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REVIEW ARTICLE

Mycology

Lichens of Sri Lanka: Past discoveries, present knowledge, and future directions

B Weerakoon[1], P Wolseley[2], S Wijesundara[3], S Nissanka[4] and G Weerakoon[2*]
[1] *Postgraduate Institute of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.*
[2] *Algae, Fungi and Plant Division, Department of Sciences, Natural History Museum, London, UK.*
[3] *National Institute of Fundamental Studies, Hantana Road, Kandy, Sri Lanka.*
[4] *Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.*

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Abstract: Lichens are an important component of Sri Lankan biodiversity and have contributed greatly to the tropical diversity as well as to their application as bioindicators of changing environmental conditions. This review summarises 49 selected research publications on the taxonomic and chemical diversity of lichens, their application as bioindicators, and as a source of bioactive compounds that have medicinal properties against microorganisms with the potential of curing some diseases. The chemical properties of lichens and associated fungi and mycobionts have been a major focus in recent years, and several useful compounds have been identified that have benefits for human health. Several areas of the country are well surveyed and further surveys in new areas will aim to discover new species and document lichen diversity, and responses to environmental pollution. These results highlighted the importance of ongoing research in Sri Lanka in a tropical and global lichen context.

Keywords: Bio-indicators, lichen diversity, pollution, taxonomy, tropical forests

INTRODUCTION

Different ecosystems and forest types in Sri Lanka

Sri Lanka is a continental island (7.8731° N, 80.7718° E) with an area of 65,610 km^2 located in the Indian Ocean, southeast of mainland India, in the tropical belt, and has a hot and humid climate (Chandrajith, 2020; Punyawardena, 2020). The mean annual temperature is 27.5 ^{0}C in the lowlands, and 15.9 ^{0}C in the highlands. Sri Lanka has two monsoon seasons and two inter monsoon seasons receiving 900 mm - 5500 mm rain p.a. The Southwest monsoon (SWM) (May- September) brings a high rainfall to the Southwest part of the country while Northeast monsoon (NEM) (December- February) causes heavy rains throughout the country. During SWM, the highest rainfall is received by the mid-elevations of the western slopes of the highlands. During NEM period, the highest rainfall is received by north-eastern parts of the central highlands (Punyawardena, 2020). According to the topography, Sri Lanka is divided into three topographical zones; low-country (< 300 m amsl), mid-country (300-900 m amsl), and upcountry (> 900 m amsl) (Chandrajith, 2020). Following the amount of rainfall received and its distribution, Sri Lanka is divided into three climatic zones; wet zone, intermediate zone and dry zone (Punyawardena, 2020).

Within the tropical climatic belt, several forest types can be seen in Sri Lanka relating to their geographical distribution (MOE, 2012). Dry forests, lowland rainforests, sub montane forests, and montane forests are the main forest vegetation types recorded (Kathriachchi,

* Corresponding author (gothamie.weerakoon2@nhm.ac.uk; https://orcid.org/0000-0001-8290-2910)

2012; Perera, 2012; Wijesundara, 2012). Grasslands and mangroves are the main components of the non-forest vegetation type of the country (Jayatissa, 2012; Perera, 2012).

Present understanding about lichens

A lichen is a self-sustaining ecosystem formed by the interaction of an exhabitant fungus (mycobiont) and an extracellular arrangement of one or more photosynthetic partners (photobionts) and an intermediate number of other microscopic organisms (Hawksworth & Grube, 2020). The photosynthetic partner of a lichen is an alga and/or a cyanobacterium. In addition, bacteria, secondary fungi, and endolichenic fungi can be involved in the lichen symbiosis association (Weerakoon, 2015; Lücking & Spribille, 2024). The photobionts produce carbohydrates, and the mycobiont produces the lichen structure, including protective mechanisms to maintain photobiont viability. There is a growing suggestion that the association is an obligate parasitism maintained by the mycobiont (Morillas *et al.*, 2022).

