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Microenvironmental drivers and phorophyte associations shaping the distribution of the national orchid *Cattleya trianae* in an educational campus of Colombia

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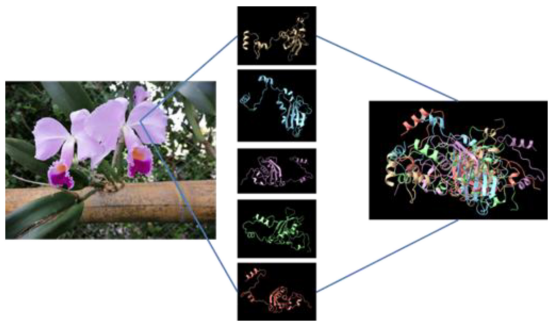
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Epiphytic orchids, which represent between 67 and 70% of the Orchidaceae family, have developed remarkable adaptations to thrive in irregular canopy environments in tropical and subtropical forests. *Cattleya trianae*, in particular, shows different zones of spatial distribution in urban sites due to anthropogenic actions, which have been little studied. This research article shows the relationship between microenvironmental characteristics and distribution in five different zones characterizing orchid diversity including an urban forest in the municipality of Garzón, Colombia. In the present study a systematic stratified sampling design was implemented, taking into account two heights (1.5 and 3.5 m) for microclimatic parameters in the phorophytes. Multivariate analyses revealed that the abundance of *Cattleya trianae* was significantly correlated with microenvironmental conditions, particularly relative humidity (> 80%) and moderate temperatures (~23°C) daily averages during specific seasonal winter peaks. In the case of the correspondence analysis, significant associations were found between the characteristics of the phorophytes (texture and canopy architecture) and *Cattleya trianae*. In addition, the highest abundance of orchids above 40 individuals/10 m^2 was found in areas with higher dew rates (0.15 mm/h). This provides important information for the conservation of the orchid *Cattleya trianae* in urban environments and contributes to the understanding of the factors that influence the spatial distribution of the orchid *Cattleya trianae* in ecosystems modified by humans.

KEYWORDS
***Cattleya trianae*, microenvironment, orchid conservation, phorophyte, urban forest**

1 Introduction

The Orchidaceae family is the largest in the world, with an estimated 27,000–30,000 species of flowering plants (Chase et al., 2015). Between 67 and 70% are epiphytes, such as *Cattleya trianae* (Figure 1; Bogar et al., 2024; Jiménez-López et al., 2026; Rosa-Manzano et al., 2014; Wu et al., 2024). Orchids are found in different ecosystems around the world,



Graphical Abstract

Cattleya trianae voucher ORDNA00703 ribulose-1,5-bisphosphate carboxylase/oxygenase large subunit (rbcL) gene, partial cds; chloroplast.

mainly in tropical and subtropical forests (Cortés-Anzúres et al., 2020; Jiménez-López et al., 2026; Liu et al., 2014; Yu and Xu, 2007).

The diversity of orchids in tropical America is greater than in other regions of the world, with the northwestern part of South America hosting the highest concentration of species of these plants (Bogar et al., 2024; Forero et al., 2020). Their occurrence in epiphytic habitats reflects species-specific evolutionary adaptations rather than a facultative response to water availability. Epiphytic orchids possess structural and physiological traits that allow them to cope with the heterogeneous and often intermittent water supply typical of the canopy. In this context, environmental variables such as air temperature, relative humidity, and light availability (PPFD) influence microhabitat conditions and may affect species performance and distribution. Pollination interactions with specific animal assemblages are ecologically relevant for reproduction but are independent of the epiphytic growth habit (Ai et al., 2023; Cadena Vargas et al., 2020; Carmona et al., 2025; Fay and Bachman, 2025; Swarts and Dixon, 2009; Wraith and Pickering, 2017a, 2017b).

Globally, orchids face unprecedented levels of threat, with most species at risk of extinction due to the small size of their populations (Ai et al., 2023; Cadena Vargas et al., 2020; Swarts and Dixon, 2009). In Colombia, orchids are present in almost all natural environments (Forero et al., 2020). Despite their distribution across different regions, they top the list of botanical families with the most species in danger of extinction (Calderón, 2007; Forero et al., 2020).

The *Cattleya trianae*, commonly known as "Flor de Mayo," was declared Colombia's national flower in 1936 due to its striking morphology and coloration. Beyond its cultural significance, this species is of particular interest because it is endemic to Colombia and exhibits notable ecological specialization across different ecosystems, especially in inter-Andean valleys and tropical dry forests. Its distribution, phenotypic variation, and adaptation to specific microenvironmental conditions make it a valuable model for studying plant–environment interactions and conservation in fragmented habitats (Aldana-Jauregui et al., 2026; WWF, 2018). However, the situation is particularly worrying due to two main factors: the high degree of endemism of Colombian orchids and the rapid transformation of their natural habitats into areas used for activities such as agriculture, livestock farming, and urbanization (Forero et al., 2020; Hernández-Rivera et al., 2024; Rica et al., 2007).

Currently, more than half of the world's population lives in cities, and at least two-thirds are projected to live in urban environments by 2025, especially in developed countries (United Nations, 2019). This has caused a reduction and fragmentation of the original forests, modifying climatic conditions, especially sudden changes in temperature and alterations in precipitation, thereby altering the availability of biological resources (Biella et al., 2022; Theodorou et al., 2020). Likewise, epiphytic life poses unique challenges for orchids, especially for the species *Cattleya trianae*, such as irregular water and nutrient supply, exposure to extreme light and temperature conditions, habitat disturbances due to human activities or global warming, and the need for specific interactions with pollinators (Ai et al., 2023; Phillips et al., 2020; Wraith and Pickering, 2019). Epiphytic orchids have evolved a suite of structural and physiological adaptations that enable them to cope with the heterogeneous and often limiting conditions of the canopy environment, including specific requirements for light, humidity, temperature, and ventilation (Granados-Sanchéz et al., 2007). These adaptations are not unique to a single species but are shared across many epiphytic taxa, allowing them to optimize water use, regulate microclimatic exposure, and maintain physiological performance under fluctuating environmental conditions. Understanding these adaptive mechanisms is essential not only for appreciating the diversity and resilience of epiphytic plants, but also for informing conservation and cultivation strategies for these ecologically significant species.

Previous studies have identified consistent environmental and structural patterns influencing the richness and distribution of epiphytic orchids across spatial gradients (Djordjević et al., 2022; Timsina et al., 2021). In general, orchid richness tends to decline under conditions of high temperature, reduced vegetation cover, and increased environmental stress, which limit suitable microhabitats in the canopy. Conversely, higher species richness is associated with intermediate and more stable environmental conditions, including adequate relative humidity, moderate temperatures, and sufficient light availability.

At the local scale, host tree characteristics such as canopy architecture and bark texture also play a crucial role by influencing water retention, substrate stability, and microclimatic buffering. These relationships often result in a unimodal (hump-shaped) pattern of species richness along environmental gradients, where diversity peaks under optimal conditions and decreases toward more extreme environments (Djordjević et al., 2022; Timsina et al., 2021; Zhang S. B. et al., 2015).

