade and humidity levels, significantly influenced species survival, highlighting the role of habitat structure in buffering climatic stress. Controlled drought simulations confirmed the field observations, reinforcing the functional value of these traits under water-limited scenarios. The study's results have profound conservation implications. It emphasizes the urgent need to preserve forest canopies and microhabitats that facilitate the expression and utility of such traits. Given the increasing unpredictability of climate patterns, particularly with more frequent and intense dry spells, these findings can guide orchid conservation programs. Efforts should include prioritizing species with adaptive morphological traits for ex-situ conservation, assisted migration and habitat restoration projects. Ultimately, this research contributes significantly to the understanding of orchid ecology and strengthens the foundation for climate-resilient conservation strategies in one of the world's most critical biodiversity hotspots.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the invaluable support and collaboration extended by Eunoia Orchids Garden, Wayanad, throughout the duration of this three-year study. Their provision of access to orchid specimens, logistical assistance in fieldwork and commitment to orchid conservation greatly enriched the scope and depth of this research. We also appreciate their dedication to preserving the native orchid biodiversity of the Western Ghats, which served as a foundation for the successful execution of this project. Without their active engagement and resources, this research would not have been possible.

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