

Original Article

Spatial Distribution of Lichen-Inferred Sensitivity and Functional Traits of Manglicolous Lichens in Davao City, Philippines

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Abstract. Manglicolous lichens inhabit a dynamic terrestrial-marine interface, yet their effectiveness as bioindicators in rapidly urbanizing tropical coasts remains insufficiently understood. This study aimed to assess the ecological responses of manglicolous lichen communities to varying levels of human disturbance along an urban-industrial-rural gradient in Davao City, Philippines. Community sensitivity was evaluated using the Lichen Inferred Sensitivity Index (LISI) and a functional trait-based framework, based on assemblages recorded from 90 phorophytes. A total of 32 taxa were documented, with crustose growth forms comprising 91% of all observations. Functional morphotypes did not differ significantly among sites ($p = 0.681$), suggesting that abiotic factors, such as salinity and tidal inundation, likely act as primary environmental filters, resulting in relatively conserved morphological traits across the gradient. In contrast, LISI values varied across sites, distinguishing a depauperate assemblage in the industrial Panacan area (LISI = 1.60) from a relatively higher sensitivity in the protected Matina biozone (LISI = 3.06). These differences are interpreted as indicative of variation in environmental disturbance, rather than direct pollutant measurements. Spatial outputs are presented as site-level thematic mapping to illustrate patterns in community sensitivity. Overall, the results provide preliminary support for the use of manglicolous lichens as bioindicators of environmental disturbance in coastal ecosystems, with abundance-weighted sensitivity indices offering a potentially useful approach for ecological monitoring in rapidly changing coastal landscapes.

Keywords: Bioindicators; Environmental disturbance; Lichen Inferred Sensitivity Index (LISI); Manglicolous lichens; Spatial analysis.

Manglicolous lichens, which grow on the trunks, branches, and aerial roots of mangroves, occupy a specialized ecological niche at the interface between terrestrial and marine environments. These epiphytes are exposed to both continental and marine air masses due to tidal flooding and the coastal location of mangrove forests. Consequently, they are influenced by a mixture of natural aerosols and anthropogenic emissions originating from nearby urban, industrial, and maritime activities. Similar to other epiphytic lichens, manglicolous lichens obtain water and nutrients directly from atmospheric deposition rather than from soil substrates. Through this process, their thalli gradually accumulate substances present in the surrounding atmosphere, including trace metals, sulfur and nitrogen compounds, and particulate-bound

contaminants (Delves et al., 2023; Yatawara & Dayananda, 2019; Abas et al., 2022; Niepsch et al., 2023).

Because of these physiological characteristics, lichen communities have long been recognized as indirect bioindicators of environmental conditions and disturbance, particularly in relation to air quality gradients. Rather than measuring pollutant concentrations directly, lichen assemblages reflect cumulative environmental stress through shifts in species composition, abundance, and functional traits. Previous studies have shown that traits such as growth form, photobiont type, and ecological tolerance (e.g., nitrophilous versus oligotrophic preferences) influence how lichens respond to atmospheric stressors (Delves et al., 2023; Yatawara & Dayananda, 2019; Frati & Brunialti, 2023; Bahinskyi et al., 2025). Consequently, variations in manglicolous lichen assemblages may provide insights into spatial patterns of environmental disturbance along coastal landscapes.

Globally, lichen biomonitoring has been widely applied as a complementary approach to conventional air quality monitoring, particularly in regions where instrumental monitoring networks are limited or financially demanding to maintain (Abas et al., 2022; Niepsch et al., 2023; Bahinskyi et al., 2025; Conti & Cecchetti, 2001). Epiphytic lichens have been used to investigate spatial patterns of nitrogen enrichment, heavy metal deposition, acidic gases, and particulate matter across urban–rural gradients and industrial landscapes. These studies often employ lichen diversity indices, functional groups, or trait-based classifications to infer environmental stress patterns rather than directly quantify pollutant concentrations (Delves et al., 2023; Taurozzi et al., 2024; Yatawara & Dayananda, 2019; Correa-Ochoa et al., 2021; Niepsch et al., 2023; Belguidoum et al., 2022).

Recent syntheses highlight two complementary trends in lichen biomonitoring research. First, dense sampling networks of epiphytic lichens are increasingly employed to generate high-resolution spatial representations of environmental gradients. Second, functional trait and ecological tolerance frameworks are being developed to improve the transferability of lichen-based bioindicator systems across regions (Delves et al., 2023; Yatawara & Dayananda, 2019; Frati & Brunialti, 2023; Correa-Ochoa et al., 2021; Niepsch et al., 2023; Belguidoum et al., 2022). Despite these advances, most studies remain concentrated in temperate ecosystems, resulting in a pronounced geographic bias in the existing body of knowledge. Tropical and coastal ecosystems—particularly mangrove forests—are still comparatively understudied within global biomonitoring frameworks (Delves et al., 2023; Yatawara & Dayananda, 2019). While previous research has leveraged dense sampling networks to produce spatially explicit representations of environmental gradients, the present study instead emphasizes site-level thematic visualization.

In Southeast Asia, lichen-based biomonitoring studies are gradually increasing but remain unevenly distributed. Previous research in tropical urban environments has utilized corticolous lichens to examine rural–urban gradients, estimate atmospheric purity indices, and generate spatial maps of environmental quality (Yatawara & Dayananda, 2019; Correa-Ochoa et al., 2021; Hakim et al., 2025). Studies from Malaysia and other parts of the region have also demonstrated that epiphytic lichen assemblages respond to gradients of gaseous pollutants and particulate matter, supporting their usefulness as low-cost indicators of environmental stress in tropical settings (Abas et al., 2022; Hakim et al., 2025). Nevertheless, the integration of mangrove-associated lichen communities into biomonitoring frameworks remains limited, and systematic assessments of manglicolous lichens as indicators of environmental conditions are still in their early stages.

