Wild Epiphytic Orchid Diversity and Host Tree Preference along Micro-environmental Gradients in North-Eastern Forest Protected Areas of Bangladesh

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Abstract

Understanding epiphytic orchid diversity and their ecological associations with host trees is critical for effective forest conservation. This study assessed species richness, diversity, and orchid-host interactions along eight micro-environmental habitat variables across four protected forest areas in northeastern Bangladesh: Rema-Kalenga Wildlife Sanctuary (RKWS), Lawachara National Park (LNP), Satchari National Park (SNP), and Khadimnagar National Park (KNP). A total of 21 wild epiphytic orchid species under 12 genera were recorded, hosted by 68 tree species across 31 families. RKWS and LNP exhibited the highest species richness (20 species each), with RKWS also having the highest Shannon Diversity Index (2.84) and evenness (0.95), indicating a balanced and diverse orchid community. KNP demonstrated the lowest diversity ($H' = 1.945$) and species richness (9 sp.), indicating a fragmented ecosystem. Rank-abundance curves visualized dominant orchid species like *Cymbidium finalaysonianum* in RKWS and *Dendrobium lindleyi* in LNP. Host specificity analysis revealed *Aerides* and *Cymbidium* as generalists occurring on 26 host species, while *Camarotis* and *Phalaenopsis* were specialists, found on only 3 host species. *Artocarpus* emerged as the most supportive host, associating with 11 orchid species. Micro-environmental factors such as host tree height, crown height, bark thickness, and orchid attachment height showed significant positive correlations with orchid abundance. PCA and Mantel tests indicated that environmental gradients, particularly edge distance and altitude along with variables like- canopy coverage and host tree diameter, influenced orchid distribution patterns. These findings depicted that both host tree diversity and habitat microclimatic conditions play vital roles in colonizing sustaining wild epiphytic orchid populations. Conservation strategies should prioritize maintaining host diversity and favorable microhabitat conditions to ensure the persistence of these epiphytic orchid species under environmental change scenario.

Keywords: Epiphytic orchids, Orchid diversity, Orchid-host preference, Micro-environmental gradient, Orchid distribution patterns

Introduction

Epiphytic orchids fall under the family Orchidaceae, which comprises approximately 25,000 known species, the most varied angiosperms in the world (Cribb et al., 2003; Gale et al., 2018). They are generally terrestrial, epiphytes, or lithophytes. Fundamentally, epiphytic orchids grow most abundantly in tropical and subtropical forests. They are important aesthetically, medicinally, and denoted as ecological indicators (Ding et al., 2016; Djordjević & Tsiftsis, 2020; Rozali et al., 2021). The wild epiphytic orchids are now under severe threat due to anthropogenic actions (particularly ornamental plant trade), eventual pollution, and climate change (Fay, 2018; Gale et al., 2018; IUCN, 2024). In Bangladesh, orchid species are losing available niches due to forest degradation (Rashid et al., 2017; Tsiftsis et al., 2018). They face severe risks of illegal collection, habitat fragmentation, and agricultural encroachment (Islam et al., 2018). Additionally, invasive species and the expansion of monoculture plantations further threaten their natural habitats (M. A. Rahman et al., 2017). Given their ecological importance, conserving these species has become a priority in tropical conservation efforts (M. A. Rahman et al., 2017). It has been reported that, during peak season, a single orchid flower vendor earns 2,450 USD from wild orchid trading in Nepal (Dressler, 1993). In different parts of the world, many different cultures use orchids in their cultural norms (Acharya & Rokaya, 2014; Kasulo et al., 2009). One of the important food products derived from orchids is vanilla (Vanilla planifolia) (Acharya & Rokaya, 2014; Kasulo et al., 2009). Recent surveys in the northeastern forests of Bangladesh have revealed the indiscriminate extraction of several rare epiphytic orchids, primarily for traditional medicine and decorative plant use (M. A. Rahman et al., 2017).

Huda, (2007) compiled a checklist comprising 160 species under 63 genera of the family Orchidaceae in Bangladesh, of which 106 were identified as epiphytic and 56 as terrestrial. Seventy-six different species were identified from the southeastern part of Bangladesh (Huda et al., 2017). Many orchids are rare in nature despite this diversity and are on the edge of extinction. A study conducted by Rashid et al., (2017). revealed that 54 species from the checklist were not found in their previously recorded habitats, indicating significant habitat loss, while forests in Bangladesh are being destroyed at an annual rate of 2.6%, double the global annual rate of deforestation (TIB, 2021). 32 orchid species are recorded to be extinct due to the destruction of forests, and the resultant fragmentation, unplanned development, and illegal collection pose continuous threats (Huda & Jahan, 2019; Masum et al., 2015; Wraith & Pickering, 2017).

Despite the abundant information on orchid species richness, phenology, and distribution, studies focused on orchids within forest-protected areas in Bangladesh remain sparse (Huda et al., 2017; Islam et al., 2018; M. A. Rahman et al., 2017; Rashid et al., 2017). Epiphytic orchids are mostly understudied, though comprising a large part of forest canopy biodiversity (Masum et al., 2015). Orchids occur in various parts of Bangladesh on different host plant species, both in forests and outside (Islam et al., 2018). Supplementary factors that are affecting epiphytic plants are the host species and their characteristics (e.g., age, height, diameter, bark thickness), and some habitat attributes like canopy coverage, canopy height, and crown size (Adhikari et al., 2017; Furtado &

Neto, 2018; Timsina et al., 2016). Which can significantly influence the capacity of orchid colonization and survival in microclimatic conditions (Huda et al., 2017; Masum et al., 2017). Studies from tropical regions, especially in Asia, have revealed that the interaction between orchids and their host plants is specific depending on certain characteristics of the host for the sustainability of orchid populations (M. A. Rahman et al., 2017). The current fact of insufficient research on their host preferences confines our understanding of their complex interactions within ecosystems (Huda et al., 2017).

Globally, orchids are used as indicators for monitoring changes in ecosystems. Thus, recognizing the mechanisms that influence "where orchids occur and why" is crucial for evaluating the factors responsible for their diversity and distribution patterns. Realizing these dynamics can result in more efficient conservation efforts specific to the needs of orchid species in forest ecosystems (Zotz et al., 2021). However, it is evident that the findings available so far are scant, and several information gaps remain, either due to controversial reports or a lack of intensive data (Rashid et al., 2017). Diversity, status, and distribution of orchids have been evaluated for various regions of Bangladesh, but their status in forest-protected areas has not been fully examined (Rashid et al., 2017). An assessment of their diversity is necessary for the conservation of orchid species in forests, especially in protected areas that are vital biodiversity shelters.

Despite their significance, forests in Bangladesh, which harbor most terrestrial plants, have received little attention regarding orchid diversity. Previous research on epiphytic orchids in Bangladesh has focused on region-wise species richness (Huda et al., 2019; Islam et al., 2018; M. A. Rahman et al., 2017), herbarium status (Huda, 2007; M. A. Rahman et al., 2017; Rashid et al., 2017), country-wise conservation status (Huda & Jahan, 2019), and medicinal and ethno-botanical values (Hoque & Huda, 2020; Huda et al., 2017; Shahimi et al., 2023). Their host trees, features and their interaction with orchids are still mysterious, which prevents us from fully understanding the ecological mechanisms that allow orchids to thrive. So, this study aims to reveal some of these unknown facts within four northeastern forest-protected areas of Bangladesh. The objectives of this study are twofold: (1) to assess wild epiphytic orchid diversity in all four forest-protected areas of northeastern Bangladesh; and (2) To evaluate orchid preferences for host tree characteristics and micro-environmental variables. Finally, this study provides a comprehensive monograph of the orchids in these vital forest-protected areas of Bangladesh, shedding light on the significant habitat and host-related gradients that influence their survival in the ecosystems.