Lichens can have both sexual and asexual reproduction. Both photobiont and mycobiont may reproduce asexually within the lichen. However, sexual reproduction only occurs in the mycobiont partner. Spores and asexual thallus propagules with both symbionts can be dispersed by wind, water, or mechanical forces. After being dispersed, a new lichen thallus may establish in the new habitat, if it is environmentally suitable (Purvis, 2000; Weerakoon, 2015). According to Brunialti *et al.* (2021), species which show sexual reproduction are more widely distributed than the species with asexual vegetative reproduction. Also, they reported a nested assemblage of vegetatively reproducing lichens mainly in old growth forests, while sexually reproducing lichen species showed a high turnover.

There are about 20,000 lichen species identified throughout the world (Lücking *et al.*, 2017; Finger Lakes Land Trust, 2024), and lichenologists believe there are more species yet to be discovered (Lücking & Spribille, 2024). In Sri Lanka, the lichen flora is poorly studied. Most Sri Lankan surveys have been conducted in the central highlands and wet zone lowlands, however, the intermediate zone and the dry zone lichens are less explored (Weerakoon, 2015; Jayalal *et al.*, 2020).

Lichens are found on a wide variety of substrates including soil (terricolous), rock (saxicolous), decaying wood (lignicolous), trees (corticolous), and leaves (foliicolous). Lichens are grouped according to the shape and morphology of the thallus (Purvis, 2000). The main types being crustose (a crust-like thallus), foliose (a leaf-like thallus), fruticose (a bush-like thallus), filamentous (a bushy thread-like thallus), and squamulose (a micro leafy thallus). Foliose, filamentous and fruticose lichens are known as macro-lichens and the remainder are referred to as micro-lichens (Purvis, 2000; Weerakoon, 2015).

In the Eastern Himalaya and Western Ghats, the majority of lichens are recorded on tree trunks and the dominant group on tree trunks is crustose (Pinokiyo et al., 2008, Vinayaka et al., 2016). Also crustose lichens are recorded as the most abundant group across all habitats in temperate and tropical regions (Nayaka & Upreti, 2005; Rout *et al.*, 2010; Dudani *et al.*, 2015). Foliose and fruticose lichens are common in well-lit canopy gaps and openings and become more common at higher elevations in tropical forests (Joshi *et al.*, 2011; Kumar *et al.*, 2011; Abas & Din, 2021; Orock & Fonge, 2022).

Research conducted in tropical regions has shown that Graphidaceae is the largest and most diverse family of crustose lichens in the tropics, and that the global hotspot for this family is South India and Sri Lanka (Lücking *et al.*, 2014). Lichens in tropical regions become more abundant, dense, and widely scattered with increasing elevation above 1000 m (Baniya *et al.*, 2010; Kumar *et al.*, 2011; Costas *et al.*, 2021; Bhagarathi *et al.*, 2022; Orock & Fonge, 2022). Further, Pinokiyo *et al.* (2008) also recorded a unimodal pattern in lichen diversity in relation to altitude from a study conducted in Arunachal Pradesh in India.

Lichens produce both primary and secondary metabolites (Ren *et al.*, 2023). Primary metabolites are used in structural growth and development of the lichen thallus by both symbionts, while secondary compounds are only produced by the fungus and have a range of protective functions in the lichen. Secondary metabolites are small, complex, water insoluble, crystalline compounds deposited on the hyphae of the fungus. There are three main pathways for synthesizing these compounds; acetyl-malonate, mevalonate, and shikimate pathways (Ren *et al.*, 2023). There are over 1000 lichen secondary compounds identified so far (Ren *et al.*, 2023). These compounds have been known to protect the thallus from herbivory and UV radiation (Schweiger *et al.*, 2021), and to contribute to ecological services such as nutrient cycling, habitat formation, and soil formation (Prokopiev *et al.*, 2025). Lichen secondary compounds also have an active pharmaceutical role in human health as anti-bacterial, anti-cancer, anti-fungal, anti-inflammatory, anti-microbial, antioxidant, and wound healing agents (Moreira *et al.*, 2015; Bhattacharyya *et al.*, 2016; Ren *et al.*, 2023).