This gap is particularly important in countries with extensive coastlines and archipelagic geography, such as the Philippines, where mangrove ecosystems provide critical ecosystem services, including shoreline protection, fisheries support, and carbon storage. Rapid urbanization in coastal cities may alter atmospheric conditions and environmental quality in mangrove areas. However, ecological monitoring systems capable of detecting such changes remain limited. In many secondary cities in the Philippines, including Davao City, conventional air quality monitoring stations are scarce, limiting the availability of fine-scale environmental data needed for local planning and conservation initiatives.

Given these circumstances, exploring the potential of manglicolous lichens as bioindicators of environmental disturbance in mangrove ecosystems may provide valuable complementary information for ecological monitoring. Therefore, this study applies a trait-based approach to manglicolous lichen assemblages in the mangrove forests of Davao City. Specifically, the research aims to: (i) classify mangrove lichens according to functional traits associated with ecological tolerance and sensitivity, (ii) examine how urbanization gradients influence the composition of lichen functional groups, and (iii) develop spatial representations of Lichen-Inferred

Sensitivity across the mangrove fringe to highlight potential environmental hotspots and relatively less-disturbed areas.

By providing spatially explicit ecological indicators derived from mangrove-associated lichens, this study contributes to improving the understanding of environmental patterns in coastal urban ecosystems where instrumental monitoring is limited. Furthermore, the research supports Sustainable Development Goal 11 (Sustainable Cities and Communities) by contributing locally relevant ecological information that may assist urban planners and coastal managers in identifying areas that require environmental attention or prioritization for conservation (United Nations DESA, 2018). Through this approach, manglicolous lichens may serve as a scalable and cost-effective component of environmental monitoring strategies in resource-limited coastal regions (Abas et al., 2022; Delves et al., 2023).

Methodology

Research Design

A quantitative, descriptive-comparative, and geographical modeling research design was used in this study. The ecological response of manglicolous lichens to urbanization was evaluated using a functional trait-based approach, recognizing that particular thallus morphologies determine physiological reactions to environmental stress (Nash, 2008). In contrast to continuous forest evaluations, a discrete spatial analysis approach was used to account for the lichens' tree-bound presence and the fragmented nature of mangrove stands (Potenza et al., 2022). In accordance with accepted reasoning for evaluating anthropogenic disturbance through changing biological indices, our method employed a "Lichen Inferred Sensitivity" concept to convert community composition into site-level environmental quality indicators (Gombert et al., 2004; Pinho et al., 2012). Moreover, this study represents the second phase of a broader investigation on mangrove lichens in Davao City, Philippines, focusing on their spatial distribution. The initial phase identified and classified the lichen species present in the study sites as reported by Tadena and Dedal (2026).

Study Area and Site Stratification

The study was conducted in mangrove forests in Davao City, Philippines. Three sampling locations were chosen to illustrate a gradient of anthropogenic disturbance. The Matina Aplaya (protected urban zone) in Figure 1 is situated in the southern sector and is impacted by residential development, major road networks, exposure to domestic effluents, and vehicular emissions. Figure 2 shows the Panacan (industrial/peri-urban) zone, which is near Davao Sasa Port and other industrial facilities. It is exposed to moderate automotive traffic, dust, and potential heavy-metal deposition from port and shipping operations. Last but not least, Figure 3 illustrates Lasang (rural/reference zone), located at the city's northern edge and comparatively far from heavy industry and the core business center, making it a reference site with less visible anthropogenic disruption.

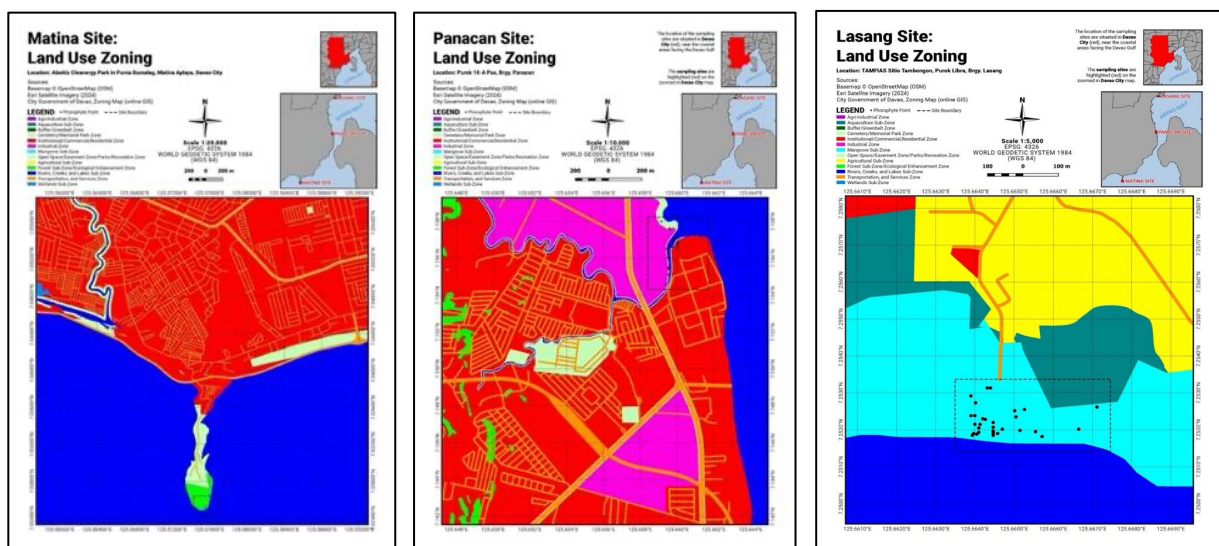


Figure 1. Land Use and Zoning Map of the Matina Site (left), Panacan Site (middle), Lasang Site (right)

Data Collection and Sampling Procedure

Mature mangrove trees that provide stable microhabitats for lichen colonization were purposively sampled at three stations in Davao City to evaluate the geographic distribution of manglicolous lichens. Thirty phorophytes were selected at each station, with a minimum of 10 meters separating trees, in compliance with recognized procedures to reduce spatial autocorrelation and ensure sample independence (Reynolds et al., 2017). To standardize the observation of standing bark features, phorophyte selection prioritized accessible mature trees with developed trunks and stable root systems, avoiding those in inaccessible, flooded areas. Using revised local assessments (Barcelete et al., 2016; Pototan et al., 2017) and regional field keys from Primavera (2009) and Lebata-Ramos (2013), these mangrove hosts were identified.