Methodology

Study Areas

The study was conducted in four forest protected areas (Fig. 1) in the north-eastern region of Bangladesh: Rema-Kalenga Wildlife Sanctuary (RKWS), Khadimnagar National Park (KNP), Lawachara National Park (LNP), Satchari National Park (SNP). These areas represent diverse tropical and subtropical forest ecosystems that provide critical habitats for wild epiphytic orchids and their host trees.

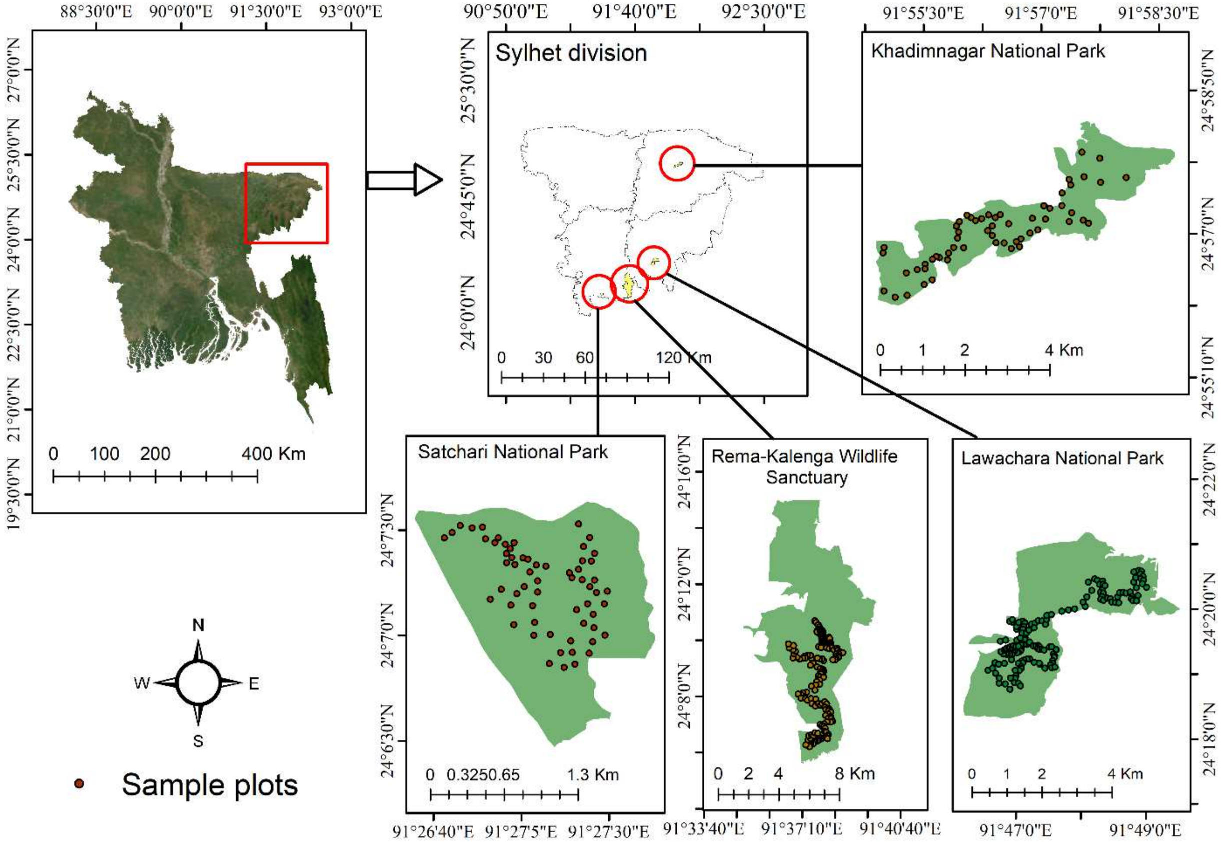


Fig.1: Four studied areas of north eastern forest protected areas of Bangladesh.

RKWS is located in Chunarughat Upazila of Habiganj district, between 24°06'–24°14' N latitude and 91°34'–91°41' E longitude. Established in 1982, the sanctuary now covers approximately 1,795.54 hectares. It is one of the largest semi-evergreen forests in Bangladesh, characterized by a mix of primary and secondary forests with a high diversity of flora and fauna. With a humid environment and mature tree stands it provides ideal conditions for epiphytic orchids.

LNP is part of the West Bhanugach Reserved Forest in Moulvibazar district. It spans 1,250 hectares and is located between 24°30'00"–24°32'00" N latitude and 91°37'00"–91°39'00" E longitude. Established in 1996, this semi-evergreen forest has dense canopy cover, providing a suitable microclimate for epiphytes.

KNP, situated in Sylhet Sadar Upazila, was declared a protected area in 2006. It lies between 24°56′–24°58′N latitude and 91°55′–91°59′E longitude, covering 678.80 hectares of hilly terrain. Surrounded by tea estates (Kalagool, Bhurjan, and Goolni), the park consists of secondary tropical forests that support various orchid species. The park's fragmented forest patches provide insights into how orchid diversity responds to human disturbances.

SNP is a protected area within the Raghunandan Hill Reserve Forest, located in Chunarughat Upazila of Habiganj district. It covers 243 hectares, lying between 24°5’–24°10’ N latitude and

91°25’–91°30’ E longitude. Declared a national park in 2006, it features semi-evergreen and deciduous forest patches along with varied elevation and dense tree cover making it a crucial site for studying orchid diversity along micro-environmental gradients.

Data Collection

Field data were collected using a modified arbitrary sampling method following Focho et al. (2010). Each study area was divided into transect lines, spaced 500 m apart along major forest trails. The number of transects varied depending on the size of the study area. Each of these transects has been walked and each epiphytic orchid has been recorded with its host tree traits detail (Timsina et al. 2016). Circular plots with a 5.461 m radius (100 m² plot) were taken around each identified orchid, with data collected on orchid species, individual height of attachment, and host tree characteristics, including average height, diameter at 1.3 m, canopy height and bark thickness. Additionally, canopy cover (%) of the plot, elevation and distance from the nearest forest edge were recorded as the micro-environmental variables.

Statistical Approaches

Diversity Indices

The dataset was compiled based on field observations, where the presence and abundance of orchids were recorded in four study sites: RKWS, LNP, KNP, and SNP. Then to assess the diversity of orchid species across the study sites, various biodiversity indices were employed to quantify species composition, distribution, and dominance patterns. Species richness (S) quantified the total number of species in each site, while the Shannon Diversity Index (H’) incorporated both richness and evenness to provide a more comprehensive measure of diversity. Evenness (E) further refined this by assessing how uniformly species are distributed. Beyond individual site diversity, Beta Diversity (βsor), using the Sørensen Dissimilarity Index, measured species turnover between sites, highlighting habitat differentiation. Gamma Diversity (γ) represented the total species richness across all study sites, offering a regional perspective on species diversity. Additionally, Rank Abundance analysis was conducted to understand the relative dominance and distribution patterns of the orchids and their host tree species. Together, these indices provide a holistic understanding of epiphytic orchids diversity and host tree composition across the study areas.

Table 1. Diversity indices with formula and description

Index	Formula	Description
Species richness (S)	$S = \sum I\,(n_i > 0)$	$I\,(n_i > 0)$, an indicator function that equals 1 when the species is present and 0 when absent.
Shannon Diversity Index (H')	$H' = -\sum p_i \ln p_i$	$p_i = \frac{n_i}{N}$, relative abundance of the species i n_i, abundance of the species I N, total abundance of all the species
Evenness (E)	$E = \frac{H'}{\ln S}$	S, species richness. An E value close to 1 indicated an even species distribution, while lower values suggested dominance by a few species.
Beta Diversity (β_{sor})	$\beta sor = \frac{2B}{2B + A}$	A, Number of species shared between two sites B, Number of species unique to one of the sites $\beta_{sor} = 0$ indicates identical species composition, while $\beta_{sor} = 1$ means completely different species compositions.
Gamma Diversity (γ)	$\gamma = \sum I\,(n_i > 0)$ [For all sites]	$I\,(n_i > 0)$, an indicator function that equals 1 when the species is present and 0 when absent.
Rank Abundance	Log Relative Rank Abundance = $log\,(\frac{n_i}{N})$	N, the total abundance of all species of a given site.