Lichens are one of the commonly used bioindicators for assessing atmospheric air quality since their growth and development depend on air borne resources, thus any atmospheric changes may have an impact on them (Nimis *et al.*, 2002 Conti, 2008; Delves *et al.*, 2023). A significant change in lichen communities can be observed due to air pollutants such as sulphur dioxide (SO_2) from burning coal and fossil fuels, and ammonia (NH_3) from agricultural activity (Sutton *et al.*, 2009). In temperate countries and conditions, lichen communities have been widely used to recognise the impact of atmospheric pollution. An Index of Atmospheric Purity (IAP) was developed by Leblanc and DeSloover in 1970 as a method to assess air quality using lichens as bioindicators, and has since been widely used in temperate regions (Gombert *et al*., 2004). Biomonitoring studies using lichens have contributed to creating regional policies such as introducing critical levels and loads of pollutants affecting the lichens, such as NH_3 (Sutton *et al.*, 2009). NH_3 is a pollutant alkaline gas that causes an increase in the bark pH of the surrounding vegetation. Lichens that prefer a lower bark acidity (acidophytes) are eliminated from the habitat and replaced by lichens that are tolerant of the increased bark pH (Wolseley *et al.*, 2006). Modelling studies have shown that natural habitats in South Asia, such as Himalayan forests, are threatened by increasing atmospheric nitrogen deposition (Ellis *et al.*, 2022). Further, deposited particulate matter has been shown to affect lichen thalli close to highways (Marmor & Randlane, 2007), and lichens have been used to monitor heavy metal pollution due to Pb in urban areas (Hasairin *et al.*, 2020).

Globally, lichens are well studied in many research fields such as ecology, environmental monitoring, air quality, and medical studies as well as having commercial and cultural values in some countries (Lücking & Spribille, 2024). However, the lichen flora in Sri Lanka is less studied compared to other countries in tropical Asia (Weerakoon *et al*., 2019). This review summarizes the findings of selected lichenological research in Sri Lanka, the status, and the potential for lichenology in Sri Lanka.

Lichen diversity and distribution in Sri Lanka

History of lichen surveys in Sri Lanka

G.H.K. Thwaites was the director of the Botanic Gardens in Sri Lanka from 1857-1880 and made the first lichen collection in Sri Lanka, duplicates of which are deposited in the Natural History Museum in London and other herbaria in Europe (Weerakoon, 2013). Using this collection, Leighton in 1869, published 196 lichen species for Sri Lanka, including 43 species new to science. Many foreign lichenologists conducted field explorations in the country and results were published in late 19th and 20th centuries (Nylander 1866:1900; Alston, 1938; Kurokawa, 1973; Kurokawa & Mineta 1973). Under the 'Flora of Ceylon' project by the Smithsonian Institute, R. Santesson, A. Tehler and L. Wheeler (1970 - 1976) studied the lichen diversity in different parts of the country. Mason Hale made a significant contribution to the lichen flora in Sri Lanka from 1976 to 1981 including 'A revision of the lichen family Thelotremataceae in Sri Lanka' in 1981 (Hale, 1981). Brunnbauer (1984 - 1987) updated the Sri Lankan lichen flora to 546 species. Lichen discoveries by Jayasuriya (1984), Moberg (1986 and 1987), Awasthi (1991), Makhija and Patwardhan (1992) and Vezda *et al.* (1997) brought the lichen checklist to 659 species (Weerakoon, 2015). A group of local and foreign lichenologists initiated a series of lichen workshops from 1999 onwards and continued to increase the lichen knowledge and interest of Sri Lankan researchers (Wijesundara & Karunaratne, 2015). After 2010, local experts contributed more to reporting and describing new lichen species.