For the purpose of maintaining the health of the phorophyte, lichen samples were collected using conventional non-destructive methods. Only the part of the bark with the thalli was excised using a flat-edged chisel, and the exposed areas were painted with colorless nail polish (Nayaka, 2014). To prevent deterioration, at least two thalli per morphospecies were collected and stored in polythene containers lined with newspaper blotters (Fajardo & Bawingan, 2019). In order to identify diagnostic lichen acids, subsequent characterization included a thorough morpho-anatomical examination of reproductive structures (ascocarps, spores) using stereomicroscopy and compound microscopy in addition to standard chemical spot tests (K, C, P, and I) (Fajardo & Bawingan, 2019; Joshi et al., 2018). For complex taxa such as *Bacidia*, *Graphis*, and *Lecanora*, specialized keys were used for final taxonomic verification (Ekman, 2001; Lee & Hur, 2022; Lücking et al., 2009; Santos et al., 2023). The dataset utilized in this study was largely based on the lichen specimens documented in the initial phase of the research (Tadena & Dedal, 2026). However, upon further taxonomic verification and detailed examination, one additional manglicolous lichen species was identified and subsequently included in the present analysis. Particularly, the *Psilolechia lucida* (Ach.) M. Choisy, which was sighted in all the sampling sites on the following mangrove hosts: *Avicennia marina*, *Ceriops tagal*, *Rhizophora mucronata*, *Rhizophora stylosa*, *Sonneratia alba*.

Classification of Functional Traits and Inferred Sensitivity

Functional Morphotypes. According to Barkman (1958) and Nash (2008), lichen taxa were categorized into three functional growth forms: crustose, foliose, and fruticose. These growth forms represent basic variations in thallus morphology that affect their surface-to-volume ratio, water relations, and ability to intercept pollutants. Crustose lichens are thought to be the most toxitolerant of these categories because their thalli firmly attach to the substrate (Seaward, 2008). According to Conti and Cecchetti (2001), foliose lichens are distinguished by leaf-like thalli with different surfaces and frequently exhibit intermediate sensitivity. According to Hawksworth and Rose (1970) and Nimis et al. (2002), fruticose lichens, which produce shrub-like or pendulous thalli, have the most exposed surface area and are therefore usually the most sensitive category to pollution and disturbance gradients.

Inferred Sensitivity Scoring. Using information from studies on disturbance and air quality in tropical and Southeast Asia, species lists were cross-referenced with global and regional lichen-sensitivity frameworks to predict pollution-sensitivity ratings (Felicia Sampe et al., 2020). Based on well-established studies on nitrophytes and acidophytes (van Herk, 2001; Wolseley et al., 2013), urban-rural gradients (Grifoni et al., 2025; Hawksworth & Rose, 1970), and lichen-based air quality indices (Conti & Cecchetti, 2001; LeBlanc & De Sloover, 1970), these indicator concepts differentiate between tolerant, moderately sensitive, and highly sensitive taxa. These frameworks were used to classify each species into one of three groups: moderately sensitive taxa, which exhibit intermediate ecological amplitude and usually decline in heavily polluted or highly disturbed zones; tolerant taxa, which persist or proliferate in eutrophicated or polluted environments and frequently include crustose or nitrophilous forms; and sensitive taxa, which are restricted to relatively undisturbed sites characterized by high humidity and clean air, frequently comprising fruticose and specialized foliose species.

Data Analysis Procedure

Quantification of Functional Composition. The relative abundance of crustose, foliose, and fruticose morphotypes was computed for each site. The null hypothesis that urbanization level does not shape functional community composition was tested using a Chi-Square Test of Independence (χ^2) to determine whether growth-form composition is independent of location.

Lichen Inferred Sensitivity Index (LISI). To quantify environmental quality, a site-level Lichen Inferred Sensitivity Index (LISI) was computed using a modified Index of Atmospheric Purity (IAP) logic (Gombert et al., 2004; LeBlanc & De Sloover, 1970; Conti & Cecchetti, 2001):

$$LISI = (\sum (F_i \times S_i)) / n$$

where (F_i) is the frequency of species (i) at the site, (S_i) is the assigned sensitivity score of species (i), and (n) is the total number of species recorded at that site. According to Gombert et al. (2004), LeBlanc & De Sloover (1970), and Conti & Cecchetti (2001), higher LISI values indicate lichen assemblages containing a greater contribution of sensitive taxa and higher overall abundance, which are typically associated with less disturbed environmental conditions.

The interpretation of lichen assemblage patterns in this study follows a bioindicator-based inference framework. Manglicolous lichens were not used to directly quantify atmospheric pollutant concentrations. Instead, variations in species composition, functional traits, and ecological tolerance were interpreted as indirect indicators of environmental disturbance potentially associated with atmospheric stressors. This approach is consistent with established lichen biomonitoring methods in which community responses reflect cumulative environmental conditions rather than direct pollutant measurements. Consequently, the observed patterns in Lichen Inferred Sensitivity Index (LISI) values were interpreted as relative indications of environmental stress gradients across sites rather than precise measures of pollution levels.

Spatial Analysis and Mapping

QGIS (version 3.28) was used for geospatial processing. A vector-based point classification approach was used instead of raster interpolation because mangrove lichens are found on individual trees rather than forming continuous carpets. This method prevented the formation of artificial surfaces and incorrect bridging between spatially disjunct mangrove patches and non-vegetated areas (Ye & Zhou, 2024; Wang et al., 2018; Soffianian et al., 2023). GPS coordinates of each phorophytes were loaded into QGIS as point features, each ascribed with a Lichen Sensitivity Rating to Pollution and Lichen Inferred Sensitivity Index (LISI-derived classes).