Orchid-Host Association

To assess orchid-host associations, only host trees supporting more than one orchid species were considered. Orchid specificity was determined by counting the number of host species per orchid genus, while the specificity of host trees was assessed by the number of orchid species they supported. This approach identified generalist orchids with broad host ranges and specialist orchids with restricted associations, along with the key host trees that support orchid diversity.

Orchid-Host Relationship along micro-environmental variables

A number of statistical tests were carried out to assess the correlation between orchid species composition and micro-environmental factors. Firstly, Pearson correlation analysis was conducted to measure the linear relationship between individual variables within the datasets. Following this, the Standard Mantel Test was applied using the Euclidean Distance method to evaluate the correlation between the two distance matrices, one representing species composition and the other representing microenvironmental variables. This method allowed for the quantification of ecological distance relationships, ensured that the patterns were statistically significant rather than random.

Table 2. Summary of statistical methods used to analyze the correlation between orchid species composition and microenvironmental factors, including their purpose, input data, and output measures.

Method	Purpose	Input data	Output	Formula
Pearson Correlation	Measures linear relationship between two variables.	Two continuous variables.	Correlation coefficient (r) ranging from -1 to 1.	$r = \frac{\sum(X_i - X)(Y_i - Y)}{\sqrt{\sum(X_i - X)^2} \cdot \sqrt{\sum(Y_i - Y)^2}}$
Mantel Test	Tests correlation between two distance/proximity matrices.	Two distance matrices.	Correlation coefficient (often with permutation-based p-value).	$D_X(i,j) = \sqrt{\sum_{k=1}^{p} \left(X_{ik} - X_{jk}\right)^2}$; $D_Y(i,j) = \sqrt{\sum_{k=1}^{q} \left(Y_{ik} - Y_{jk}\right)^2}$ $r_M = \frac{\Sigma_i \Sigma_j (D_X(i,j) - \overline{D}_x)\,(D_Y(i,j) - \overline{D}_Y)}{\sqrt{\Sigma_i \Sigma_j (D_X(i,j) - \overline{D}_x)^2} \cdot \sqrt{\Sigma_i \Sigma_j (D_Y(i,j) - \overline{D}_Y)^2}}$ $p = \frac{999\ of\ times\ r_M^* \geq r_M}{N}$
PCA	Reduces dimensionality and identifies patterns in multivariate data.	Multiple continuous variables.	Principal components (uncorrelated linear combinations of original variables).	$C = \frac{1}{n-1} Z^T Z$, $\mathrm{C} = \mathrm{V} \Lambda V^T$, $\mathrm{Y} = \mathrm{ZV}$

Afterwards, Principal Component Analysis (PCA) was conducted to reduce dimensionality and identify dominant patterns within the multivariate dataset. The Mantel Test results were further validated using permutation testing to assess the robustness of the observed correlations. Collectively, these statistical approaches provided a comprehensive framework for understanding the orchid-host relationship by integrating direct variable correlations, distance-based association tests, and multivariate pattern recognition.

Results

Orchid Species Diversity and Abundance

Species Richness

RKWS is found to have the highest species richness (20 species), which aligns with its high Shannon Diversity Index and evenness (Fig.2). Similar species richness (20 species) is also seen in LNP. SNP has 15 species, which is lower than RKWS and LNP but still indicates a reasonably diverse ecosystem (Fig.2). KNP showed the lowest species richness (9 species) (Fig.2), which explains its low Shannon Diversity Index (1.94) (Fig.2). This suggests that KNP has fewer species compared to the other locations.

Shannon Diversity Index (Shannon_*H'*):

RKWS has the highest Shannon Diversity Index (2.84) among the four locations, indicating that it is the most diverse in terms of species richness and evenness (Fig.2). This suggests that RKWS is a thriving ecosystem with a balanced distribution of species. LNP follows closely behind RKWS with a Shannon Index of 2.632 indicating a rich biodiversity of orchid species here (Fig.2). However, its slightly lower Shannon Index suggests that the distribution of species is not as even as in RKWS. SNP has a Shannon Index of 2.217, which is lower than RKWS and LNP but still indicates a reasonably diverse ecosystem. KNP has the lowest Shannon Index (1.945), suggesting that it has the least diversity among the four locations (Fig.2). This could be due to fewer species or an uneven distribution of species.

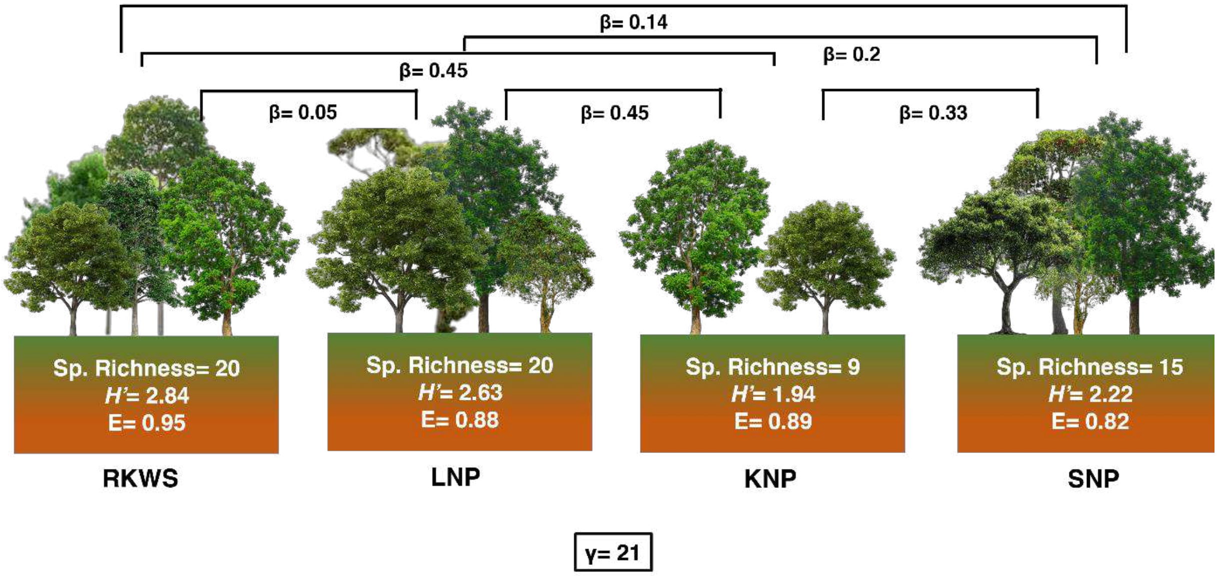


Fig. 2 Diversity Indices of Epiphytic Orchids in the four studied areas. RKWS: Rema Kalenga Wildlife Sanctuary; LNP: Lawachara National Park; KNP: Khadim Nagar Park; SNP: Satchari National Park.