The study was conducted at the La Presentación Cooperative School, located in the municipality of Garzón, Huila, Colombia. The study area covers approximately 25,000 m^2 and includes green spaces with planted and remnant trees that serve as phorophytes for epiphytic species. Within this area, individuals of Cattleya trianae were recorded at different locations on host trees. The site is characterized by heterogeneous canopy conditions, including variations in light availability, temperature, and relative humidity, which generate a range of microhabitats. These conditions allow for the evaluation of the distribution of epiphytic orchids in relation to environmental and structural variables (Banderas Villate and Ramos Cerón, 2021; Guarnizo Lozada et al., 2019).

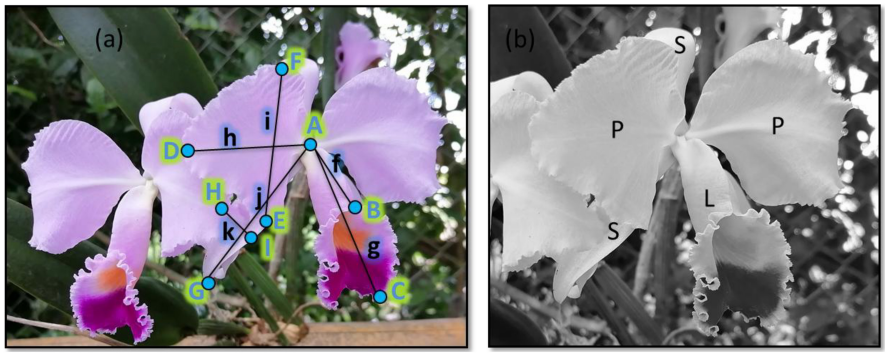


FIGURE 1
Cattleya trianae orchid. **(a)** Measurements of the parts of an orchid. **(b)** Parts: sepal (S), petal (P), and lip (L).

To date, there have been no studies on the *Cattleya trianae* orchid in the municipality of Garzón. Therefore, this study aims to fill that gap by identifying the relationship between microenvironmental characteristics and the identification of phorophytes in five different areas, characterizing the distribution and diversity of *Cattleya trianae* orchids, including an urban forest in the municipality of Garzón, Huila.

This work not only contributes to knowledge about the ecology of *Cattleya trianae* epiphytic orchids in urban environments but also provides crucial information for the effective conservation of this species. The results of this research are significant in contributing to Sustainable Development Goal 15 (SDG 15), "Life on Land" (ONU, 2022), which focuses on the sustainable management of terrestrial ecosystems, land restoration, and the prevention of biodiversity loss. In this sense, the management and conservation of species such as *Cattleya trianae*, and possibly other species from ecosystems that have been modified by human intervention, is essential in the context of climate change and increasing urbanization. Furthermore, the study lays the groundwork for future research on the adaptability of species to urbanization and, therefore, contributes to our overall understanding of species resilience in the face of ecosystem anthropization.

Despite increasing interest in epiphytic orchid ecology, the environmental and structural factors influencing their local abundance remain insufficiently understood, particularly in fragmented and anthropogenic landscapes. In this context, the present study addresses the following research question: Which environmental and host tree characteristics determine the abundance of Cattleya trianae in the study area?

Accordingly, the main objective of this study was to evaluate the relationship between microenvironmental variables (e.g., temperature, relative humidity, and light availability) and host tree traits (e.g., bark texture and canopy structure) with the abundance of Cattleya trianae.

Based on ecological theory of epiphytic plants, which highlights the importance of moisture availability, microclimatic stability, and substrate characteristics for establishment and persistence, we hypothesized that the abundance of Cattleya trianae is positively associated with higher relative humidity and greater bark stability of phorophytes, and negatively associated with higher temperatures and reduced canopy cover.

2 Materials and methods

2.1 Study area

This study was conducted in the municipality of Garzón, Huila, Colombia (2°11'24.23"N, −75°37'36.471"W); at an elevation of 850 m above sea level (Figure 2). The climate in Garzón is varied, influenced by altitude, topography, wind, and rainfall. The rainy season extends from April to May and from October to December, although sporadic rainfall also occurs during the rest of the year, which is considered the dry season. The territory is divided into warm (4.1 km^2), temperate (369.11 km^2), cold (584.68 km^2), and bioclimatic moorland (380.39 km^2) thermal zones (IGAC, 2019; Spark, 2020). This thermal heterogeneity is relevant because it reflects strong spatial variation in temperature and humidity regimes, which directly influence the distribution of vegetation types and the availability of suitable microhabitats for epiphytic species. In particular, these gradients provide a broader environmental context for understanding local microclimatic conditions and their potential effects on the abundance and distribution of epiphytic orchids.

In this context, the La Presentación Cooperative School represents a semi-natural environment that combines managed green areas with elements of native vegetation. The study area covers approximately 2.5 hectares and includes trees that serve as phorophytes for epiphytic species. Individuals of Cattleya trianae present in the area were intentionally introduced several decades ago as part of educational and conservation initiatives rather than originating from natural populations (Banderas Villate and Ramos Cerón, 2021). While this managed origin may influence large-scale distribution patterns, it provides a controlled framework to evaluate how microenvironmental variables (e.g., temperature, relative humidity, and light availability) and host tree characteristics affect the local abundance and persistence of the species. Therefore, this study does not aim to infer natural distribution patterns, but rather to assess the species'

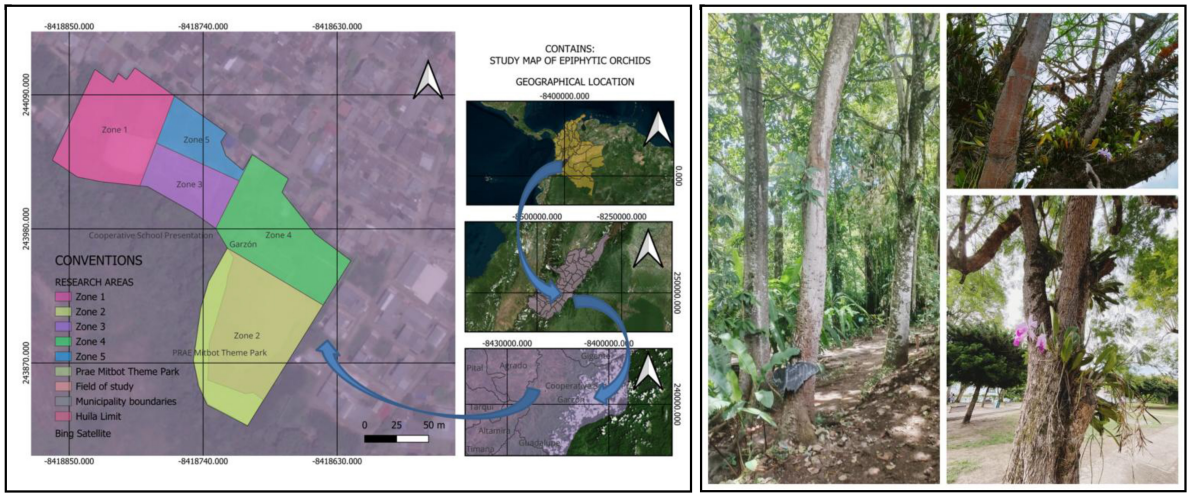


FIGURE 2
Study site. Orchids were studied in five areas of La Presentación Cooperative School. **(a)** Study site. **(b)** Types of vegetation. The type of vegetation was named by synthesizing all the natural areas present in each zone.

ecological responses and adaptive performance under semi-natural conditions with anthropogenic influence.

