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Lichen diversity as an air quality bioindicator in the Mount Tilu Nature Reserve (MTNR) Bandung

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ABSTRACT

MTNR in Pangalengan, West Java, is a conservation area with high biodiversity that is increasingly pressured by tourism and agricultural activities, which may affect air quality. This study aimed to examine the relationship between air quality and lichen diversity as bioindicators of air pollution. A descriptive exploratory method was applied at four site types representing different levels of human activity: forest, roadside, plantation, and tourist areas. The results showed that microclimatic conditions and air quality at all sites were classified as good according to Government Regulation No. 22/2021. However, lichen diversity and thallus composition varied among sites in response to environmental conditions. Crustose lichens dominated roadside and plantation areas with higher environmental stress, while foliose and fruticose lichens were more abundant in forest areas characterized by lower temperatures, higher humidity, and minimal pollution. The presence of sensitive species such as Usnea sp. and Ramalina sp. indicated superior air quality in forest sites. In conclusion, lichen distribution reflects an air quality gradient across the study area, confirming the effectiveness of lichens as reliable bioindicators for ecological monitoring in conservation areas.

Key words: bioindicator; Mount Tilu Nature Reserve (MTNR); lichens; air quality.

INTRODUCTION

Mount Tilu Nature Reserve (MTNR) located in the Pangalengan area of West Java, is a conservation area characterized by high biodiversity. The region comprises a tropical montane forest ecosystem with environmental conditions that support various ecological functions as well as tourism activities. Air is one of the essential components required to sustain life on Earth, and its quality has a significant influence on living organisms. Clean air, containing balanced concentrations of oxygen, nitrogen, and other gases, is necessary for respiration and the maintenance of biological processes (Ramadhani *et al.*, 2022). However, the rapid development of tourism, including the construction of accommodations and the expansion of outdoor recreational activities around MTNR, poses potential risks of air pollution. Such pollution can negatively affect not only natural ecosystems but also human communities that depend on environmental resources.

One effective approach to assessing air pollution in conservation areas is the use of bioindicators. Bioindicators are living organisms that reflect environmental conditions through their responses to physical, chemical, and biological changes. Recent studies across Southeast Asia confirm that epiphytic lichen

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communities respond strongly to gradients of atmospheric pollution, with diversity indices negatively correlated with particulate and gaseous pollutants in urban–rural comparisons (Hakim *et al*., 2025). Identifying appropriate bioindicators within an ecosystem can provide valuable insight into pollution levels and their ecological impacts. Lichens, which are symbiotic organisms composed of fungi and algae or cyanobacteria, possess a unique ability to absorb water and nutrients directly from the atmosphere due to the absence of vascular tissues (Kurniasih *et al*., 2020; Suharno *et al.,* 2021). This physiological characteristic makes lichens highly sensitive to changes in air quality and microclimatic conditions, thereby rendering them effective natural bioindicators for monitoring air pollution (Conti & Cecchetti, 2001; Erlangga *et al*., 2022). Recent international studies further confirm that lichens respond measurably even to low concentrations of particulate matter and gaseous pollutants, making them particularly suitable for detecting subtle air quality gradients in protected and semi-natural ecosystems (Paoli *et al*., 2015; Munzi *et al*., 2014).

Previous studies have shown that lichen thallus structure is closely associated with air pollution levels. Crustose lichens are generally more tolerant of environmental stress and pollutant exposure, whereas foliose and fruticose lichens are more commonly found in areas with better air quality and more stable environmental conditions (Giordani *et al*., 2012; Nascimbene *et al*., 2017). Pangalengan, with its combination of mountainous forests, plantation areas, and varying degrees of human activity, represents an ideal location to examine the relationship between lichen diversity, air quality, and local microclimatic conditions. Therefore, this study aims to provide scientific evidence on the relationship between lichen diversity and air quality and to support environmental conservation efforts through improved management of the Mount Tilu Nature Reserve.