Evenness

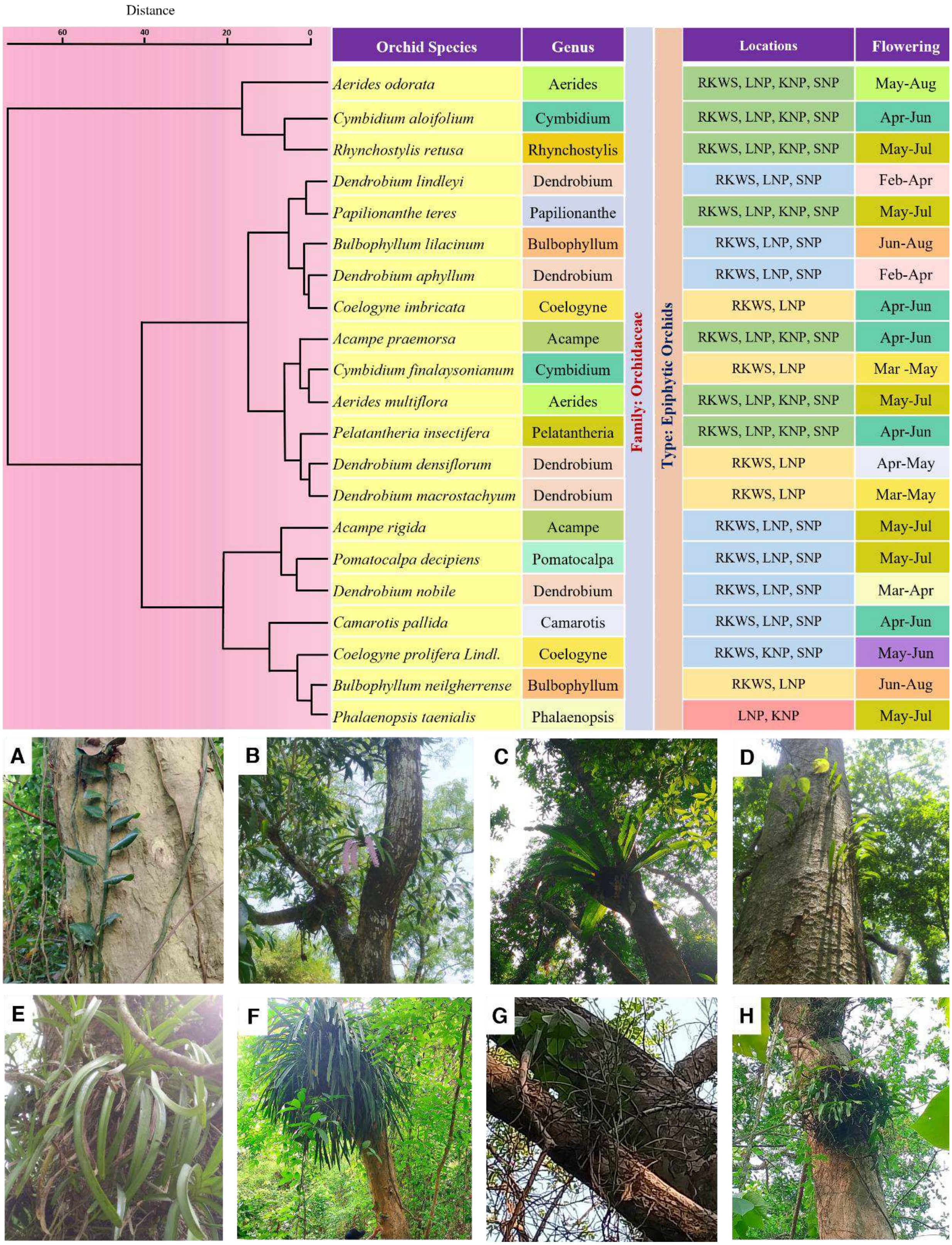
RKWS has the highest evenness (0.95), meaning that the species in this sanctuary are evenly distributed (Fig.2). This also indicates a balanced ecosystem. LNP has an evenness of 0.88, which is slightly lower than RKWS but still indicates a fairly even distribution of species (Fig.2). KNP has an evenness of 0.89 (Fig.2), which is almost similar to LNP. Despite having the lowest Shannon Index, the species in KNP are relatively evenly distributed. SNP has the lowest evenness (0.82), suggesting that some species dominate the ecosystem more than others (Fig.2).

Sorensen Beta Diversity:

RKWS and LNP have a very low beta diversity (0.05), meaning they share a high proportion of species (Fig.2). These two locations show ecologically very similar conditions. LNP and KNP have a beta diversity of 0.45, indicating moderate dissimilarity. They share some species but also have distinct differences in their species composition. LNP and SNP have a beta diversity of 0.20, suggesting that they are somewhat similar but not as similar as RKWS and LNP (Fig.2). RKWS and KNP have a beta diversity of 0.45, similar to LNP-KNP (Fig.2). This indicates moderate dissimilarity between these two locations. RKWS and SNP have a beta diversity of 0.14, indicating that they are relatively similar in species composition. KNP and SNP have a beta diversity of 0.33, suggesting moderate dissimilarity (Fig.2). They share some species but also have distinct differences.

Gamma Diversity

All four locations combinedly presented 21 different species (Fig.2) under 12 distinct genera (Fig.3) of epiphytic orchids hosting on a broad range of diversified tree species (68) under 31 families in Northeastern region of Bangladesh.



Orchid Species	Genus	Locations	Flowering
Aerides odorata	Aerides	RKWS, LNP, KNP, SNP	May-Aug
Cymbidium aloifolium	Cymbidium	RKWS, LNP, KNP, SNP	Apr-Jun
Rhynchostylis retusa	Rhynchostylis	RKWS, LNP, KNP, SNP	May-Jul
Dendrobium lindleyi	Dendrobium	RKWS, LNP, SNP	Feb-Apr
Papilionanthe teres	Papilionanthe	RKWS, LNP, KNP, SNP	May-Jul
Bulbophyllum lilacinum	Bulbophyllum	RKWS, LNP, SNP	Jun-Aug
Dendrobium aphyllum	Dendrobium	RKWS, LNP, SNP	Feb-Apr
Coelogyne imbricata	Coelogyne	RKWS, LNP	Apr-Jun
Acampe praemorsa	Acampe	RKWS, LNP, KNP, SNP	Apr-Jun
Cymbidium finalaysonianum	Cymbidium	RKWS, LNP	Mar -May
Aerides multiflora	Aerides	RKWS, LNP, KNP, SNP	May-Jul
Pelatantheria insectifera	Pelatantheria	RKWS, LNP, KNP, SNP	Apr-Jun
Dendrobium densiflorum	Dendrobium	RKWS, LNP	Apr-May
Dendrobium macrostachyum	Dendrobium	RKWS, LNP	Mar-May
Acampe rigida	Acampe	RKWS, LNP, SNP	May-Jul
Pomatocalpa decipiens	Pomatocalpa	RKWS, LNP, SNP	May-Jul
Dendrobium nobile	Dendrobium	RKWS, LNP, SNP	Mar-Apr
Camarotis pallida	Camarotis	RKWS, LNP, SNP	Apr-Jun
Coelogyne prolifera Lindl.	Coelogyne	RKWS, KNP, SNP	May-Jun
Bulbophyllum neilgherrense	Bulbophyllum	RKWS, LNP	Jun-Aug
Phalaenopsis taenialis	Phalaenopsis	LNP, KNP	May-Jul

Fig.3 Dendrogram illustration of the clusters of orchid species based on their number of individuals across four protected areas: Rema Kalenga Wildlife Sanctuary (RKWS), Lawachara National Park (LNP), Khadimnagar National Park (KNP), and Satchari National Park (SNP). The branching patterns

reflect the similarity in abundance and distribution of orchid species, highlighting their ecological preferences in different habitats. **A** (*Dendrobium densiflorum*); **B** (*Aerides multiflora*); **C** (*Coelogyne imbricata*); **D** (*Bulbophyllum neilgherrense*); **E** (*Acampe praemorsa*); **F** (*Cymbidium aloifolium*); **G** (*Papilionanthe teres*); **H** (*Coelogyne prolifera*).

Rank Abundance

Rank Abundance of Orchid Species

RKWS showed the highest orchid abundance, with a peak rank value of 1.362 (Fig. 4a) by the species *Cymbidium finalaysonianum* followed by LNP at 1.415 with the species *Dendrobium lindleyi.* Both sites exhibited a gradual decline in abundance, suggesting high species richness with a few dominant species. SNP showed slightly lower diversity, with a peak value of 1.322 (*Aerides odorata*) and a steeper decline in abundance (Fig. 4a). KNP had the lowest diversity, with a peak value of 1.230 (*Rhynchostylis retusa*) and a sharp drop in abundance, indicating fewer dominant species (Fig. 4a). These variations highlight differences in habitat conditions and ecological factors influencing orchid species distribution in these protected areas.