To visualize spatial patterns in the biological response to urbanization, the LISI-derived classes classified points based on site-level sensitivity scores. For the sensitivity rating, points were assigned to the tolerance category of the dominant or representative species at each tree (e.g., green for tolerant, yellow for moderately sensitive, and red for sensitive) (Pinho et al., 2012). The identification of potential environmental hotspots and coldspots along the urban-industrial-rural gradient was made easier by these thematic maps, which enabled visualization of geographical groupings of tolerant vs. sensitive groups (Loppi & Frati, 2006; Gombert et al., 2004). The resulting map represents a site-level thematic visualization of LISI values, illustrating spatial variation in lichen-based environmental sensitivity among the surveyed mangrove areas.

It is important to note that the generated map does not represent a predictive or high-resolution spatial model of atmospheric pollution. Rather, it provides a descriptive spatial representation of bioindicator patterns derived from sampled locations, enabling the identification of potential environmental hotspots and relatively less disturbed areas within the study sites.

Ethical Considerations

Before the field survey began, the necessary ethical and administrative concerns were addressed. In addition to the general locational approval granted by the Cleanergy Park administration and the barangay local government units, the Department of Environment and Natural Resources (DENR) Region XI issued a gratuitous permit for the study. The research design used non-invasive sampling techniques to ensure the health of the phorophytes and the integrity of the ecosystem. Throughout the data-gathering and analysis process, clarity was achieved, ensuring the accuracy of biodiversity data without modification. The study complies with all institutional and national standards for conducting ecological research, as confirmed by the official ethical oversight provided by the University Research Ethics Board of Davao Oriental State University (Mati City) through a Research Ethics Clearance.

Results and Discussion

Diversity and Ecological Traits of Mangrove Lichens

The three mangrove forests examined in Davao City yielded a total of 32 lichen taxa (Table 1). The assemblage was strongly dominated by crustose growth forms, which represented 84% (27 species) of the recorded diversity. Such dominance of crustose lichens is consistent with patterns reported in mangrove and coastal ecosystems globally. For example, epiphytic lichen communities in Ecuadorian salt flats bordering mangrove habitats were also dominated by crustose taxa, many of which are associated with the photobiont *Trentepohlia*, an alga known to tolerate high light exposure, salinity, and moisture stress (Benítez et al., 2024). Similarly, studies conducted in mangrove forests of Indonesia, India, and the Moroccan Atlantic coast have documented crustose lichens as the most prevalent morphological group. At the same time, foliose and fruticose forms occur less frequently and are often associated with relatively stable microhabitats (Benítez et al., 2024; Panda, 2017; Pratama & Trianto, 2020; Mohamed et al., 2021).

The high proportion of crustose species recorded in Davao is consistent with reports indicating that 60–90% of manglicolous lichen communities in Southeast Asia are crustose (Lucban, 2019; Pratama & Trianto, 2020). In contrast, foliose lichens were comparatively rare and were represented only by species belonging to *Dirinaria*, *Heterodermia*, and *Pyxine*. No fruticose lichens were recorded within the surveyed sites. Previous studies have suggested that fruticose lichens are generally more sensitive to environmental disturbance and microclimatic fluctuations. Their absence in coastal or urban habitats has sometimes been interpreted as an indicator of environmental stress (Lucban, 2019; Mohamed et al., 2021). However, the absence of fruticose taxa in the present study should be interpreted cautiously, as mangrove environments themselves present naturally harsh conditions that may limit the establishment of such morphologies.

Table 1. Taxonomic Diversity, Phorophyte Associations, and Ecological Traits of Mangrove Lichens

Lichen Species	Phorophyte(s)	Observed Location(s)	Growth Form	Sensitivity Rating
<i>Arthothelium</i> sp.	<i>Aegiceras floridum</i> , <i>Bruguiera cylindrica</i> , <i>Ceriops tagal</i>	Matina	Crustose	1
<i>Bacidia</i> cf. <i>arceutina</i>	<i>Sonneratia alba</i>	Lasang	Crustose	1
<i>Biatora</i> sp.	<i>Sonneratia alba</i>	Lasang	Crustose	1
<i>Candelariella</i> sp.	<i>Rhizophora apiculata</i> <i>Bruguiera gymnorrhiza</i> , <i>Rhizophora mucronata</i>	Panacan, Lasang	Crustose	1
<i>Chrysothrix xanthina</i> (Vain.) Kalb	<i>Avicennia lanata</i> (Panacan), <i>Sonneratia alba</i> , <i>Rhizophora apiculata</i>	Panacan, Lasang	Crustose	1
<i>Cryptothecia</i> sp. 1	<i>Sonneratia alba</i>	Panacan	Crustose	1
<i>Cryptothecia</i> sp. 2	<i>Excoecaria agallocha</i> , <i>Sonneratia alba</i> , <i>Bruguiera gymnorrhiza</i>	Panacan, Lasang	Crustose	1
<i>Diorygma pruinsum</i>	<i>Bruguiera cylindrica</i> , <i>Rhizophora stylosa</i> , <i>Ceriops tagal</i>	Matina	Crustose	1
<i>Dirinaria</i> cf. <i>minuta</i>	<i>Bruguiera cylindrica</i> , <i>Ceriops tagal</i> , <i>Rhizophora mucronata</i>	Matina, Panacan	Foliose	2
<i>Graphis cincta</i>	<i>Sonneratia caseolaris</i>	Panacan	Crustose	1
<i>Graphis fujianensis</i>	<i>Bruguiera cylindrica</i> , <i>Sonneratia alba</i> , <i>Ceriops tagal</i>	Matina	Crustose	1
<i>Graphis immersicans</i>	<i>Bruguiera cylindrica</i> , <i>Rhizophora stylosa</i>	Matina	Crustose	1
A.W. Archer				
<i>Graphis</i> cf. <i>kelongana</i>	<i>Bruguiera cylindrica</i> , <i>Rhizophora stylosa</i>	Matina	Crustose	1
<i>Graphis modesta</i> Zahlbr.	<i>Bruguiera cylindrica</i> , <i>Rhizophora stylosa</i> , <i>Rhizophora mucronata</i>	Matina, Panacan	Crustose	1
<i>Graphis nuda</i> (H. Magn.) Staiger	<i>Bruguiera cylindrica</i> , <i>Rhizophora stylosa</i>	Matina	Crustose	1
<i>Heterodermia</i> cf. <i>tremulans</i>	<i>Rhizophora stylosa</i>	Matina	Foliose	2
<i>Heterodermia</i> sp.	<i>Bruguiera cylindrica</i> , <i>Ceriops tagal</i>	Matina	Foliose	2
<i>Lecanora helva</i> Stizenb.	<i>Rhizophora mucronata</i>	Lasang	Crustose	1
<i>Lepra</i> cf. <i>albopunctata</i>	<i>Sonneratia alba</i>	Panacan	Crustose	1
<i>Lepra corallina</i>	<i>Rhizophora stylosa</i> , <i>Rhizophora mucronata</i>	Matina, Panacan	Crustose	1
<i>Lepra corallina</i> var. <i>minor</i>	<i>Rhizophora mucronata</i>	Panacan	Crustose	1