MATERIALS AND METHODS

Research location

This study was conducted in the MTNR, Pangalengan District, Bandung Regency, West

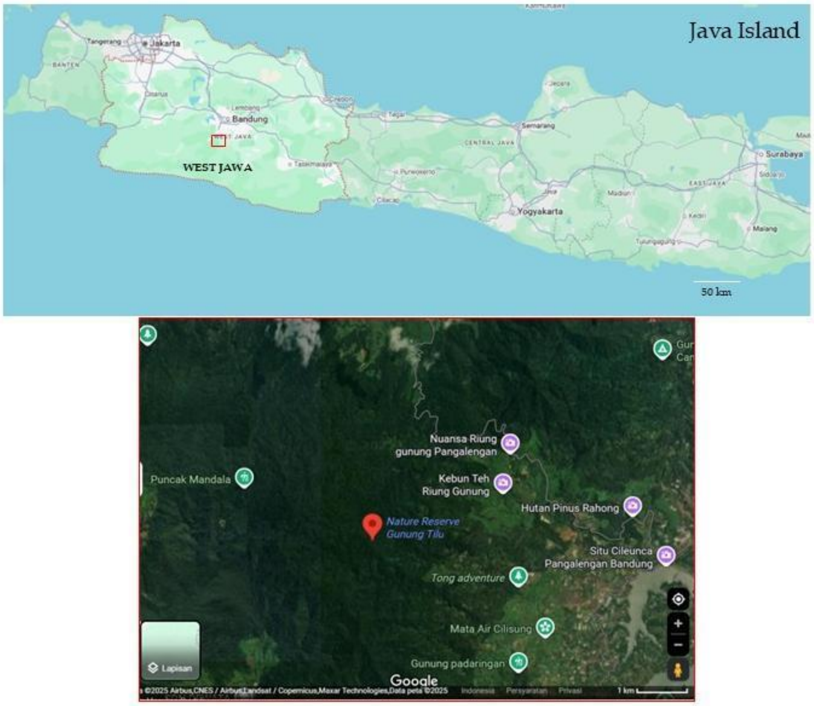

Figure 1. Research location.

Java Province (Figure 1) Coordinates: 7.184645° S, 107.500066° E. The research was carried out over a period of 10 months, from February to November 2025.

Data collection methods

Data collection was conducted using a descriptive exploratory method with a purposive sampling approach, in which sites were selected based on differences in human activity levels assumed to influence air quality. This approach is widely applied in lichen bioindicator studies because it effectively represents spatial gradients of environmental pressure (Bajpai *et al.*, 2012; Kłos *et al.*, 2011). The four observation sites were as follows: tourist area, roadside, agricultural activity area, and forest.

Sampling was conducted at four observation sites located progressively farther from emission sources. At each site, observations were carried out using a line transect measuring 100 m × 10 m, with 10 m between transects (Chandra & Priyono, 2015). Each line transect was divided into ten quadrats, with each quadrat measuring 10 m × 10 m, to facilitate sample collection. Lichen samples were collected from trees at the height of the first branch or approximately 100 cm above ground, with one tree selected within each 10 m × 10 m subplot (Figure 2).

The line transects and quadrat methods are illustrated in the corresponding figure. Lichen colony sampling was performed by establishing three vertically arranged plots measuring 10 cm × 10 cm on the tree trunk within each sampling subplot. All lichens found within each quadrat were recorded based on the host tree, photographed, and measured for thallus diameter. Environmental factors, including air temperature, air humidity, and wind speed, were also measured. This procedure was consistently applied across all study sites.