Lichen species delimitation in Sri Lanka was supported by morphology and gene-based analyses conducted on specimens collected from the Central Mountain range. Studies in Knuckles showed that lichen specimens in the genus *Pyrenula* of family Pyrenulaceae are not derived from the same ancestor and can be divided into two groups (Weerakoon *et al.*, 2012 a). In the Horton Plains, Jayalal *et al.* (2012) described two new foliose lichen species in genus *Anzia*. Also, morphological descriptions continued, particularly in crustose species, following Weerakoon's research in the Knuckles Mountain range (Weerakoon *et al.*, 2012a; 2012b; 2012c; Wijeyaratne *et al.*, 2012). Further, three new lichen species in genera *Heterodermia*, *Malmidea*, and *Protoparmelia* and an identification key for the genus *Heterodermia* were published for Sri Lanka (Weerakoon & Aptroot, 2013). Research on the family Graphidaceae added 13 new species (Weerakoon *et al.*, 2014) and 6 new species from the montane forests of Horton Plains by Weerakoon *et al.* (2015). From an examination of a collection made in the early 1990's, Weerakoon & Aptroot (2014) recorded 207 lichens new to Sri Lanka including three species new to science, 91 new records for the Indian subcontinent, and four new records for Asia.

Further research by Weerakoon *et al.* (2016) and Weerakoon and Aptroot (2016) increased the number of new records for Sri Lanka to 152 species of which 17 were described as new to science, 86 records as new to the Indian subcontinent and eight as new to Asia. In the same year the first record of genus *Cora* in the eastern palaeotropics was described from the Sinharaja rain forest reserve, Sri Lanka (Lucking *et al.*, 2016). Furthermore, three new *Ocellularia* species (Family Graphidaceae) were identified from Sri Lanka (Li *et al.*, 2016). In 2018, further ten species were recorded with three species new to science by Aptroot & Weerakoon (2018). *Leightoniella zeylanensis,* an endemic species, was rediscovered and classified under family Pannariaceae using molecular analysis (Weerakoon *et al.*, 2018).

In 2019, the first record of palaeotropical *Allographa* with pigmented lirellae (Family Graphidaceae) was recorded from Sri Lanka together with a global key for all *Allographa* species with colourful lirellae. These *Allographa* species were previously recorded only from the Neotropics and from Africa (Jatnika *et al.*, 2019).

Six new species of *Allographa* and *Graphis* of Graphidaceae with 106 new records were reported with a key to genera for Sri Lanka by Weerakoon *et al.* in 2019. The total number of species of *Allographa* and *Graphis* in Sri Lanka amounted to 124 species, making Sri Lanka the hotspot for *Allographa* and *Graphis* diversity in the world. Research on genus *Phyllopsora* in Asia documented 18 species for Sri Lanka and a taxonomic key for Asian species (Kistenich *et al.*, 2019). In 2020, Kistenich *et al.* also recorded *Aciculopsora* in Sri Lanka*,* the first record in the paleotropics of a genus previously known only in neotropics.

With the contribution of local and foreign lichenologists, the documented lichen flora in Sri Lanka (as of 2020) stands at 876 species across 233 genera in 60 families (Jayalal *et al.*, 2020). Since then following further research on historic lichen collections from Sri Lanka, Elvebakk (2021) has described a new species of cyanolichen, *Gibbosporina cyanea*, based on the holotype collected by Thwaites in the 1860s.

Factors affecting the lichen distribution in Sri Lanka

Lichens are distributed across all climatic regions of Sri Lanka and the distribution pattern differs in each region. Environmental variables such as rainfall, humidity, and temperature affect this variation (Weerakoon, 2015). Altitude strongly affects lichen distribution and community composition (Weerakoon *et al.*, 2020) so that lichen diversity increased with altitude. As observed in mountain forests in the wet-zone (Weerakoon *et al.*, 2020), Gunawardena and Wijeyaratne, (2020) also described high lichen diversity in the Ritigala forest, an isolated mountain in the dry-zone of the country. The study also reported the influence of light exposure on lichen communities, the preference for sunny areas by lichens with a green algal photobiont and for shaded habitats by cyanobacterial lichens.