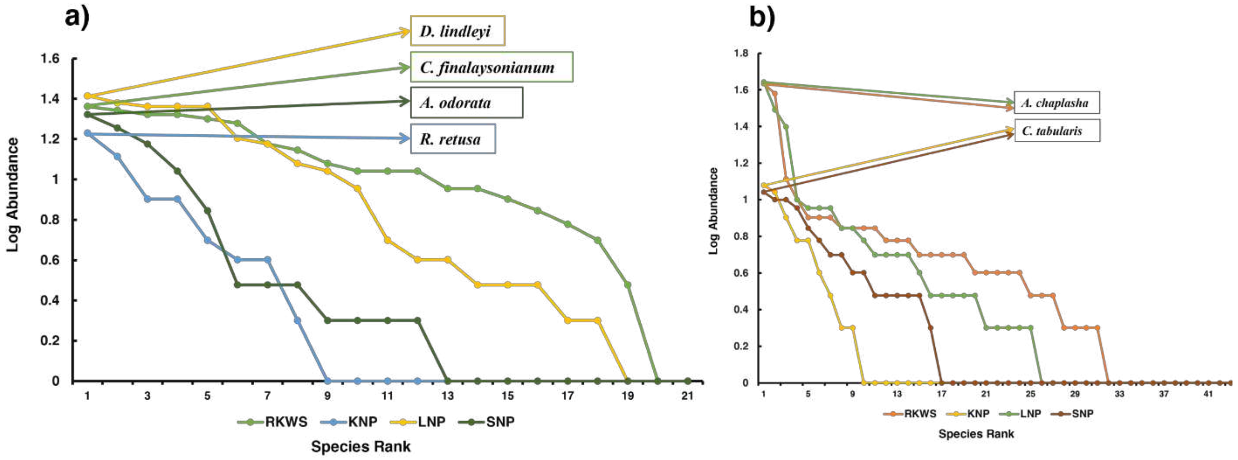


Fig. 4 Species Rank Abundance of both Epiphytic orchids and Host tree species (**a-** Orchid species; **b-** Host tree species)
RKWS- Rema-Kalenga Wildlife Sanctuary; KNP- Khadimnagar National Park; LNP- Lawachara National Park; SNP- Satchari National Park

Rank Abundance of Host Tree Species

The rank abundance analysis of host tree species followed similar trends. RKWS had the highest diversity, with a peak rank abundance of 1.633, followed closely by LNP at 1.643, both with the species *Artocarpus chaplasha*, showing a gradual decline in abundance (Fig. 4b). SNP exhibited lower diversity, with a peak value of 1.041 and a sharper decline, while KNP had the lowest diversity, with a peak value of 1.079 (Fig. 4b) and a steep drop in abundance both ranked with the species *Chukrassia tabularis*. The sharp decline in abundance values in SNP and KNP indicates a more fragmented host tree community, which may impact orchid species richness and distribution in these protected areas.

Orchid-Host Association

Host Specificity of Orchids

Among all the orchid genera, Aerides and Cymbidium exhibited the broadest host range, occurring on 26 different host species (Fig. 5). This indicates a high degree of ecological adaptability and generalist behavior in these orchids, allowing them to thrive across a wide variety of host trees. Dendrobium and Rhynchostylis also demonstrated a relatively wide host range, occurring on 25 and 19 host species, respectively.

On the other hand, Camarotis and Phalaenopsis were found to be the most specialized orchids, occurring on only 3 host species (Fig. 5). Pelatantheria and Pomatocalpa also displayed limited host ranges, occurring on 8 and 5 host species, respectively.

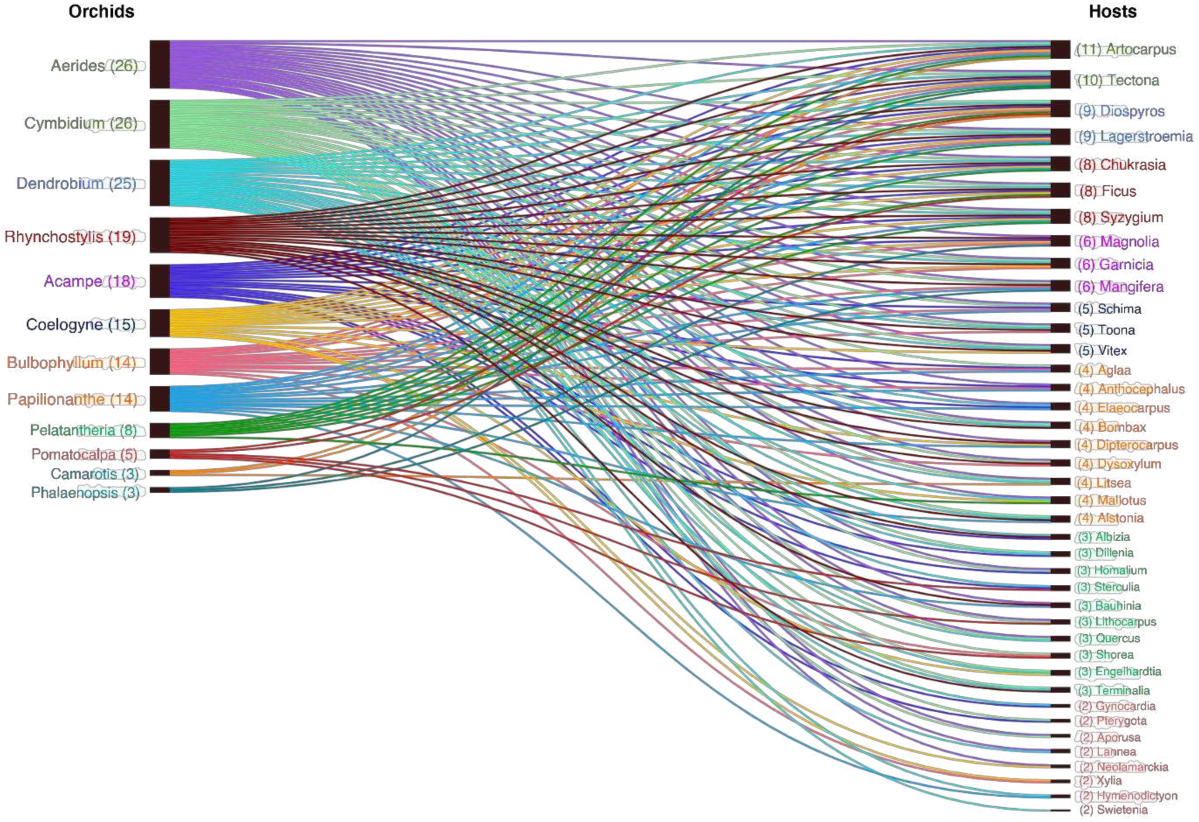


Fig. 5 Alluvial diagram illustrating the orchid-host association. Connection widths depicting the frequency of occurrence, highlighting generalist and specialist orchid relationships.