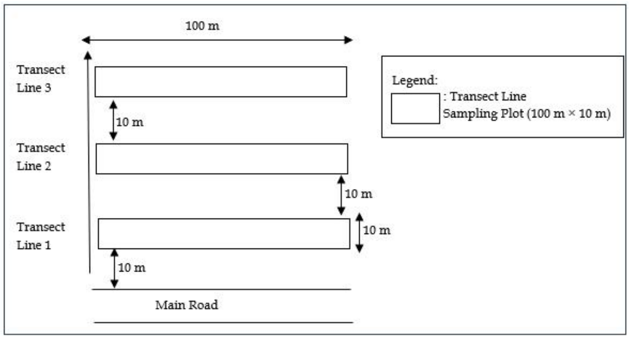

Figure 2. Line transect for sampling.

Data analysis

Lichen samples were carefully scraped from the tree bark surface and placed in envelopes for further identification. Identification was conducted based on morphological characteristics using determination keys (Divakar & Upreti, 2005) and verified through comparison with photographic references. Data analysis was carried out using a qualitative descriptive approach by describing each epiphytic lichen species based on external morphological features observed at the study sites. The identification process involved comparing samples with reference books, including Lichens of East Java, Lichen Biology, Lichen Species Diversity in Bukit Barisan Grand Forest Park Based on Research, Field-Oriented Keys to the Florida Lichens, as well as relevant literature from previous studies on lichens. The data collected was presented in the form of tables and figures.

RESULTS AND DISCUSSION

Lichens are symbiotic organisms whose distribution is strongly influenced by substrate characteristics, particularly the type of host tree on which they grow. Based on the data presented in Table 1, most host trees were recorded in natural forest areas, including Rasamala, Banyan (*Ficus* sp.), Kiara, Puspa, Baros, Eucalyptus (*Melaleuca* sp.), Saninten, Pasang, and Pine. Forest tree species generally provide higher environmental humidity, relatively stable bark surfaces, and dense canopy cover, which help regulate microclimatic factors such as temperature and light intensity, thereby strongly supporting lichen colonization.

Many lichen species, especially those belonging to the foliose and fruticose growth

Table 1. Diversity of lichen host trees in MTNR Bandung.

No	Tree species		Location
	Local names	Scientific names	
1	Rasamala	*Altingia excelsa*	Forest
2	Beringin	*Ficus benjamina* L.	Forest
3	Kiara	*Ficus* sp.	Forest
4	Puspa	*Schima wallichii*	Forest
5	Baros	*Michelia champaca* L.	Forest
6	Kayu Putih	*Melaleuca cajuputi*	Forest
7	Saninten	*Castanopsis argentea*	Forest
8	Pasang	*Quercus* sp.	Forest
9	Nangka	*Artocarpus heterophyllus*	Forest
10	Alpukat	*Persea americana* Mill.	Forest
11	Pinus	*Pinus merkusii*	Roadside
12	Teh	*Camellia sinensis*	Plantation

Table 2. Results of environmental parameter measurements at MTNR, Bandung.

Parameters	**Forest**	**Roadside**	**Plantation**	**Tourist Area**
Temperature (°C)	21,5	25	25	24
Humidity (%)	60	55	50	53
Wind Speed (m/s)	0.5	0.5	2	0.5

forms, were more frequently observed on trees with rough bark textures, such as Rasamala and Pine. Rough bark surfaces offer better attachment sites and micro-crevices that enhance water retention and facilitate the absorption of atmospheric nutrients, conditions that are favorable for lichen growth (Brodo *et al*., 2001).

In contrast, lichen occurrence in plantation areas, particularly tea plantations, was influenced by more intensive human activities, including regular pruning and exposure to chemical inputs such as pesticides. These factors generally result in lower lichen diversity compared to natural forest habitats, as many lichen species are sensitive to pollutants and microhabitat disturbances (Nash, 2008). Consequently, variation in host tree species and the ecosystems in which they occur play a crucial role in shaping the composition and diversity of lichen communities across different land-use types.