<i>Lepraria</i> sp. 1	<i>Rhizophora stylosa</i> , <i>Rhizophora mucronata</i> , <i>Excoecaria agallocha</i> , <i>Avicennia lanata</i> , <i>Avicennia lanata</i>	Matina, Panacan, Lasang	Crustose	1
<i>Lepraria</i> sp. 2	<i>Sonneratia alba</i>	Lasang	Crustose	1
<i>Lepraria</i> sp. 3	<i>Avicennia lanata</i>	Panacan	Crustose	1
<i>Opegrapha</i> cf. <i>astraea</i>	<i>Aegiceras floridum</i> , <i>Bruguiera cylindrica</i> , <i>Ceriops tagal</i>	Matina	Crustose	1
<i>Opegrapha</i> cf. <i>dimidiata</i>	<i>Aegiceras floridum</i> , <i>Bruguiera cylindrica</i> , <i>Ceriops tagal</i>	Matina	Crustose	1
<i>Pertusaria</i> sp.	<i>Sonneratia alba</i>	Matina	Crustose	1
<i>Phaeographis</i> sp.	<i>Sonneratia alba</i> , <i>Lumnitzera racemosa</i>	Panacan, Lasang	Crustose	1
<i>Psilolechia lucida</i> (Ach.) M. Choisy	<i>Ceriops tagal</i> , <i>Rhizophora stylosa</i> , <i>Avicennia marina</i> , <i>Rhizophora mucronata</i> , <i>Sonneratia alba</i>	Matina, Panacan, Lasang	Crustose	1
<i>Pyrenula</i> sp.	<i>Sonneratia alba</i>	Panacan	Crustose	1
<i>Pyxine</i> sp. 1	<i>Sonneratia alba</i>	Lasang	Foliose	2
<i>Pyxine</i> sp. 2	<i>Rhizophora mucronata</i>	Panacan	Foliose	2

Note: Sensitivity Scale: 3 = Highly sensitive; 2 = Moderately tolerant; 1 = Highly tolerant of salinity, moisture, and disturbance

The occurrence of the foliose genus *Pyxine* in the Panacan and Lasang sites is also noteworthy. Species of *Pyxine* are frequently described as nitrophilous or nutrient-tolerant lichens and have been reported from coastal and urban environments influenced by atmospheric nitrogen deposition or nutrient enrichment (Benítez et al., 2018; Moreno-Palacios et al., 2024; Mohamed et al., 2021). While the present study did not directly measure atmospheric pollutants, the presence of such taxa may suggest localized nutrient enrichment or disturbance in these areas.

Overall, the lichen assemblage documented in this study reflects a community composed largely of stress-tolerant morphotypes, a pattern commonly observed in coastal mangrove ecosystems where environmental conditions such as salinity, tidal inundation, and exposure to wind and sunlight act as strong ecological filters.

Phorophyte Specificity and Bark Traits

The distribution of lichen taxa among mangrove host trees (phorophytes) showed clear patterns of host-tree association, suggesting that bark characteristics may influence the composition of epiphytic communities. For example, *Sonneratia alba* in the Lasang site supported a distinct assemblage including *Bacidia*, *Biatora*, and the foliose genus *Pyxine*. At the same time, several script lichens belonging to the family Graphidaceae (*Graphis* and *Opegrapha*) were predominantly associated with *Bruguiera cylindrica* in the Matina site.

Such patterns are consistent with studies demonstrating that bark physiognomy and chemical properties influence epiphytic lichen colonization (Jüriado & Paal, 2019; Paukov et al., 2022). Bark texture, pH, moisture retention capacity, and tree diameter can influence the availability of suitable microsites for lichen establishment. In tropical forest ecosystems, smooth-barked trees with larger trunk diameters have often been associated with higher lichen richness and the occurrence of taxa such as *Bacidia* and members of the Graphidaceae (Benítez et al., 2024; Martínez-Habibe et al., 2025).

Research conducted in *Avicennia marina*-dominated mangroves in New Zealand has also demonstrated that local microclimatic conditions and tree size can strongly influence lichen diversity (Reynolds et al., 2017). Similarly, bark roughness and canopy structure may determine the distribution of different functional groups, particularly macrolichens that require greater moisture retention and stable substrates (Martínez-Habibe et al., 2025; Villagra et al., 2023; Pablo et al., 2023).

It is therefore important to acknowledge that host-tree composition may confound the interpretation of spatial differences in lichen assemblages. Mangrove species such as *Excoecaria agallocha*, *Rhizophora apiculata*, and *Rhizophora mucronata* have been reported to host distinct and diverse lichen communities (Panda, 2017; Lucban, 2019; Fajardo, 2024; Pratama & Trianto, 2020). Consequently, some differences observed among sites in this study may partly reflect variation in phorophyte availability rather than environmental disturbance alone.

Bioindication and Environmental Stress

The environmental health of the study areas is clarified by using lichen functional characteristics and sensitivity scales (LISI). The trend in Davao, typified by the restricted abundance of nitrophiles, the rarity of moderately

tolerant taxa, and the predominance of high-tolerance (LISI Rating 1) crustose species such as *Cryptothecia* and *Lepraria*, is consistent with broader bioindication findings. Lichen species richness and functional-trait diversity have been demonstrated to decrease from forest to urban sites along land-use gradients in Andean riparian forests, with tolerant, stress-adapted growth forms predominating disturbed areas (Chuquimarca et al., 2019; Benítez et al., 2018). Communities in disturbed forests are biased toward species with stress-tolerant morphologies. At the same time, sensitive competitors (such as cyanolichens, gelatinous, and squamulose forms) vanish, according to trait-based research (Benítez et al., 2018).