Orchid Specificity of Hosts

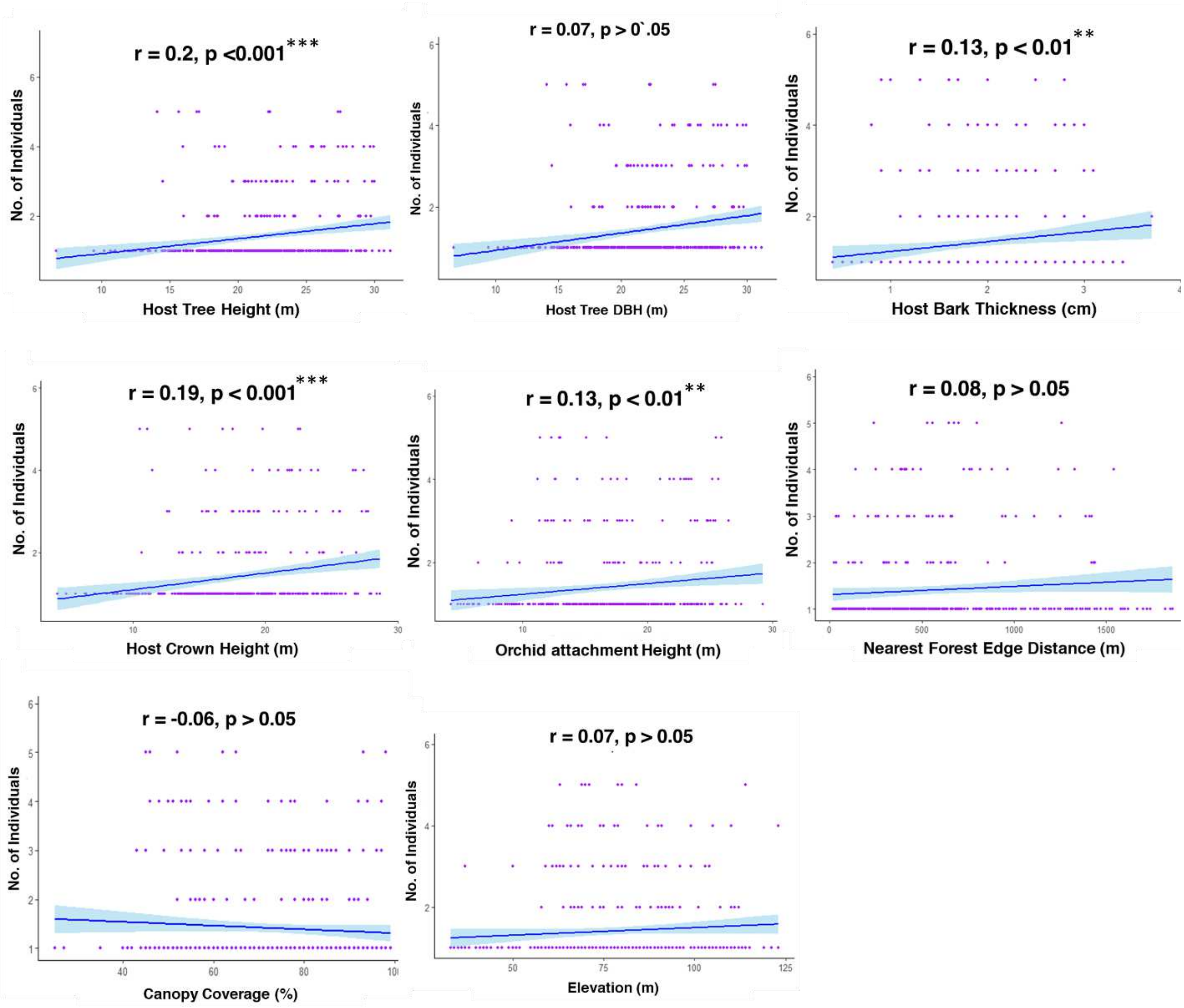
The host tree Artocarpus emerged as the most supportive host, harboring the highest number of orchid species (11 species) (Fig. 5). This indicates that Artocarpus provides a highly suitable habitat and ecological niche for a diverse range of orchids. Other hosts that supported a relatively high number of orchid species include Chukrasia, Diospyros, Ficus, Lagerstroemia, Syzygium, and Tectona, each hosting 8 to 10 orchid species (Fig. 5).

In contrast, the host Gynocardia was found to support the least number of orchids (2 species), with only Acampe and Dendrobium recorded as associates (Fig. 5). Similarly, Hymenodictyon and Swietenia were also among the least supportive hosts, each hosting only two orchid species (Fig. 5). These results suggest that certain host trees may offer less favorable conditions or have limited ecological compatibility with orchids.

Orchid-Host Relationship along micro-environmental variables

Pearson Correlation

Pearson's correlation analysis revealed that four variables (host tree height, bark thickness, crown height, and orchid attachment height) positively influenced orchid abundance, with some showing strong correlations (Fig. 6). Host tree height exhibited a very strong correlation ($r = 0.20$, $p < 0.001$) (Fig. 6). In contrast, host tree DBH showed a weak, statistically insignificant correlation with orchid abundance ($r = 0.07$, $p > 0.05$) (Fig. 6). However, DBH significantly correlated with host tree height and moderately with bark thickness and crown height. Bark thickness showed a weak but significant positive correlation with orchid abundance ($r = 0.13$, $p < 0.01$); Crown height demonstrated a moderate positive correlation ($r = 0.19$, $p < 0.001$) (Fig. 6). Orchid attachment height showed a weak but significant positive correlation ($r = 0.13$, $p < 0.01$) (Fig. 6).



P< 0.05- significant; P< 0.01** - strongly significant; P< 0.05*** - very strongly significant*

Fig. 6 Pearson Correlation between orchid occurrence and host tree, micro-environmental variables.

A weak negative correlation was observed with the distance to the nearest forest edge (r = -0.08, p > 0.05); Canopy coverage showed a weak negative correlation (r = -0.06, p > 0.05); Elevation had a weak, insignificant correlation (r = 0.07, p > 0.05) (Fig. 6).

Mantel Test

The Mantel test analysis revealed varying degrees of correlation between orchid species and micro environmental variables. Aerides showed a significant positive correlation with canopy coverage (r = 0.067, p < 0.01) (Fig. 7), indicating a preference for areas with greater canopy coverage. Phalaenopsis exhibited a significant positive correlation with host tree DBH (r = 0.121, p = 0.023), suggesting a preference for trees with larger diameters; Acampe displayed a significant positive correlation with altitude (r = 0.060, p = 0.032) (Fig. 7), indicating a tendency to occur at higher elevations. Bulbophyllum showed a near-significant positive correlation with orchid attachment height (r = 0.037, p = 0.090), hinting at a potential preference for higher attachment points within host trees (Fig. 7).

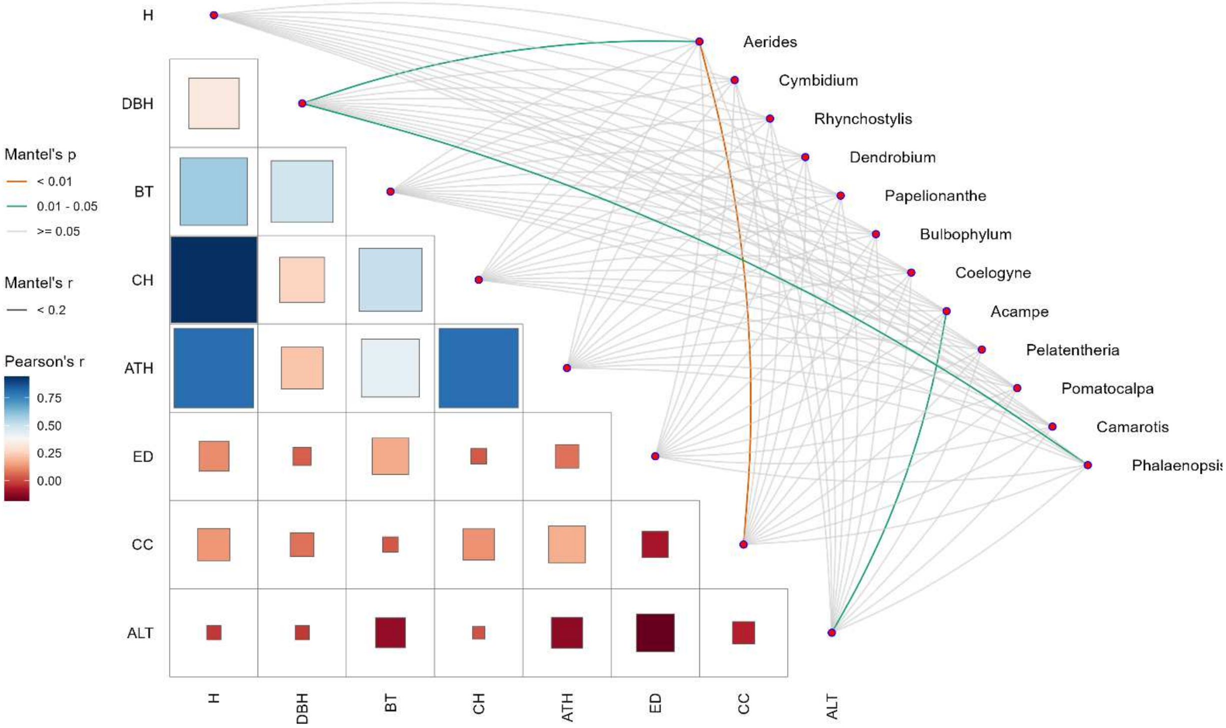


Fig. 7 Mantel test showing the correlation between orchid species and host tree, microenvironmental variables based on Euclidean distance

In contrast, Cymbidium, Rhynchostylis, Dendrobium, Papilionanthe, Coelogyne, Pelatantheria, Pomatocalpa, and Camarotis exhibited no significant correlations with the environmental variables, but weak trends were observed. For instance, Rhynchostylis and Cymbidium showed weak, non-significant correlations with canopy coverage (r = 0.032, p = 0.099 and r = 0.005, p = 0.410, respectively) (Fig. 7), while Dendrobium and Coelogyne displayed weak negative correlations with altitude (r = -0.040, p = 0.928 and r = -0.058, p = 0.975, respectively) (Fig. 7).