Environmental conditions such as temperature, humidity, and wind speed strongly influence lichen abundance and diversity at a given site. Based on the data presented in Table 2, forest areas exhibited the lowest temperature (21.5 °C) and the highest humidity (60%), conditions that are considered optimal for lichen growth because lichens rely heavily on atmospheric moisture (Suharno *et al.*, 2024). Due to the absence of vascular tissues, high humidity is essential for maintaining thallus hydration and supporting efficient photosynthetic activity. Relatively low and stable temperatures also favor the occurrence of lichen species that are sensitive to thermal stress and desiccation (Nash, 2008; Pinho *et al*., 2018).

In contrast, tourist and roadside areas showed higher temperatures and lower humidity, indicating drier microclimatic conditions. Such environments tend to support only stress-tolerant lichen species, particularly those with crustose thallus forms, which are more resistant to moisture limitation and temperature fluctuations. Open environments, including plantation areas, similarly exhibit conditions that restrict the growth of more sensitive lichen groups.

Wind speed further contributes to differences in lichen community composition. Plantation areas recorded the highest wind speed (2 m/s), which can accelerate thallus desiccation and limit lichen

Table 3. Air pollution parameters.

Parameters	Forest	Roadside	Plantation	Tourist area	Standard (PP 22/2021)	Category
HC (mg/m^3)	0.005	0.007	0.005	0.004	≤ 0.1	Good
PM 2,5 (µg/m^3)	27	40	38	35	≤ 65	Good
TVOC (mg/m^3)	0.001	0.03	0,02	0,01	≤ 0.3	Good
CO (ppm)	0	1	1	1	≤ 10	Good
CO_2 (ppm)	400	538	455	420	≤ 1000	Good

Table 4. Epiphytic Lichen Species Found at Each Location.

Species name	Thallus type	Location
Phlyctis agalaea	crustose	Roadside, plantation, tourist area, and forest
Parmelia perlata	foliose	Forest
Parmelia caperata (L.) Ach	foliose	Forest
Lepraria sp.	crustose	Roadside, plantation, tourist area, and forest
Lepraria barbatica	crustose	Roadside, plantation, tourist area, and forest
Lepraria incana (L.)	crustose	Roadside, plantation, tourist area, and forest
Lepraria rigidula	crustose	Roadside, plantation, tourist area, and forest
Cryptothecia striata	crustose	Roadside, plantation, tourist area, and forest
Lecidella sp.	crustose	Roadside, plantation, tourist area, and forest
Leptogium sp.	foliose	Forest
Heterodermia sp.	crustose	Roadside, plantation, tourist area, and forest
Heterodermia japonica	crustose	Roadside, plantation, tourist area, and forest
Heterodermia leucomela	crustose	Roadside, plantation, tourist area, and forest
Heterodermia obscurata	crustose	Roadside, plantation, tourist area, and forest
Usnea filipendula	fructicose	Forest
Usnea cornuta	fructicose	Forest
Usnea hirta (L.)	fructicose	Forest
Usnea trichodea Ach	fructicose	Forest

survival to drought-tolerant or small-structured species, primarily crustose lichens. In contrast, forest, roadside, and tourist areas experienced lower wind speeds (0.5 m/s), allowing lichens to retain moisture for longer periods and maintain physiological activity.

Roadside locations are additionally subject to vehicular emissions. Although temperature and wind conditions at roadside sites were comparable to those in tourist areas, lichen diversity was generally lower due to exposure to air pollutants, particularly sulfur dioxide and particulate matter, to which many lichens are highly sensitive.