2.2 Sampling design

A systematic stratified sampling design was implemented to capture spatial and environmental variability within the study area, which is semi-natural and artificial. Zone 1, covering 6,153 m^2, comprises a mature wooded area, a school garden, and a sports field. Zone 2, covering 8,568 m^2, includes a mixed vegetation zone, a riparian area next to a small stream, and a sports field. Zone 3, with 2,061 m^2, consists of the forest edge and artificial infrastructure. Zone 4, covering 6,086 m^2, consists of green areas, gardens, and infrastructure. Finally, Zone 5, covering 2,150 m^2, contains gardens, ornamental plants, and a parking area. This division allows for a detailed characterization of the different ecosystems and spaces within the study area.

In each zone, *Cattleya trianae* orchids were found, and linear transects were established using the modified line intercept sampling method (Artigas and Del Olmo, 2013). Three 50-m transects were laid out in each zone, oriented randomly but maintaining a minimum distance of 20 m between them to ensure the independence of the samples.

Along each transect, all trees with a diameter at breast height (DBH) > 10 cm that were within a 2 m strip on either side of the transect line were examined (resulting in a sampling area of 200 m^2 per transect). The sampling height extended up to 3 m from the ground, using binoculars and an extendable pole to observe the highest branches (Artigas and Del Olmo, 2013). To ensure adequate temporal coverage and capture seasonal variability, sampling was conducted in two periods: one during the dry season (January-February) and another during the rainy season (April-May). Each sampling period lasted 4 weeks, with weekly visits to each area.

To minimize observer bias, a team of four researchers was formed, who rotated between the different areas and transects. Before the study began, a calibration phase was carried out in which all researchers jointly sampled several test transects to standardize observation and recording methods. An individual accumulation curve was constructed to assess sampling adequacy, plotting the cumulative number of Cattleya trianae individuals against the sequential number of surveyed host trees, ordered by zone.

The areas were monitored to observe the dynamics of orchid populations. In addition, they were geo-referenced using a high-precision GPS (Garmin GPSMAP 66sr) to facilitate future follow-up studies. To complement the transect data and capture rare or hard-to-detect species, random searches were conducted in each area, dedicating an additional 2 h per area in each sampling period.

This sampling design allowed us to obtain robust quantitative data on the abundance and distribution of *Cattleya trianae* orchids, as well as detailed information on their microhabitat preferences and the characteristics of the phorophytes that host them.

2.3 Field sampling

Sampling was carried out at the facilities of School Cooperative La Presentación, a private educational institution. Permission for sampling was obtained from the school administration for the purpose of conducting the research. Taxonomic identification of the phorophytes and the *Cattleya trianae* orchid was based on taxonomic keys and confirmed through peer review with botanical experts.

During the flowering season, individuals of Cattleya trianae were surveyed along the established transects. Only adult individuals were quantified, using the presence of flowers as a criterion for maturity. Juvenile individuals and seedlings were recorded but not included in abundance analyses due to the difficulty in reliably determining their developmental stage in the field.

To assess microenvironmental conditions, measurements were conducted on a representative subset of host trees

(phorophytes) selected within each transect, based on the presence of Cattleya trianae and variation in canopy structure. Measurements were taken at two height levels (1.5 and 3.5 m) on each selected tree to characterize the immediate microenvironment experienced by the orchids.

Air temperature and relative humidity were measured using HMP35C-L sensors (Vaisala Campbell Scientific, Inc., Logan, Utah), installed within fan-aspirated radiation shields (model Met One Instruments 076B Aspirated Radiation Shield, Met One Instruments, Inc.), which minimize radiation-induced heating and improve measurement accuracy under low wind and high solar radiation conditions typical of tropical environments (Andrade, 2003; Jones, 1992). Vapor pressure deficit (VPD) was calculated following Jones (1992). Leaf temperature was determined using thermocouples placed on the abaxial surfaces of leaves. The dew deposition rate was estimated using the method described by Andrade (2003).

These measurements characterize the immediate microenvironment at the level of the host tree (phorophyte microhabitat). To provide a reference for broader atmospheric conditions, additional sensors were installed above the canopy to record PPFD, air temperature, relative humidity, and dew duration.

All sensors were connected to data loggers (CR21X and CR10X, Campbell Scientific), which recorded 10-min averages over periods of 6–10 days in each vegetation type, covering the wet, early dry, and dry seasons.

2.4 Data analysis

Statistical analyses were performed using InfoStat version 2020 with installed R libraries. Before performing the analysis, the normality of the data was evaluated using the Shapiro–Wilk test and homoscedasticity was assessed using the Levene test. All environmental variables (air temperature, relative humidity, vapor pressure, leaf temperature, dew rate, PPFD, and dew duration) showed significant deviations from normality (Shapiro–Wilk, $W < 0.82$, $p < 0.001$ for all variables), and orchid abundance also departed from normality ($W = 0.613$, $p < 0.001$). Levene's test confirmed homoscedasticity for all environmental variables ($F < 0.80$, $p > 0.05$), but not for orchid abundance ($F = 3.13$, $p = 0.029$). Therefore, all environmental variables and orchid abundance were log(x+1)-transformed prior to analysis, and non-parametric Kruskal–Wallis tests were used in place of parametric ANOVA for between-zone comparisons.

Kruskal–Wallis tests revealed significant differences among zones for all environmental variables ($H > 80$, $p < 0.001$ for temperature, relative humidity, vapor pressure, leaf temperature, dew rate, PPFD, and dew duration). Orchid abundance did not differ significantly among zones ($H = 5.22$, df = 4, $p = 0.265$). Total abundance of Cattleya trianae individuals across all zones was 113 individuals recorded on 102 host trees. Zone 1 had the highest abundance (51 individuals on 18 trees; mean = 8.50 ± 9.14 individuals/tree), followed by Zone 5 (28 individuals on 30 trees; mean = 2.80 ± 2.20), Zone 2 (17 individuals on 27 trees; mean = 1.89 ± 1.76), Zone 4 (13 individuals on 18 trees; mean = 2.17 ± 2.40), and Zone 3 (4 individuals on 9 trees; mean = 1.33 ± 0.58). Pairwise Mann–Whitney comparisons showed no statistically significant differences between individual zones (all $p > 0.09$), consistent with high individual-level variability within zones.

To group host trees according to structural similarity and identify phorophyte traits associated with higher orchid abundance, a hierarchical cluster analysis was performed. A data matrix was constructed including the structural characteristics of each phorophyte recorded across the five study zones. For the characterization of the phorophytes, attributes such as diameter at breast height (DBH), bark texture (smooth, rough, fissured, or scaly), and canopy architecture (closed, open, stratified, patch, gallery) were considered.