Principal Component Analysis (PCA) of Host & Environmental Variables

The Principal Component Analysis (PCA) revealed that the first two principal components (PCA1 and PCA2) together accounted for the majority of the variance in orchid distribution, with PCA1 explaining 99.7% of the variance (standard deviation = 429.38) and PCA2 contributing 0.2% (standard deviation = 18.08) (Fig. 8). PCA1 was dominated by Edge Distance (ED), with a loading value of 0.99996, while PCA2 was strongly influenced by Altitude (ALT), with a loading value of 0.96797 (Fig. 8).

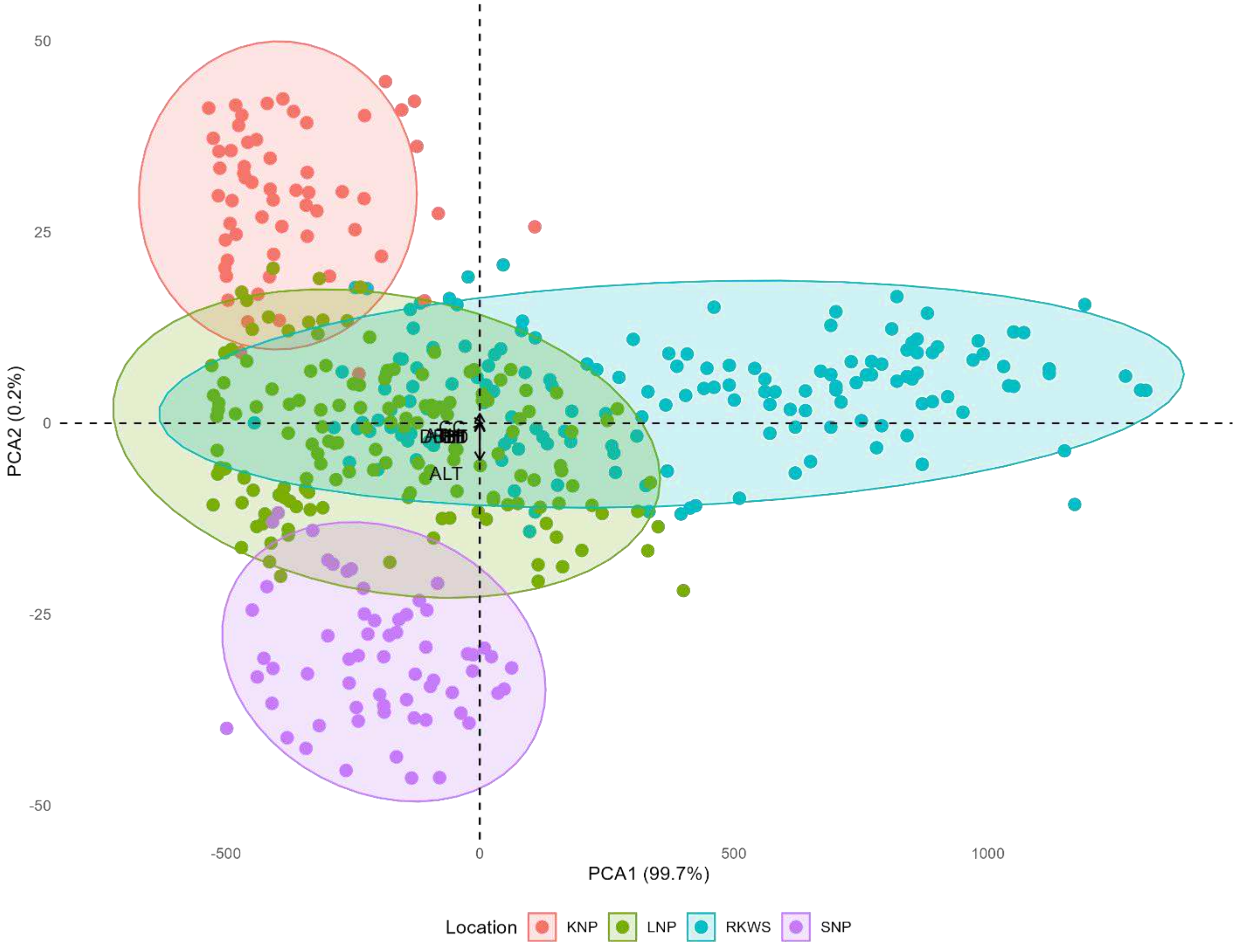


Fig. 8 Principal Component Analysis (PCA) to reduce dimensionality and identify major environmental gradients influencing orchid-host species composition

Other PCA components demonstrated that canopy-related factors (CC, CH, and ATH) are the primary drivers of orchid distribution, while other variables such as bark thickness and tree diameter play secondary roles (Fig. 8).

Table 3. Summary of Orchid-Microenvironmental Variables Correlation

Correlation test	Variables	r- value	P value	Significance	PCA covariances
Pearson					
	HH	0.20	<0.001	***	
	BT	0.13	<0.01	**	
	CH	0.19	<0.001	***	
	ATH	0.13	<0.01	**	
Mantel test					
	DBH	0.121	0.023	*	
	CC	0.067	<0.01	**	
	ALT	0.060	0.032	*	
PCA					
	PCA1				99.7% variance
	PCA2				0.2% variance
	ED (PCA1)				0.99996 (loading)
	ALT (PCA2)				0.96797 (loading)

HH- Host Height; BT- Bark Thickness; CH- Crown Height; ATH- Attachment Height; DBH- Diameter at Breast Height; CC- Canopy Cover; ALT- Altitude; ED- Distance of nearest forest Edge.

(- significant; ** - strongly significant; *** - very strongly significant)*

Discussion

Diversity Indices

The assessment of orchid diversity across the four forest protected areas revealed noticeable variations in species richness, evenness, and overall diversity. Rema-Kalenga Wildlife Sanctuary (RKWS) and Lawachara National Park (LNP) emerged as the most species-rich sites, indicating biologically diverse and ecologically stable habitats for epiphytic orchids. These areas also reflected a relatively balanced distribution of orchid species, suggesting favorable ecological conditions that promote community evenness. The mature, stratified forest structure and stable microclimatic conditions in these sites likely provide suitable niches for a wide range of orchid species. Additionally, lower levels of anthropogenic disturbance and effective conservation management practices may enhance host tree availability and habitat integrity, further supporting orchid diversity.