Although all air pollution parameters measured in this study were below national regulatory thresholds, variations in $PM_{2.5}$ and total volatile organic compound (TVOC) concentrations among sites may still influence lichen community structure. Studies investigating urban, suburban, and rural gradients illustrate that lichen diversity and atmospheric purity indices correlate inversely with fine particle concentrations ($PM_{2.5}$ and PM_{10}), reinforcing the sensitivity of lichen communities to incremental pollution changes in tropical regions (Hakim *et al.*, 2025). Previous studies have demonstrated that shifts in lichen composition can occur even at

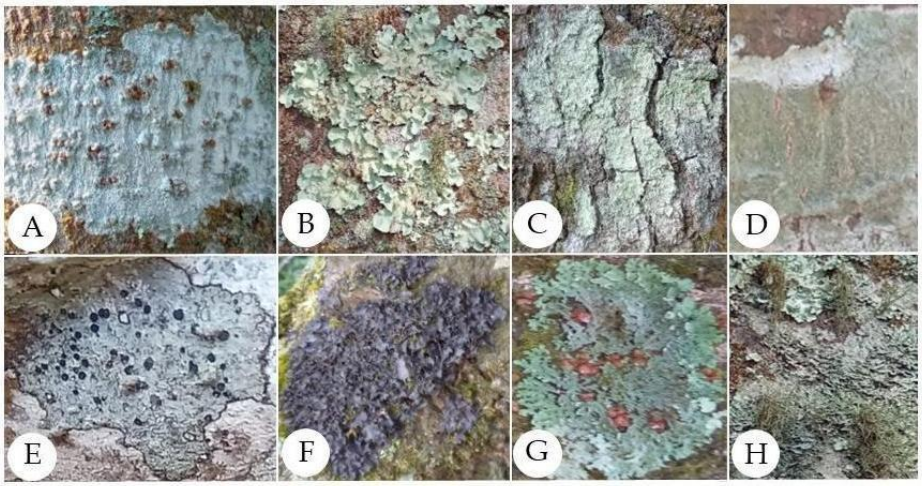

Figure 3. The lichen species found at the research site and dominant in the MTNR area. *Phlyctis agalaea* (A), *Parmelia perlata* (B), *Lepraria* sp. (C), *Cryptothecia striata* (D), *Lecidella* sp. (E), *Leptogium* sp. (F), *Heterodermia* sp. (G), *Usnea filipendula* (H).

relatively low pollutant concentrations, especially among foliose and fruticose species, which are more sensitive to atmospheric contamination (Karmacharya *et al*., 2022). Recent evidence also shows that changes in particulate matter ($PM_{2.5}$) and nitrogen-based pollutants can significantly alter lichen functional traits and community structure before exceeding regulatory air quality thresholds (Munzi *et al*., 2014; Paoli *et al*., 2015). Overall, the interaction between microclimatic factors and air quality plays a critical role in shaping lichen community composition across different habitats.

Based on the air quality parameters measured at the four site types presented in Table 3, all pollutant concentrations were well below the threshold limits established by Government Regulation No. 22/2021 and were therefore classified as good. This condition is highly relevant to lichen occurrence, as lichens are well known as sensitive bioindicators of air pollution, particularly to gases such as sulphur dioxide, ozone, hydrocarbons, and fine particulate matter. Moreover, lichens have been shown to trap and accumulate airborne microplastics along pollution gradients, highlighting their value as broad environmental bioindicators beyond traditional gaseous and particulate matter (Taurozzi *et al*., 2024).

Among the study sites, roadside areas exhibited the highest concentrations of $PM_{2.5}$ (40 µg/m^3) and total volatile organic compounds (TVOC; 0.03 mg/m^3), indicating the influence of vehicular activity and associated emissions. Although these values remain within regulatory limits, sensitive lichen species may still experience reduced diversity at roadside locations compared to forest and tourist areas, which recorded lower pollutant concentrations. This pattern is consistent with previous findings showing that elevated particulate matter and volatile organic compounds can inhibit lichen respiration and photosynthetic processes.