Additionally, transitions from diversified communities to assemblages dominated by a few toxictolerant crustose taxa are documented in urban and peri-urban lichen surveys; this tendency is closely associated with elevated levels of NO_x, SO₂, O₃, and CO (Moreno-Palacios et al., 2024; Mohamed et al., 2021). The predominance of tolerant crustose taxa in Davao is therefore interpreted as evidence of anthropogenic stress, including urbanization and agricultural inputs, even though lichens in mangrove regions are naturally salt-tolerant but still highly responsive to pollution (Panda, 2017; Lucban, 2019; Fajardo, 2024; Pratama & Trianto, 2020).

Comparative Context of Mangrove Lichen Diversity

The 32 taxa identified in Davao are quantitatively within the lower-to-moderate range of mangrove lichen richness reported worldwide. In contrast, Indian mangroves in Bhitarkanika supported 49 species over eight sites. In comparison, single-species mangrove stands in New Zealand maintained 106 lichen species on *Avicennia* alone (Reynolds et al., 2017). Mangroves in Calabarzon, the Philippines, produced forty manglicolous species, several of which were new national records, with a significant foliose component in areas with less disturbance (Lucban, 2019). On the other hand, recently surveyed mangrove reserves in the Philippines, such as Bangrin Marine Protected Area, exhibit extremely low crustose species richness, likely due to the immature plantation structure and poor phorophyte diversity (Fajardo, 2024). When compared to less disturbed or structurally more complex mangrove forests, these studies collectively imply that Davao's mangrove lichen flora is species-poor and functionally biased, supporting the idea that it is a stressed, compositionally filtered community shaped by both severe anthropogenic pressures and the harsh mangrove microclimate.

Quantification of Functional Composition

To evaluate the functional structure of the lichen communities, species were classified according to thallus growth form, distinguishing between crustose and foliose lichens. Growth form is commonly used as a functional trait in lichen ecology and biomonitoring studies because it reflects differences in substrate attachment, exposure to environmental stress, and physiological tolerance (Ellis et al., 2021; Asplund & Wardle, 2017).

Across the three mangrove sites, crustose lichens accounted for more than 91% of the recorded taxa, indicating a strong dominance of this growth form (Table 2). However, the results of the Chi-Square Test of Independence were not statistically significant ($p = 0.681$), suggesting that the proportion of crustose and foliose lichens did not differ significantly among the sites.

Table 2. Quantification of Functional Composition

Site	Crustose (%)	Foliose (%)	Dominant Form
Matina	94.25%	5.75%	Crustose
Lasang	91.67%	8.33%	Crustose
Panacan	95.65%	4.35%	Crustose

Under the present classification scheme, the functional composition of the communities appears broadly similar across locations. However, this result should be interpreted cautiously, as the functional analysis was based solely on growth-form categories, which constitute a simplified classification of lichen functional traits. Additional traits—such as photobiont type, reproductive strategy, or physiological tolerance—may reveal more subtle ecological differences among sites. Therefore, rather than indicating a uniform ecological filtering process, the results simply suggest that growth-form composition did not vary significantly across the sampled sites within the limits of the trait classification used in this study.

Lichen Inferred Sensitivity Index (LISI)

The Lichen Inferred Sensitivity Index (LISI) in Table 3 showed that although the types of lichens (functional groups) were consistent across locations, the environmental quality indicated by community health differed

dramatically. A distinct gradient of environmental deterioration, overlooked by functional analysis, was revealed by this index, which combines species' specific sensitivity and abundance (frequency). With a strong lichen population, indicating a microclimate and air quality stable enough to support colonization, Matina was found to have the highest environmental quality (LISI = 3.06). On the other hand, with a score almost half that of Matina, Panacan was determined to be the most disturbed or polluted area (LISI = 1.60). This is an indication of a "lichen desert," an area where environmental stress, most likely air pollution or physical disturbance, has reduced the population size. Lasang had a position in between (LISI = 2.16).

Table 3. *Lichen Inferred Sensitivity Index (LISI)*

Site	Total Frequency (ΣFi)	LISI Score	Rank
Matina	High	3.06	1 (Best)
Lasang	Moderate	2.16	2
Panacan	Low	1.60	3 (Poorest)

These results are in line with numerous lichen studies showing that environmental degradation can be detected by community-level indices that incorporate species sensitivity and abundance, even when basic functional composition appears similar across sites (Correa-Ochoa *et al.*, 2021; Will-Wolf *et al.*, 2015; Okon *et al.*, 2024). The Index of Atmospheric Purity (IAP) and Lichen Diversity Value (LDV), which weight species by tolerance and use frequency to infer environmental quality, are two well-known bioindication metrics that the LISI adheres to (Agnan *et al.*, 2017; Rocha *et al.*, 2022). These indices have frequently revealed pollution gradients that are not apparent from growth-form data alone. For example, Agnan *et al.* (2017) found that abundance-based indices were more sensitive indicators of pollution than diversity-focused metrics.

According to multiple urban biomonitoring studies, high pollution loads consistently yield low index values and depauperate lichen cover, similar to the "lichen desert" phenomenon observed in Panacan (Gagić-Serdar *et al.*, 2023; Mikhaylov, 2020; Belguidoum *et al.*, 2022). Thus, even in mangrove settings where the fundamental functional group composition is preserved, the clear gradient observed in this work demonstrates that sensitivity indices such as LISI are effective tools for assessing the degree of urban and industrial impact.

Spatial Map of Lichen Inferred Sensitivity

The spatial analysis presented in Figures 4–6 provides a site-level visualization of lichen sensitivity patterns across the three mangrove locations. These maps illustrate how lichen communities vary with surrounding land use and vegetation structure.