For data processing, the hierarchical clustering method was used, employing Ward's algorithm (Ward.D2 method) with a Euclidean distance matrix. This method was selected for its ability to minimize variance within groups and maximize variance between groups. Prior to analysis, quantitative variables were standardized (z-score normalization) to eliminate the effect of different measurement scales; specifically, diameter at breast height (DBH), dew deposition rate (mm/h), and photosynthetic photon flux density (PPFD) were standardized before clustering.

The optimal number of clusters was determined using two complementary criteria: the cophenetic correlation coefficient (CPC, values ≥ 0.8 indicate good dendrogram fit; Sokal and Rohlf, 1962) and the Cubic Clustering Criterion (CCC), which identifies local maxima corresponding to cluster solutions that maximize between-group variance relative to within-group variance (Sarle, 1983). When both criteria converged, that solution was selected; when they diverged, the dendrogram structure and biological interpretability guided the final decision (Sokal and Rohlf, 1962). A cutoff point was established in the dendrogram based on the distance that maximized the differences between groups while maintaining an interpretable number of clusters.

To validate the robustness of the groups formed, a multivariate analysis of variance (MANOVA) was performed with the original variables. Additionally, the R-squared was calculated to determine the proportion of variability explained by the classification obtained. The results were visualized as a dendrogram color-coded by botanical family, which allowed the identification of whether taxonomically related host trees also shared structural characteristics relevant to orchid establishment (e.g., similar bark texture or canopy architecture). This facilitated the ecological interpretation of the cluster groups.

To find the relationship between the distribution of *Cattleya trianae* orchids and environmental variables, a Principal Component Analysis (PCA) was performed. Data standardization was performed prior to PCA to account for different measurement scales. Air temperature, relative humidity, vapor pressure deficit (VPD), leaf temperature, photosynthetic photon flux density (PPFD), and dew deposition rate were the environmental variables included in the analysis.

Correspondence analysis (CA) was implemented to evaluate associations between the occurrence of Cattleya trianae individuals and phorophyte characteristics (zone, tree species, bark texture, and canopy architecture), and the significance of these associations was assessed using Pearson's chi-square test.

Spatial analyses were performed using QGIS 3.34.1 software to produce geo-referenced maps of orchid abundance per zone, visualize phorophyte cluster distribution across the study area, and identify spatial patterns in microenvironmental conditions. Maps

were created using the "tmap" package in R. Statistical significance was set at $\alpha = 0.05$ for all analyses.

3 Results

3.1 Identification of phorophytes with *Cattleya trianae* orchids

A total of 20 phorophyte records belonging to five botanical families were identified across the five study zones (Table 1). Bignoniaceae and Fabaceae were the most represented families (5 and 6 records, respectively), followed by Anacardiaceae (3), with Rutaceae and Araucariaceae each represented by one record. Leaf temperature and PPFD varied significantly among zones ($H > 80$, $p < 0.001$), with higher values in zones 2, 3, and 4 (Table 2).

Leaf temperatures were consistently lower than ambient air temperature across all zones (Table 2), with the greatest difference recorded in zones 2–4 where air temperatures were highest (Table 3). This pattern is consistent with transpiratory cooling in epiphytic plants (Jones, 1992; Larcher, 2003).

3.2 Incidence curve

The individual accumulation curve (Figure 3) shows the cumulative number of Cattleya trianae individuals across 102 surveyed host trees. A total of 113 individuals were recorded. The curve reveals a steep initial increase in Zone 1 (trees 1–18, accumulating 51 individuals), followed by a plateau across Zones 2 and 3, a secondary increase in Zones 4–5, and an asymptotic trend toward the final trees, indicating adequate sampling coverage.

3.3 Morphological characterization of *Cattleya trianae* orchids

Floral measurements of Cattleya trianae individuals recorded at La Presentación Cooperative School are presented in Figure 4. The dorsal sepal measured 9.67 ± 0.33 cm (length) × 2.52 ± 0.28 cm (width); petals were larger (10.14 ± 0.46 × 6.61 ± 0.015 cm) and more conspicuous. The column (10.98 ± 0.43 × 1.07 ± 0.08 cm) contains both reproductive organs, and the lip (9.0 ± 0.02 × 7.01 ± 0.08 cm) exhibits vivid coloration serving as a pollinator landing platform. These dimensions are consistent with reported values for the species (Forero et al., 2020; Mercado and Contreras, 2017).

3.4 Microenvironmental characteristics

Table 3 summarizes the microenvironmental conditions recorded across the five study zones and at two sampling heights (1.5 and 3.5 m) on host trees of *Cattleya trianae*. The parameters measured included air temperature, relative humidity, vapor pressure deficit (VPD), leaf temperature, dew deposition rate, photosynthetic photon flux density (PPFD), dew duration, and orchid abundance. These variables provide a detailed characterization of the microclimatic heterogeneity within the urban forest and allow the identification of environmental conditions most favorable for orchid establishment. The table highlights contrasts among zones, particularly the higher humidity, longer dew duration, and moderate temperatures observed in zones 1 and 5, which were associated with greater orchid abundance compared to the drier and warmer conditions in zones 2, 3, and 4.

Hierarchical cluster analysis (Ward.D2, Euclidean distance) grouped the 20 phorophyte records into four conglomerates (Figure 5). Conglomerate 1 comprised species with smooth bark and closed or open canopies (e.g., Acacia mangium, Tabebuia nodosa). Conglomerate 2 included species with intermediate bark and stratified canopies (Tabebuia rosea, Fagus sylvatica). Conglomerate 3 grouped rough-bark species with closed canopies (Samanea saman). Conglomerate 4 included species with rough bark and stratified canopies (Araucaria heterophylla, Anacardium excelsum). Conglomerates 3 and 4, associated with rough or intermediate bark, corresponded to zones 1 and 5 where orchid abundance was highest.

Principal Component Analysis (PCA) (Figure 6) illustrates the relationship between environmental variables and the distribution of *Cattleya trianae* orchids. The vectors in the graph indicate the direction and magnitude of the influence of each environmental variable, while the distribution of the points reveals the correlations between the different study areas and microenvironmental conditions.

The first principal component (PCA1) captured 99.9% and PCA2 captured 0.1% of the total variance. This concentration of variance in a single axis reflects the strong thermodynamic interdependence among the measured variables: air temperature, relative humidity, vapor pressure deficit, and dew rate are physically coupled and tend to covary strongly when environmental gradients between zones are stark (as in this study, where zones 1–5 represented a near-binary contrast between cool-humid and warm-dry conditions). While this result limits the independent contribution of each variable to the analysis, PCA1 effectively captures a single moisture-temperature gradient along which orchid abundance is clearly associated.

Therefore, relative humidity and dew are essential variables for the abundance of *Cattleya trianae*, as humid and stable microhabitats are the most recommended. This is similar to what has been reported in studies indicating that the availability of moisture, i.e., dew, is key to the survival of epiphytic orchids in dry tropical forests (Rosa-Manzano et al., 2014). In addition, variables such as vapor pressure deficit and humidity also act as driving forces for transpiration, affecting water dynamics in epiphytic species (Tobo et al., 2010; Zhang S. B. et al., 2015).