Forest and tourist areas, characterized by the lowest pollutant levels, provide more favorable conditions for lichen growth, particularly for foliose and fruticose lichens that require clean air to thrive. Relatively low carbon dioxide (CO_2) concentrations (400–420 ppm) further support physiological stability in lichens, while very low carbon monoxide (CO) levels indicate minimal influence from combustion-related pollution sources. Although plantation areas exhibited slightly higher $PM_{2.5}$ and TVOC concentrations than forest sites, these values remained within the good category, suggesting that lichens can still grow with relatively high abundance and diversity. Lichens not only respond to classical air pollutants but also accumulate microplastics and serve as effective passive biomonitors for plastic contamination, which may have cascading ecological and human health implications (Taurozzi *et al.*, 2024). Overall, air quality across all sites supports the presence of lichens; however, roadside environments may harbour less diverse lichen communities due to relatively higher exposure to air pollutants compared to forest, plantation, and tourist areas.

The presence of various lichen thallus types across different locations reflects the sensitivity of lichens to environmental conditions (Table 4). Roadside areas were dominated by crustose lichens such as *Phlyctis agalaea*. and *Cryptothecia striata*, which are recognized as the most tolerant growth forms under environmental stress, including air pollution and microclimatic fluctuations. The dominance of crustose lichens in roadside habitats is consistent with the characteristics of these environments, which typically experience higher pollutant exposure and drier microhabitat conditions, allowing only highly tolerant species to persist.

In contrast, forest areas supported foliose lichens such as *Heterodermia* sp. and *Lecidella* sp. indicating that the more humid, shaded, and environmentally stable forest conditions favor lichen species requiring higher moisture availability and cleaner air for photosynthesis. Foliose lichens, characterized by broader thallus surfaces, are generally more sensitive to environmental stress and thus tend to decline in disturbed or polluted habitats. Similar patterns have been reported in urban and peri-urban areas of Central Java, where crustose lichens dominate roadside environments while foliose and fruticose forms are more abundant in less polluted sites, reflecting gradients of air quality associated with human activities (Roziaty *et al.*, 2021).

Fruticose and foliose lichens, including *Usnea filipendula*, *Usnea cornuta*, *Usnea hirta* (L.), *Usnea trichodea* Ach, *Parmelia perlata*, and *Parmelia caperata* (L.) Ach, were found exclusively in forest habitats, suggesting very good air quality, as this growth form is considered the most sensitive to air pollution. Their occurrence is widely used as an indicator of relatively unpolluted environments. Plantation areas exhibited a mixed assemblage of lichen types, dominated primarily by crustose lichens such as Lepraria sp. This pattern suggests that although plantation environments are more open and exposed to wind, pollution levels remain sufficiently low to support tolerant lichen species.

Overall, the distribution of lichen thallus types reflects a clear environmental quality gradient, with forest habitats representing the cleanest and most stable conditions, followed by plantation areas, while roadside habitats experience the highest level of environmental stress. The dominance of crustose lichens along roadsides highlights their adaptive capacity to withstand desiccation and pollutant exposure, whereas the presence of foliose and fruticose lichens in forested areas indicates good air quality and high environmental stability (Giordani *et al.*, 2012; Nascimbene *et al.*, 2017). Fruticose lichens such as *Usnea* and *Parmelia* are widely recognized as indicators of clean air and are rarely found in environments subjected to intense anthropogenic pressure (Aptroot & van Herk, 2007). Recent large-scale biomonitoring studies have shown that the disappearance of fruticose lichens is one of the earliest biological responses to increasing atmospheric nitrogen deposition and fine particulate pollution (Paoli *et al.*, 2015).

The thallus of *Phlyctis agalaea* (Figure 3A) is crustose, white in color, thickened, and circular in shape, appearing like compact floury masses with an uneven surface. When touched, it feels like fine powdery granules. Both upper and lower cortices are absent. This species is corticolous, occurring on tree bark surfaces. Granular soredia are dispersed across the thallus, while apothecia are rare and small. *Phlytis agelaea* was found exclusively on the bark of benzoin trees. The thallus adheres firmly to its substrate, making it difficult to remove without causing damage.