At the Matina site (Aboitiz Cleanergy Park), sampling points occur within a relatively continuous mangrove canopy. The lichen community is dominated by taxa categorized as tolerant to salinity, moisture, and disturbance. Rather than indicating anthropogenic degradation, this pattern may reflect the naturally stressful conditions typical of coastal mangrove environments, including salt spray, tidal inundation, and wind exposure (Higgins *et al.*, 2015; Tindall-Jones *et al.*, 2023).

In contrast, the Lasang site occurs within a fragmented landscape characterized by aquaculture ponds and roadside vegetation strips. Fragmented habitats often experience altered microclimatic conditions such as increased light exposure, desiccation, and edge effects, which may influence lichen communities (Boggess *et al.*, 2024; Tripp *et al.*, 2019). The persistence of moderately tolerant species within these vegetated strips suggests that even small patches of mangrove vegetation may function as microrefugia for lichen diversity in modified coastal landscapes.

The Panacan site represents a coastal-industrial interface, where mangrove vegetation occurs alongside urban and industrial infrastructure. Lichen assemblages at this site include both tolerant and moderately tolerant species. This pattern may reflect the influence of the surrounding urban environment. However, vegetated buffer strips may help maintain localized microhabitats that support lichen colonization (Koch *et al.*, 2019; Moreno-Palacios *et al.*, 2024). Generally, the spatial patterns observed in this study illustrate site-specific ecological conditions rather than a generalized city-wide model of mangrove lichen response.

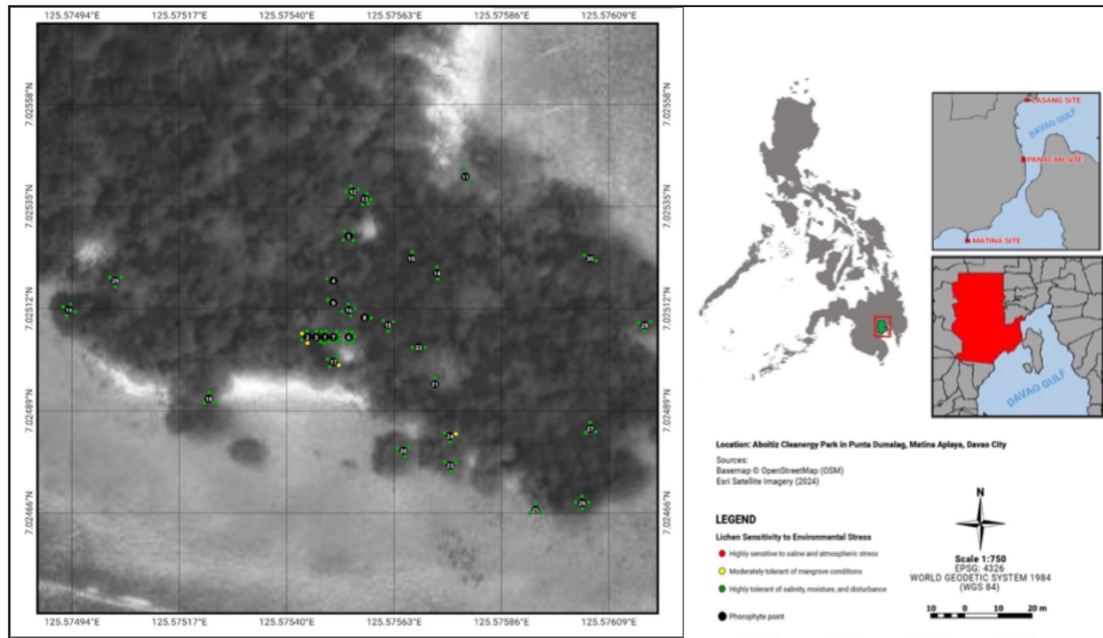


Figure 4. Matina Site Lichen Inferred Sensitivity Bioindicator Map of Mangrove Lichens

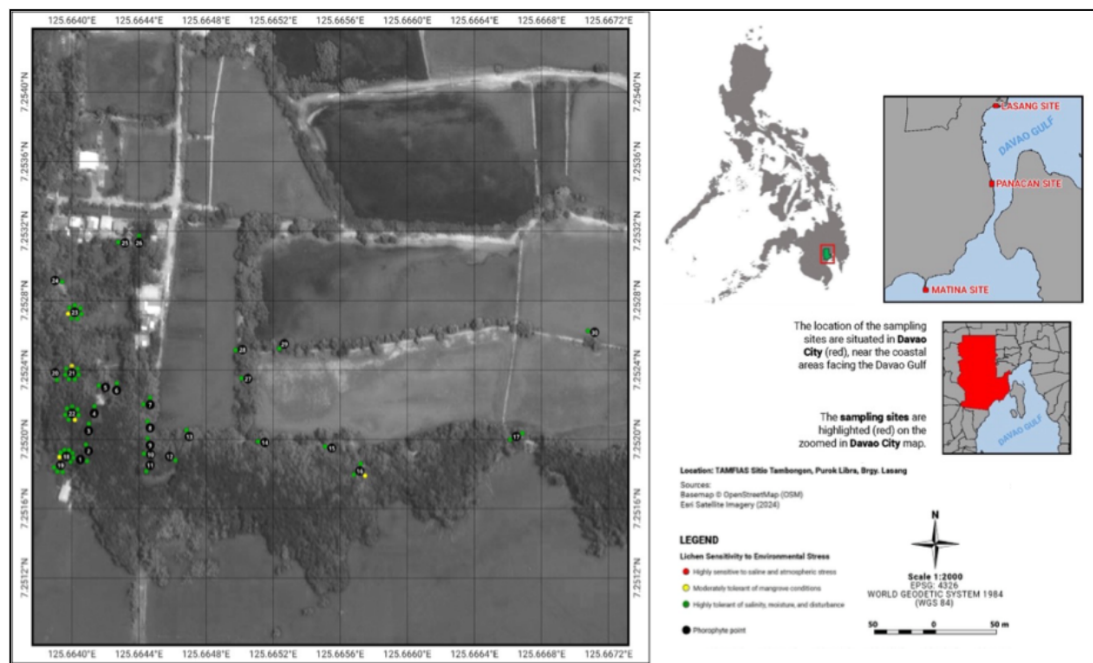


Figure 5. Lasang Site Lichen Inferred Sensitivity Bioindicator Map of Mangrove Lichens