Cluster A (zones 2, 3, and 4) was characterized by relative humidity between 65 and 68%, temperatures above 27.2°C, PPFD between 520 and 565 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and low orchid abundance (mean = 1.33–2.17 individuals/tree). Cluster B (zones 1 and 5) showed relative humidity > 80%, moderate temperatures (~23°C), dew deposition rate > 0.15 mm/h, and high orchid abundance (mean = 2.80–8.50 individuals/tree).

In the biplot, the vectors of the environmental parameters indicate that the abundance of *Cattleya trianae* is positively associated with relative humidity and dew duration, and negatively associated with air temperature and vapor pressure deficit.

TABLE 1 List of species identified as phorophytes present on *Cattleya trianae* orchids in each study area.

Zone	Common name	Scientific name	Family	Bark texture	Canopy architecture
1	Gualanday	Jacaranda mimosifolia	Bignoniaceae	Smooth	Stratified
1	Ocobo Flor Morada	Tabebuia rosea	Bignoniaceae	Intermediate	Stratified
1	Acasio	Acacia mangium	Fabaceae	Smooth	Closed
1	Limón swinglea	Swinglea glutinosa	Rutaceae	Smooth	Closed
2	Ocobo Flor Morada	Tabebuia rosea	Bignoniaceae	Intermediate	Stratified
2	Hoja de cobre	Fagus sylvatica f. purpurea	Fagaceae	Intermediate	Stratified
2	Mango tree	Mangifera indica	Anacardiaceae	Intermediate	Stratified
2	Totumo	Crescentia cujete	Bignoniaceae	Intermediate	Open
2	Palo cruz	Tabebuia nodosa	Bignoniaceae	Smooth	Open
3	Gualanday	Jacaranda mimosifolia	Bignoniaceae	Smooth	Stratified
3	Mango tree	Mangifera indica	Anacardiaceae	Intermediate	Stratified
3	Saman	Samanea saman	Fabaceae	Rough	Closed
4	Araucaria	Araucaria heterophylla	Araucariaceae	Rough	Stratified
4	Mango tree	Mangifera indica	Anacardiaceae	Intermediate	Stratified
4	Zapote	Manilkara zapota	Sapotaceae	Smooth	Stratified
4	Carbonero	Pseudosamanea carbonaria	Fabaceae	Intermediate	Stratified
5	Saman	Samanea saman	Fabaceae	Rough	Closed
5	Cachingo	Erythrina poeppigiana	Fabaceae	Smooth	Open
5	Caracoli	Anacardium excelsum	Anacardiaceae	Smooth	Stratified
5	Saman	Samanea saman	Fabaceae	Rough	Closed

TABLE 2 Vertical and spatial variation of leaf temperature (°C) and PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$) across five study zones.

Parameter	Height (m)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Leaf temperature (°C)	1.5	22.8 ± 1.0	26.2 ± 1.3	26.8 ± 1.6	26.4 ± 1.5	23.2 ± 1.1
	3.5	22.3 ± 0.9	25.7 ± 1.2	26.3 ± 1.5	25.9 ± 1.4	22.7 ± 1.0
PPFD ($\mu mol \cdot m\ m^{-2} \cdot s^{-1}$)	1.5	285 ± 45	520 ± 75	565 ± 85	545 ± 80	295 ± 50
	3.5	380 ± 55	680 ± 85	725 ± 95	695 ± 90	385 ± 60

Values represent means ± standard deviation (n = 144 measurements per day for 6–10 days). PPFD = Photosynthetic photon flux density. Data represent averages from all stations.

TABLE 3 Microenvironmental conditions measured in different areas and at two heights on host trees.

Parameter	Height (m)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Air temperature (°C)	1.5	23.4 ± 1.2	26.8 ± 1.5	27.2 ± 1.8	26.9 ± 1.7	23.8 ± 1.3
	3.5	22.8 ± 1.1	26.2 ± 1.4	26.8 ± 1.7	26.5 ± 1.6	23.2 ± 1.2
Relative humidity (%)	1.5	85.6 ± 3.2	68.4 ± 4.1	65.3 ± 4.8	67.3 ± 4.6	83.3 ± 3.5
	3.5	82.3 ± 3.5	65.1 ± 4.3	62.7 ± 4.6	64.7 ± 4.4	80.7 ± 3.3
Vapor pressure (kPa)	1.5	0.42 ± 0.05	1.12 ± 0.11	1.25 ± 0.13	1.18 ± 0.12	0.48 ± 0.06
	3.5	0.48 ± 0.06	1.19 ± 0.12	1.32 ± 0.14	1.25 ± 0.13	0.54 ± 0.07
Dew deposition rate (mm/h)	1.5	0.18 ± 0.02	0.08 ± 0.01	0.06 ± 0.01	0.07 ± 0.01	0.16 ± 0.02
	3.5	0.15 ± 0.02	0.06 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	0.14 ± 0.02
Dew duration (h/day)	1.5	5.8 ± 0.6	3.2 ± 0.4	2.8 ± 0.3	3.0 ± 0.4	5.5 ± 0.5
	3.5	5.2 ± 0.5	2.8 ± 0.3	2.4 ± 0.3	2.6 ± 0.3	5.0 ± 0.5
Orchid abundance (individuals/tree)	–	8.50 ± 9.14	1.89 ± 1.76	1.33 ± 0.58	2.17 ± 2.40	2.80 ± 2.20

Values represent means ± standard deviation (n = 144 measurements per day for 6–10 days). VPD, Vapor pressure deficit. Data represent averages from all stations.

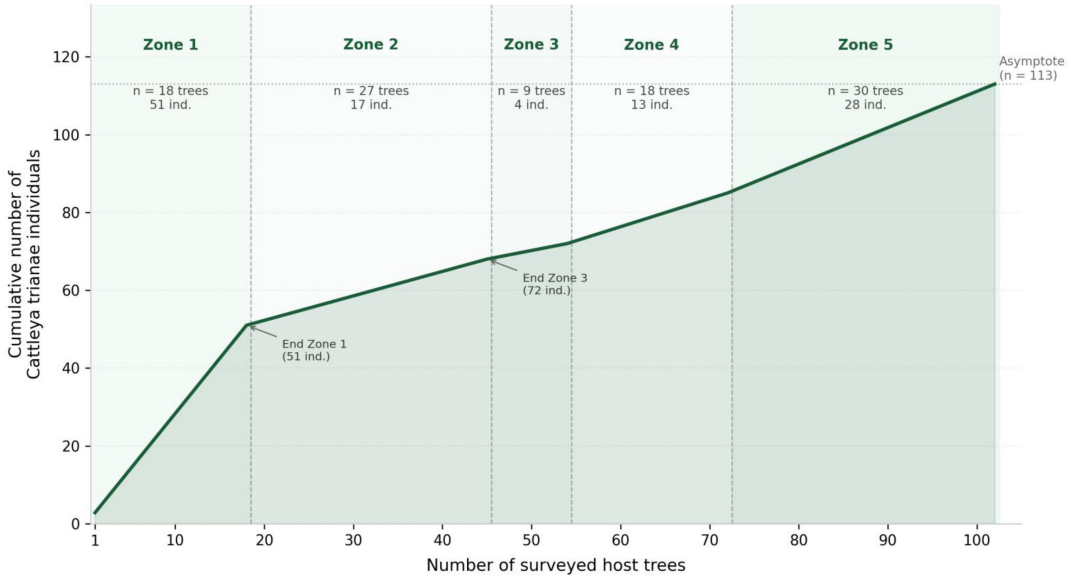


FIGURE 3
Individual accumulation curve of Cattleya trianae across 102 surveyed host trees in five study zones. The asymptotic trend indicates adequate sampling coverage.