In contrast, Khadimnagar National Park (KNP) exhibited the lowest orchid diversity, implying limited habitat heterogeneity, potential environmental stress, or anthropogenic disturbances (Sobuj & Rahman, 2011). Patterns in species evenness reinforced these differences, with more balanced population structures observed in the more diverse sites. Analysis of species turnover among sites also revealed a high degree of similarity between RKWS and LNP, reflecting shared ecological characteristics and possibly similar forest compositions. These findings align with prior research by Huda et al., (2017) who reported higher orchid diversity in relatively undisturbed and structurally complex forests of northeastern Bangladesh compared to more degraded landscapes. Similarly, studies in Chunati and Madhupur forests have also shown that habitat fragmentation and human interference lead to noticeable declines in orchid diversity (Besi et al., 2023a; Paul et al., 2015; Rahman et al., 2016), reinforcing the patterns observed in KNP. Overall, the gamma diversity of the study region underscores the ecological importance of northeastern forest reserves, highlighting their role as vital reservoirs for epiphytic orchid conservation in Bangladesh (Islam et al., 2016; Uddin & Hassan, 2010)

Orchid-Host Association

Host tree associations varied markedly among epiphytic orchid species, revealing a spectrum of ecological strategies ranging from generalist to specialist behaviors. Some species such as *Aerides* and *Cymbidium* displayed associations with a wide variety of host trees, indicating a high degree of ecological plasticity. This generalist strategy allows them to thrive across diverse forest structures and microclimatic conditions, a pattern similarly observed by Pant & Raskoti (2013) in tropical forest ecosystems. Likewise, species of *Dendrobium* and *Rhynchostylis* also demonstrated broad host adaptability, likely due to their efficient seed dispersal, high physiological flexibility, and less stringent microhabitat requirements. These findings align with previous studies that emphasize the success of generalist orchids in fragmented or heterogeneous forest landscapes (Besi et al., 2023a; Brzosko et al., 2023; Hernández-Pérez et al., 2018; Morales-Linares et al., 2022).

On the other hand, species such as *Camarotis* and *Phalaenopsis* exhibited strong host specificity, being associated with only a few tree species. This specialization suggests a narrow ecological niche and heightened sensitivity to host tree availability and associated environmental factors. Such orchid-host fidelity is consistent with research indicating that certain epiphytic orchids rely on specific bark textures, canopy conditions, or microclimatic features such as humidity and light levels (Adhikari et al., 2012; Hernández-Pérez et al., 2018; Zarate-García et al., 2020). The limited host range may also reflect co-evolutionary relationships or dependency on particular forest strata or successional stages (Ramírez-Martínez et al., 2022; Rasmussen & Rasmussen, 2018).

Among the host trees recorded, certain species like *Artocarpus*, *Chukrasia*, *Diospyros*, *Ficus*, and *Tectona* were found to support a notably diverse orchid community. These trees likely offer favorable attributes such as rough or moisture-retentive bark, extensive crown structure, and optimal microhabitat conditions for orchid attachment and growth. Similar trends have been reported in studies from Southeast Asia and the Neotropics, where trees with complex canopy architecture and stable microenvironments support richer epiphyte loads (Díaz et al., 2010; Nadkarni et al., 2013; Sporn, 2009). In contrast, tree species such as *Gynocardia*, *Hymenodictyon*, and *Swietenia* supported very few orchid species, possibly due to smooth bark texture, limited canopy structure, or microclimatic conditions less favorable to orchid establishment.

These patterns underscore the importance of both host tree traits and orchid-specific ecological strategies in shaping orchid-host interactions and highlight the need for forest management practices that maintain tree diversity and structural complexity to support epiphytic orchid populations.

Host Tree and Microenvironmental Factors Shaping Orchid Diversity

The relationship between orchid distribution and host tree characteristics or microenvironmental factors was statistically explored through Pearson correlation, Mantel tests, and Principal Component Analysis (PCA). Pearson correlation showed significant positive correlations between orchid abundance and host height, bark thickness, crown height, and attachment height, indicating that tall trees with thicker bark and extended crowns provide more suitable niches for orchid colonization (Köster et al., 2011). Taller trees are more likely to intersect diverse light gradients and moisture conditions within the canopy, enhancing microhabitat heterogeneity favorable for epiphyte establishment (Murakami et al., 2022). Similarly, thicker bark may retain more moisture and host more mosses and lichens, which facilitate seed germination and root anchorage for orchids (Tremblay et al., 1998). These findings are in line with those of Zotz & Vollrath, (2003) and Tay et al., (2023), who found that epiphytic orchids preferentially colonize hosts with complex architecture and textured bark. Interestingly, DBH did not correlate significantly with orchid abundance but had strong associations with other tree traits through this correlation test, indicating an indirect influence on orchid occupancy. This contrasts with some studies where DBH was considered a significant predictor of epiphyte load (Cardelús et al., 2006; Díaz et al., 2010), suggesting that the role of DBH may be context-dependent and influenced by forest type and age structure.

The Mantel test provided further resolution, showing species-specific environmental preferences: Aerides correlated positively with canopy coverage, Phalaenopsis with DBH, and Acampe with altitude. These associations reflect ecological niche specialization, where certain orchids preferentially occupy specific vertical strata or forest structures depending on their light and humidity requirements (Hernández-Pérez et al., 2018). For instance, species like Aerides favor denser canopies due to their moisture-dependent physiology, while species like Acampe are adapted to higher elevations where cooler temperatures may reduce competition (Adhikari et al., 2016; Hernández-Pérez et al., 2018). Similar niche partitioning based on elevation and canopy characteristics has been observed in tropical forests of Southeast Asia and the Andes, highlighting the adaptability of different orchid taxa to distinct environmental gradients (Adhikari et al., 2016; Awasthi et al., 2024; Pérez-Escobar et al., 2017)

PCA revealed that edge distance and altitude were the dominant factors structuring orchid distribution, with canopy-related variables such as canopy cover, crown height, and attachment height also playing vital roles. Forest edges typically experience greater microclimatic fluctuations, which may limit orchid colonization, while forest interiors provide more stable conditions and host diversity (Sánchez et al., 2016). Altitudinal gradients, on the other hand, influence orchid distribution through variations in temperature, light availability, and air moisture factors critical to orchid survival and reproduction (Awasthi et al., 2024; Besi et al., 2023b). These findings are consistent with global studies highlighting the importance of forest structure and microclimatic stability in shaping epiphytic orchid diversity (Besi et al., 2023a; Mccormick & Jacquemyn, 2014) Furthermore, they align with observations from Neotropical regions where orchid richness and abundance declined significantly near forest edges due to exposure-related stressors (Pérez-Escobar et al., 2017; Sánchez et al., 2016). The influence of forest edge proximity and elevation suggests that conservation strategies should prioritize maintaining habitat continuity and protecting forest interiors to sustain orchid diversity.

Conclusion

This study explored the richness and ecological patterns of wild epiphytic orchids and their host tree associations across four protected forest areas in northeastern Bangladesh. A total of 21 orchid species were recorded, exhibiting varying degrees of host specificity and distribution patterns shaped by micro-environmental gradients. Sites like Rema-Kalenga and Lawachara demonstrated higher orchid richness and diversity, while Khadimnagar showed signs of fragmentation and lower orchid abundance. Key factors influencing orchid distribution included host tree height, bark characteristics, attachment height, canopy cover, and environmental variables such as altitude and distance from forest edges. The identification of both specialist and generalist orchid species discloses the complex relationships between orchids and their hosts in tropical forest environments. These findings underline the necessity for conservation strategies that emphasize the protection of diverse host trees and the preservation of microhabitat conditions that are critical for orchid survival. The study offers crucial baseline data in order to facilitate long-term monitoring, habitat restoration, and successful biodiversity conservation in Bangladesh's forest reserves.

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Author Contributions:

Conceptualization and design was done by Kazi Mohammad Masum and Rabeya Khatun. The funding acquisition was performed by Kazi Mohammad Masum. Field work was performed by Rabeya Khatun, Md Mahbub Hasan and S M Rakib Bin Asghar Writing of original draft was done by Rabeya Khatun. Final revision was done by all authors.

Plant collection declaration

This study did not involve the collection of any plant materials. All plant identification was conducted in situ by Rabeya Khatun, Md Mahbub Hasan and S M Rakib Bin Asghar, and no specimens were removed from their natural environment. As such, no permits or ethical approvals for plant collection were required.

Data availability

All data generated or analysed during this study are included in this published article (and its supplementary information files).