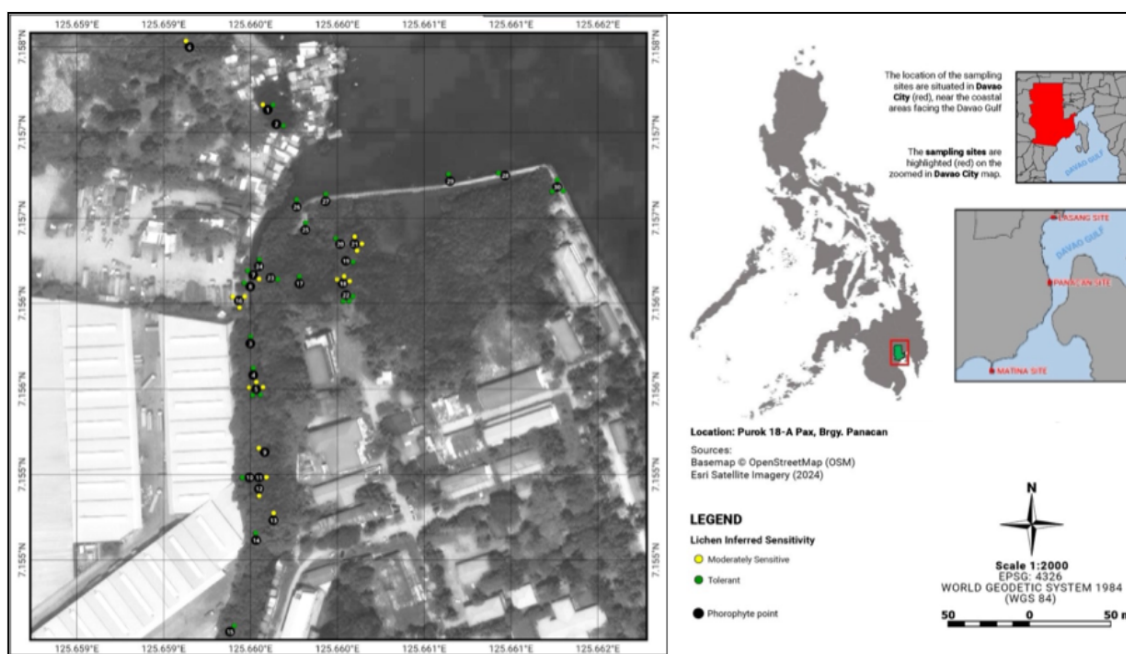


Figure 6. *Panacan Site Lichen Inferred Sensitivity Bioindicator Map of Mangrove Lichens*

Limitations of the Study

Several limitations should be considered when interpreting the results of this study.

First, the study relied on lichen bioindicators to infer environmental conditions. However, direct measurements of atmospheric pollutants (e.g., NO₂, SO₂, or particulate matter) were not conducted. Consequently, interpretations regarding potential pollution gradients are based on established ecological relationships rather than direct chemical evidence.

Second, the study included only three sampling sites, limiting the ability to generalize the findings to all mangrove ecosystems in Davao City. The results should therefore be interpreted primarily as site-based ecological observations rather than a comprehensive model of mangrove lichen dynamics across the region.

Third, variation in mangrove host-tree species (phorophytes) may influence lichen distribution independently of environmental disturbance. Differences in bark texture, chemistry, and moisture retention among mangrove species could partly explain variations in lichen assemblages observed among sites.

Fourth, the functional analysis employed a simplified trait classification based solely on growth form. While growth form provides useful ecological information, additional traits such as photobiont type, reproductive strategy, and physiological tolerance would provide a more detailed understanding of functional diversity.

Finally, the Lichen Inferred Sensitivity Index (LISI) applied in this study represents an emerging framework for environmental interpretation. Further studies with broader spatial coverage and local calibration of species sensitivity values would improve the reliability of this index for mangrove ecosystems in the Philippines.

Conclusion

This study demonstrates that, despite the strong natural stress imposed by mangrove environments, manglicolous lichens in Davao City show potential as bioindicators of environmental quality, particularly in distinguishing patterns associated with human-induced disturbance. Physical stressors such as salinity and tidal immersion act as strong ecological filters, as reflected in the dominance of crustose lichens across all sites. This suggests that functional morphology is a relatively conservative trait that remains stable even along gradients of urban influence.

Differences among sites, however, were evident in lichen abundance and sensitivity patterns. In contrast to the

relatively stable conditions observed at the Matina reference site, the industrial Panacan site exhibited characteristics consistent with a “lichen desert.” Using the Lichen Inferred Sensitivity Index (LISI), these patterns were interpreted as indicative of a gradient of environmental disturbance. These findings suggest that abundance-weighted sensitivity scores can provide useful insights into the biological integrity of coastal forests and the potential effects of habitat fragmentation and urban pressures, even within naturally limiting mangrove microclimates. However, it is important to emphasize that these interpretations are inferential and do not constitute direct measurements of atmospheric pollution.

Based on these findings, it is recommended that local environmental agencies, such as the City Environment and Natural Resources Office (CENRO), consider the LISI framework as a complementary, cost-effective, and non-intrusive tool for environmental monitoring. Conservation efforts should prioritize protecting mangrove buffer zones in industrial areas, as even fragmented systems can help mitigate environmental stress. Future research should incorporate molecular barcoding to improve taxonomic resolution of dominant crustose assemblages, as well as chemical analyses of lichen thalli (e.g., heavy metals, NO_x, SO₂) to support and validate bioindicator-based interpretations. Such integrative approaches would strengthen the scientific basis for coastal zone management while accounting for the complexities of urban mangrove ecosystems.

Contributions of Authors

The author solely contributed to all aspects of this study, including conceptualization, proposal writing, data gathering, and data analysis.

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Conflict of Interests

There is no conflict of interest.

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