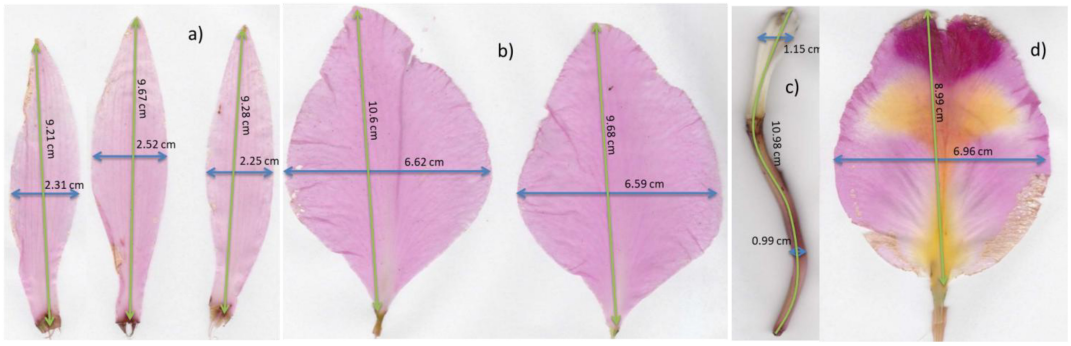


FIGURE 4
Characterization of the parts of the *Cattleya trianae* orchid. The four parts of the orchid from La Presentación Cooperative School were investigated. **(a)** Sepals. **(b)** Petals. **(c)** Column. **(d)** Lip or lower petal.

Therefore, microenvironmental conditions play an important role in the distribution of this type of orchid, with microhabitats where there are higher humidity levels and moderate temperatures.

The principal component analysis of the structural characteristics of the phorophytes and their relationship with the presence of *Cattleya trianae* orchids (Figure 7) revealed significant patterns. With the first two components explaining 97.1% of the total variance, PCA1 is accounting for 87.6% and PCA2 accounting for 9.5%, indicating a high representativeness of the analysis.

The first principal component, PCA1, showed the highest proportion of variance with a strong positive correlation between the numbers of orchids and flowering orchids, growing orchids, dry orchids, number of shoots, and diameter of the host tree trunk. This suggests that larger-diameter phorophytes provide more surface area and better microhabitats for orchid establishment, and this relationship was mainly seen in zones 1 and 5, where greater abundance was recorded, which is consistent with studies that point to the importance of tree architecture and size in epiphytic orchids (Benzing and Ohio, 1990; Zotz, 2016).

In the case of the main component PCA2, it was mainly defined by the number of leaves and growing orchids, showing a significant negative correlation between both variables. This indicates that fewer leaves or lower leaf density favors the number of growing orchids, possibly due to greater light availability and more favorable microclimatic conditions under a less dense canopy (Cardelús and Mack, 2010; Laube and Zotz, 2006).

The correspondence analysis (Figure 8) revealed significant associations between phorophyte characteristics (bark texture and canopy architecture) and Cattleya trianae occurrence ($\chi^2 = 14.39$, df = 4, $p = 0.006$). The first axis (Axis 1) explained 68.0% of the total inertia, and the second axis (Axis 2) explained the remaining 32.0%, together accounting for 100% of the variation in the contingency table. These percentages are shown on the respective axes of Figure 8.

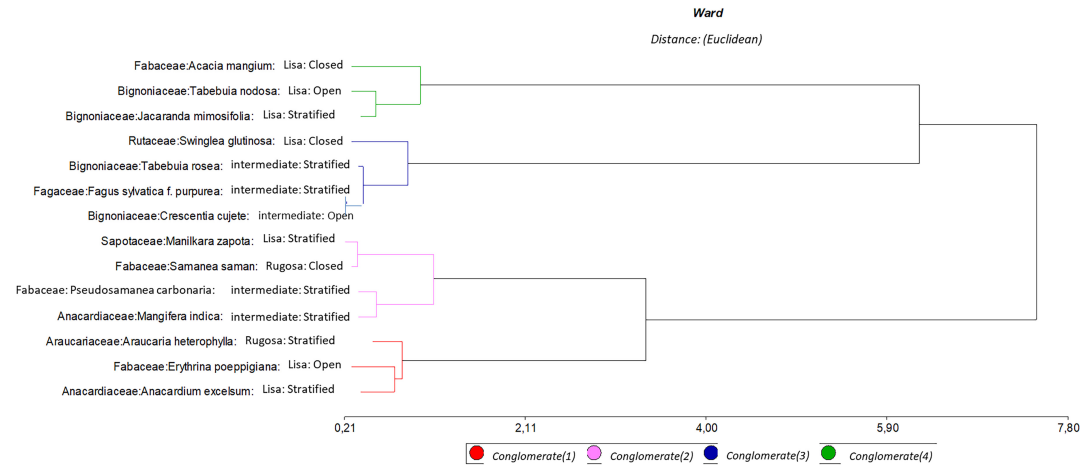


FIGURE 5
Cluster analysis of phorophytes.

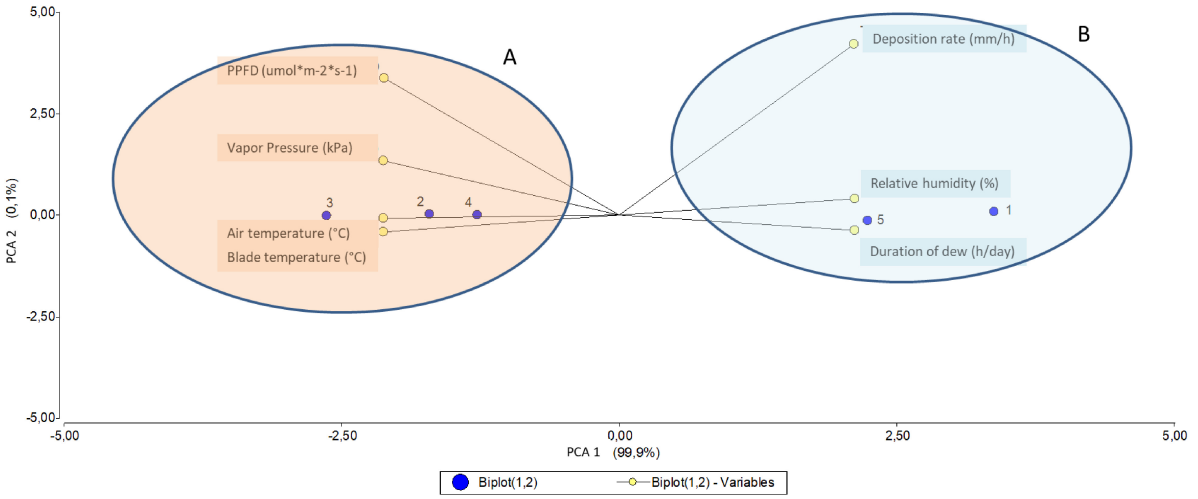


FIGURE 6
Principal component analysis of microenvironmental conditions in the five zones. **(A)** Cluster of variables associated with warm-dry conditions (PPFD, vapor pressure, air temperature, blade temperature). **(B)** Cluster of variables associated with cool-humid conditions (deposition rate, relative humidity, duration of dew).