Parmelia perlata (Figure 3B) is a foliose, corticolous lichen. The foliose type is characterized by an almost perfectly rounded thallus. The thallus is green, sometimes gray, dark brown, or brown, and grows horizontally in leaf-like lobes. This species possesses both upper and lower cortices. Attachment to the substrate is relatively loose, with a blackish lower surface bearing rhizines, except near the thallus margins. The lichen attaches to rocks or trees by means of black rhizines. No cilia or fine hairs are present along the thallus margins; however, soredia and soralia are found at the edges.

Lepraria sp. (Figure 3C) exhibits a crustose thallus type. The thallus is rounded, grayish in color, and uneven in surface texture. Like other Lepraria species, it is commonly referred to as a leprose or powdery lichen. Leprose lichens lack both upper and lower cortical layers, and apothecia are not well developed or have not been clearly identified. The thallus consists mainly of loose soredia that are easily dispersed by wind. The photobiont is generally from the genus Trebouxia. This species inhabits tree bark, rocks, or soil surfaces.

Lecidella sp. (Figure 3D) is a corticolous lichen with a crustose thallus that is sky blue in color. The apothecia appear as dark black spots that contrast distinctly with the thallus and are scattered across its surface. The thallus lacks a regular pattern and adheres firmly to tree bark. Lecidella belongs to the group of crustose lichens characterized by dark apothecia. It is commonly found on rocks, soil surfaces, or tree bark.

Cryptothecia striata (Figure 3E) has a green thallus with broad white margins, measuring approximately 7–9 cm in diameter. The entire thallus adheres tightly to the bark substrate, making separation difficult without damage. The thallus is irregularly rounded in shape and bears grayish-green powdery soredia scattered across its surface. A white prothallus is also present.

Leptogium (Figure 3F) is a genus of lichens commonly found in tropical regions and belongs to the foliose group. It has a leaf-like thallus, with colors ranging from bluish-grey to brown or blackish (Manlapaz *et al.*, 2022). The thallus can be gelatinous when wet and is attached to the substrate either loosely or firmly (Safitri *et al.*, 2020). Some species also have additional structures such as isidia or lobules on the thallus surface (Stone & McCune, 2022).

Heterodermia (Figure 3G) is a genus of foliose lichens commonly found in tropical and subtropical regions. It is characterized by a leaf-like thallus that is usually pale grey to whitish in color. The lobes are narrow, often elongated, and may have cilia (hair-like structures) along the margins. The upper surface is typically smooth, while the lower surface may lack a well-developed cortex and is often attached to the substrate by rhizines. Some species produce powdery structures such as soredia or isidia for vegetative reproduction. Heterodermia species commonly grow on tree bark, rocks, or other substrates in well-lit environments and are often used as bioindicators of air quality.

Usnea filipendula (Figure 3H) exhibits a fruticose (filamentous) thallus type, cylindrical or ribbon-like in form, hanging from the substrate surface. The thallus varies in length, appearing cylindrical or beard-like ("beard moss"). This species displays a pendent growth form, with the main thallus and fibrils hanging downward. The thalli grow densely, giving the appearance of shrubs attached to tree bark. Soredia and tubercles are distributed across the thallus surface.

CONCLUSION

Lichen diversity in the Gunung Tilu Nature Reserve reflects variations in air quality and environmental conditions. Forest areas with better air quality and higher humidity support sensitive lichen types, particularly foliose (*Parmelia*, *Leptogium*) and fruticose (*Usnea*) species. In contrast, roadside and plantation areas, which experience higher pollutant exposure and environmental stress, are dominated by more tolerant crustose lichens such as *Lepraria*, *Cryptothecia*, and *Heterodermia*. The presence of fruticose lichens, especially *Usnea*, indicates good air quality, while the dominance of crustose lichens suggests more disturbed conditions. Therefore, lichen growth forms and species composition can be effectively used as bioindicators of air quality in tropical ecosystems.

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