Factors that affect lichen diversity and distribution include forest disturbance (Weerakoon *et al.*, 2010; Weerakoon *et al.*, 2020). In the Knuckles Mountain range, Sri Lanka (in the central highlands) the highest lichen diversity was recorded in pristine forest while monoculture plantations such as tea, pine and acacia had the lowest lichen diversity (Weerakoon *et al*., 2010; Weerakoon *et al*., 2020). These studies also demonstrated that corticolous lichen diversity increased where tree diversity was high in undisturbed forests. De Silva and Senanayake (2015) recorded low lichen diversity in a monoculture pine plantation compared with adjoining secondary forest in Pussellawa in the central highlands. The lichen diversity was higher in the montane forest islands than in continuous forests in the Horton Plains National Park – the southern part of the central highlands where fire caused frequent disturbance (Jayalal *et al.*, 2017).

Other research in Sri Lankan lichenology

Although the chemical composition of lichens has been used to define lichen species, many studies have been conducted on lichens to assess the application of lichen compounds to human health and environmental problems.

Chemical compounds of lichens and their potential applicability

The chemical properties of lichens and their uses were studied in Sri Lanka from the early 2000s (Karunaratne *et al.*, 2005) including an investigation of larvicidal assays in relation to mosquito larvae (Nanayakkara *et al.*, 2005). An investigation of secondary metabolites in butterfly larvae highlighted the role of secondary metabolites in protecting lichens from herbivores (Karunaratne *et al.*, 2008). Secondary metabolites were used to define new species (Kathirgamanathar *et al.*, 2006; Bombuwela *et al.*, 2008) and then further developed to assess their application to human health. Several recent studies have highlighted the potential of secondary chemical compounds generated from lichen fungi in medical research. Studies have shown that lichens in the *Parmotrema* genus have antioxidant properties (Samanthi *et al.*, 2015). Two lichen species in genus *Parmotrema*, *P. rampoddense* and *P. tinctorum*, showed potential importance as a source for future antimicrobial drugs (Shiromi *et al.*, 2021). Additionally, the anti-diabetic properties of the secondary metabolites of *Cladonia* sp. were documented by Karunaratne *et al*. (2014).

Antibacterial compounds of lichen-associated fungi in mangrove habitats were identified by Happitiya *et al.* (2023a; 2023b). Weerasinghe *et al.* (2021) also tested the antioxidant, anti-inflammatory and antibacterial properties of the secondary metabolites extracted from endolichenic fungi from lichens which occurred in mangrove habitats in Negombo, Sri Lanka. The antioxidant, anti-lipase, and anti-amylase properties of the secondary metabolites in endolichenic fungi are documented together with their anti-inflammatory properties (Maduranga *et al.*, 2018, 2021). A novel chemical compound extracted from an endolichenic fungus *Amandinea medusulina* found in mangrove ecosystems showed a moderate activity against human lung cancer (Santhirasegaram *et al.*, 2020). In 2022, a chemical compound with high antibiotic properties was extracted from a mangrove associated lichen. The compound has high anti-oxidant properties, moderate anti-inflammatory properties, some antibacterial activities, and moderate cytotoxicity against oral cancer. This chemical was extracted from an endolichenic fungus recorded from the host lichen *Bactrospora myriadea* from the Negombo lagoon mangrove community (Weerasinghe *et al.*, 2022). Further, secondary metabolites extracted from endolichenic fungi of mangrove associated lichens *Arthonia antillarum* and *Bactrospora myriadea* have shown cytotoxicity against human breast, oral and lung cancers (Shevkar *et al.*, 2024).