Group A includes zone 1 and 3 with trees such as the saman (*Samanea saman*), swinglea lemon (*Swinglea glutinosa*), and gualanday (*Jacaranda caucana*) with rough bark textures and a closed canopy architecture.

Group B includes zone 2 and 4, with the presence of araucaria (*Araucaria heterophylla*), sapote (*Pouteria sapota*), totumo (*Crescentia cujete*), carbonero (*Calliandra pittieri*), mango (*Mangifera indica*), ocobo de flor morada (*Tabebuia rosea*), and hoja de cobre (*Brownea ariza*), with medium bark texture and a stratified canopy architecture.

Group C, where Zone 5 is located, contains caracolí (*Anacardium excelsum*), cachingo (*Erythrina poeppigiana*), and palo cruz (*Tabebuia aurea*), with smooth texture and open canopy architecture.

Therefore, the results show that *Cattleya trianae* has a greater affinity with phorophytes with rough and intermediate bark and with a more closed canopy architecture, which demonstrates the selection of host trees for the management and conservation of Cattleya trianae in semi-natural urban environments.

4 Discussion

4.1 Identification of phorophytes with *Cattleya trianae* orchids

Significant differences in PPFD were observed among zones and sampling heights ($H = 80.94$, $p < 0.001$; Table 2). The highest values were recorded in zones 2, 3, and 4, particularly at 3.5 m, reflecting greater canopy openness and direct solar radiation exposure in these zones (Larcher, 2003; Taiz et al., 2017). These differences in light availability likely contribute to the contrasting microenvironmental conditions between zone clusters, and are

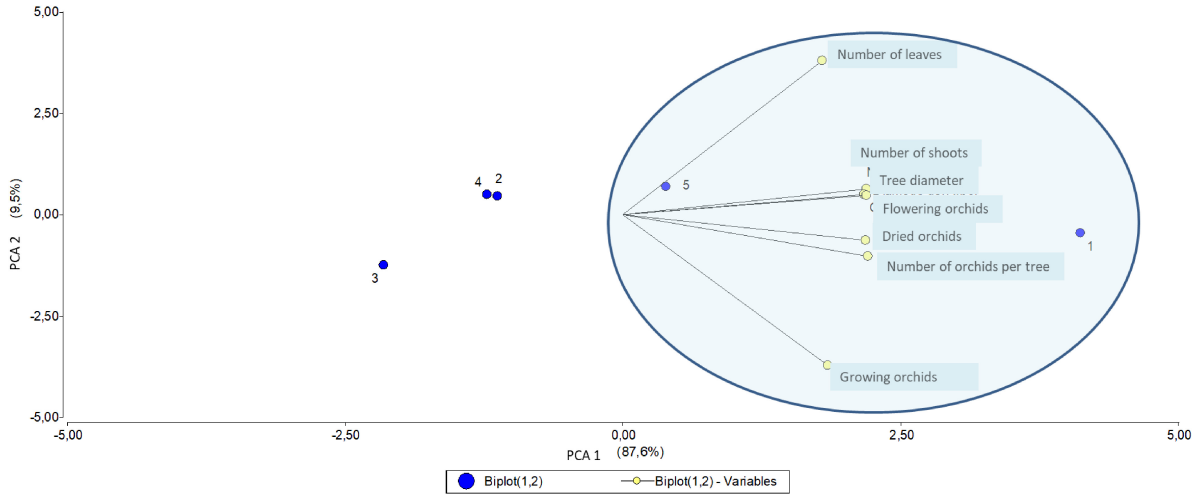


FIGURE 7
Principal component analysis for phorophytes characteristics and orchid abundance.

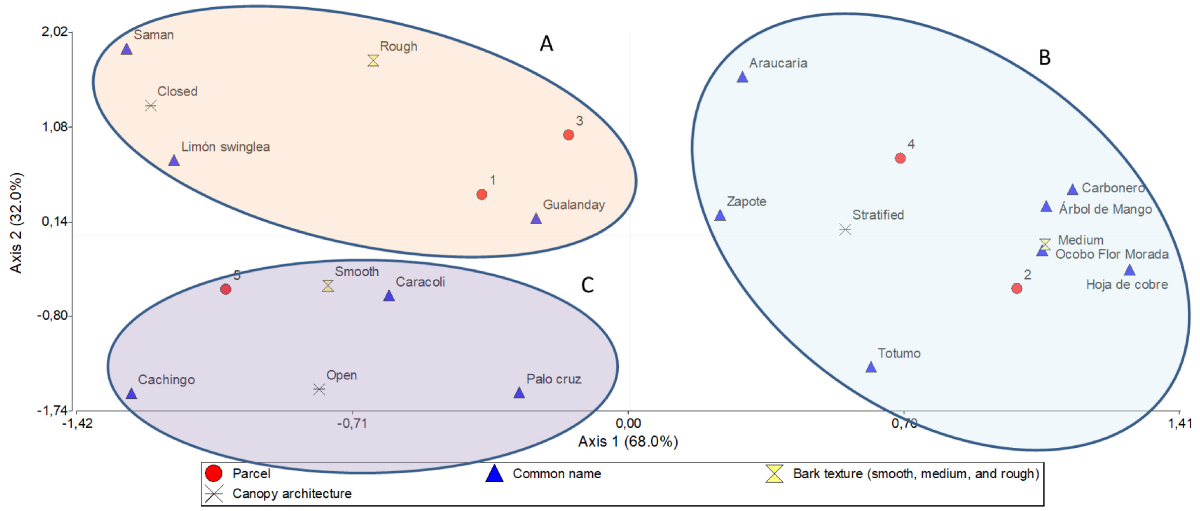


FIGURE 8
Correspondence analysis of phorophytes characteristics and orchid occurrence in different areas. **(A)** Group with rough bark and closed canopy (zones 1 and 3). **(B)** Group with intermediate bark and stratified canopy (zones 2 and 4). **(C)** Group with smooth bark and open canopy (zone 5).

consistent with the niche of Cattleya trianae in intermediate-canopy microhabitats (Baldocchi and Collineau, 1994; Pearcy, 2007).

Several limitations of this study should be acknowledged. First, the biological quality of the phorophyte substrate—specifically the presence and composition of mycorrhizal fungal communities—was not assessed. Given that orchid germination and long-term establishment depend on specific mycorrhizal associations (Swarts and Dixon, 2009), future studies integrating mycorrhizal assessments would provide a more complete picture of the factors governing orchid persistence in semi-natural environments. Second, because the individuals of Cattleya trianae present in the study area were originally introduced as part of educational and conservation initiatives rather than through natural colonization (Banderas Villate and Ramos Cerón, 2021), the distribution patterns documented here reflect long-term survival and secondary establishment rather than natural range dynamics. This distinction is ecologically relevant and should be considered when extrapolating results to natural populations. Third, the relatively small number of host trees sampled per zone (3–10 trees) limits the statistical power to detect zone-level differences in orchid abundance. While abundance trends were evident (Zones 1 and 5 consistently harbored more individuals), formal statistical tests were not significant (Kruskal–Wallis, $H = 5.22$, $p = 0.265$), likely due to high individual-level variability within zones.

4.1.1 Individual accumulation curve

The individual accumulation curve (Figure 3) showed that sampling adequacy was reached across all zones. Zone 1 contributed the steepest initial increase (51 individuals across 18 host trees), reflecting the high orchid density in the most humid zone. Zones 2 and 3 added relatively few individuals despite a

greater number of trees sampled (27 and 9 trees, respectively), consistent with their less favorable microenvironmental conditions. Zones 4 and 5 produced a secondary increase (13 and 28 individuals, respectively), and the curve approached an asymptote by the end of sampling, indicating that additional sampling would yield diminishing returns. This pattern confirms adequate coverage of the study area (Reina-Rodríguez et al., 2017; Ventre-Lespiaucq et al., 2017).

4.2 Morphological characterization of *Cattleya trianae* orchids

The floral measurements recorded in this study (Figure 4) are consistent with the morphological descriptions reported for Cattleya trianae from natural populations (Forero et al., 2020; Mercado and Contreras, 2017), suggesting that individuals established in the semi-natural campus environment have maintained typical morphological expression despite the anthropogenic context. The relatively large lip dimensions (9.0 × 7.01 cm) and vivid coloration observed confirm the species' high degree of specialization toward specific pollinator groups (Forero et al., 2020; Mercado and Contreras, 2017).

4.3 Microenvironmental characteristics

Given that all variables violated the assumption of normality (Shapiro–Wilk, $p < 0.001$), microenvironmental conditions were compared among zones using the Kruskal–Wallis non-parametric test, followed by pairwise Mann–Whitney U tests with Bonferroni correction for *post-hoc* comparisons. Parameters analyzed included: air temperature (°C), relative humidity (%), vapor pressure deficit (kPa), leaf temperature (°C), dew deposition rate (mm/h), PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$), dew duration (h/day), and orchid abundance (individuals/tree).

Significant differences in air temperature (°C) were detected among zones (Kruskal–Wallis, $H = 84.65$, $p < 0.001$). At a height of 1.5 m, zones 2, 3, and 4 showed higher temperatures (26.9 ± 1.7°C, 26.8 ± 1.5°C, and 27.2 ± 1.8°C), respectively, while zones 1 and 5 had lower temperatures (23.4 ± 1.2°C and 23.8 ± 1.3°C). In contrast, at a height of 3.5 m, the temperature tended to be slightly lower in all zones.

Relative humidity (%) differed significantly among zones ($H = 82.39$, $p < 0.001$). Zones 1 and 5 maintained higher humidity levels (85.6 ± 3.2% and 83.3 ± 3.5%) at a height of 1.5 m, while zone 3 showed lower values (65.3 ± 4.8%). At a height of 3.5 m, a smaller but significant effect was obtained.

Vapor pressure deficit (kPa) differed significantly among zones ($H = 89.70$, $p < 0.001$), with zone 1 having the lowest values at 0.42 ± 0.05 kPa and zone 3 having the highest at 1.25 ± 0.13 kPa at a height of 1.5 m. At a height of 3.5 m, a moderate but significant effect was found.

Dew deposition rate (mm/h) differed significantly among zones ($H = 83.71$, $p < 0.001$), with the highest values in zones 1 and 5 (0.18 ± 0.02 and 0.16 ± 0.02 mm/h at 1.5 m). At 3.5 m, deposition remained significant but was lower across all zones.

Dew duration (h/day) differed significantly among zones ($H = 82.70$, $p < 0.001$), with longer duration in zones 1 and 5 (5.8 ± 0.6 and 5.5 ± 0.5 h/day at 1.5 m, respectively).

Orchid abundance (individuals/100 m^2) showed no statistically significant differences among zones ($H = 5.22$, df = 4, $p = 0.265$), although zones 1 and 5 consistently exhibited the highest counts (mean = 8.50 ± 9.14 and 2.80 ± 2.20 individuals/tree, respectively), a pattern consistent with the more favorable microenvironmental conditions recorded in these zones.

Pairwise Mann–Whitney U tests with Bonferroni correction confirmed that zones 1 and 5 differed significantly from zones 2, 3, and 4 for all environmental variables (temperature, relative humidity, vapor pressure, dew rate, dew duration; all $p < 0.05$ after correction), but not for orchid abundance (all pairwise $p > 0.09$). These differences in microenvironmental conditions correlate strongly with orchid abundance, suggesting that zones 1 and 5 provide the most favorable conditions for the establishment and development of Cattleya trianae.

5 Conclusion

Multivariate analysis confirms that the spatial distribution of *Cattleya trianae* is strongly influenced by microenvironmental conditions, particularly those related to water availability (>80%) and thermal regulation (~ 23°C). However, it is not just these two variables; for example, zones 1 and 5 respond to the interaction with the structural characteristics of the phorophytes, such as the larger diameter at breast height (DBH), which provide the most favorable conditions for the establishment and development of these orchids, as reflected in their greater abundance in these areas. In addition, the intermediate shade and radiation regulation provided by the stratified canopies of these trees reduces the risk of desiccation. Another important factor in the survival of *Cattleya trianae* is dew deposition, with the most abundant populations found in different areas with a deposition rate higher than 0.15 mm/h, which constitutes an additional source of water for the roots with velamen, helping survival in anthropic environments. In contrast, zones 2, 3, and 4 have smaller trees and less suitable canopies due to drier conditions, which limit the potential colonization of this orchid. Taken together, these results show that the distribution of *Cattleya trianae* is the result of a combination of microclimate, canopy structure, and atmospheric water availability, rather than a single isolated factor.

These results in local climatic conditions of the semi-natural urban forest show the permanence of *Cattleya trianae*, including the interaction between microclimate, host tree characteristics, and atmospheric water availability. The combination of these factors explains the spatial segregation for both zone 1 and zone 5 compared to the other study zones.

Our findings demonstrate that microenvironmental variables, particularly humidity and dew deposition, are key drivers of Cattleya trianae distribution in urban forests. These insights can guide urban planning, green infrastructure design, and orchid conservation strategies in Colombia and beyond.

Finally, further research is needed to consider the interaction of pollinators and the effects of climate variability on the resilience of *Cattleya trianae*. This will create a new complementary line

of research to understand species in urban environments and improve orchid conservation strategies in landscapes transformed by anthropogenic activities.

Data availability statement

The raw data supporting the conclusions will be made available by the author upon reasonable request.

Author contributions

J-ST-P: Investigation, Writing – original draft, Writing – review & editing. LRS: Investigation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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