Using lichens as bio-indicators for assessing forest ecosystem health

Lichens have been used to detect changes in communities in response to changes in environmental conditions as well as air quality, and more recently to global warming. Changes in lichen communities of forests in relation to disturbance was quantified in plots in habitats in the Knuckles Mountain range, Sri Lanka (Weerakoon, 2013). Weerakoon *et al.* (2020) showed that 57 out of 60 indicator lichens were serving as strong and unique indicator species for an individual vegetation type in Knuckles mountain range. Of these, the prevalence of crustose species in the genera *Myriotrema*, *Ocellaria*, and *Porina* was associated with the undisturbed montane and sub-montane forests in Sri Lanka (Weerakoon *et al.*, 2010). In 2010, Jayalal also found several foliose lichen genera that were good indicators of ecological continuity in the Horton Plains National Park. These results support the use of corticolous lichens to evaluate the habitat conditions in tropical forests of Sri Lanka (Jayalal, 2010; Weerakoon, 2010; Weerakoon *et al.*, 2010; Weerakoon *et al.*, 2020).

Air pollution monitoring in Sri Lanka using lichens

Lichens have been used as air pollution indicators in several locations in Sri Lanka. The IAP in the Horton Plain National Park, Sri Lanka was calculated from the lichen diversity. The low concentrations of NO_2 and SO_2 facilitated a high lichen diversity in the area (Jayalal *et al.*, 2017). Similarly, the IAP was negatively correlated with the NO_2 and SO_2 levels at different locations in Kegalle in the Sabaragamuwa province (Yatawara & Dayananda, 2019). These studies have helped to identify air pollution tolerant indicator species, such as *Pyxine* sp. A recent study was conducted as a collaborative work in Sri Lanka and India, to assess the use of lichens as air pollution indicators. A comparison of lichen diversity and air pollution status in selected locations in and around Kandy city (Sri Lanka) showed a higher lichen diversity in less air-polluted locations. The highest species richness was recorded from the Hantana forest, which was located away from the city centre, compared to the Udawatta Kele and Gannoruwa forests, which were located in and around Kandy city (Preeti *et al.*, 2023). Further work recorded higher lichen species richness in the University of Peradeniya, a semi- disturbed area, than in the polluted area around the lake in Kandy city (Edirisinghe & Athukorala, 2024). Similarly, Gunawardena *et al.* (2021) recorded higher lichen species richness in the University of Peradeniya than in the Kandy city centre, where they also detected increased secondary metabolites produced as a response to pollution stress.

Atmospheric pollution from NH_3 is an emerging threat to both environmental and human health, and South Asia is considered a hotspot of NH_3 pollution. An experimental study is ongoing in a sub-montane forest reserve as a part of the South Asian Nitrogen Hub project to assess lichen responses to the elevated NH_3 levels in order to understand real world NH_3 pollution conditions (Sutton *et al.*, 2022). The multi-layer model used in this study is applicable for identifying the fate of NH_3 in tropical forest ecosystems with special focus on lichen bio-indicators, that will provide vital evidence to inform the establishment of NH_3 critical levels and associated nitrogen policy development in Sri Lanka and the South Asian region (Deshpande *et al.*, 2024).

Lichen biomonitoring on particle deposition in Sri Lanka

Airborne particles directly impact human health. They are one of the major factors causing respiratory tract inflammations and diseases. Very few studies were conducted using lichens as bio-monitors for pollutant deposition. Assessing metal deposition on lichens is a proxy for the status of the air quality. Samples of *Heterodermia speciosa* were collected from Colombo (Western Province) and Kurunegala (North-western Province) in Sri Lanka and analysed for metal deposition. They recorded K, Ca, Ti, Fe, Mn, Zn, and Pb from analysed lichen thalli. X-ray fluorescence spectrometry shows that metal deposition is higher in Colombo than in Kurunegala, indicating the air pollution in Colombo is more than in Kurunegala (Gunathilaka *et al.*, 2011).

CONCLUSION

The rich lichen diversity in Sri Lanka has been demonstrated from previous lichenological surveys conducted in limited geographical areas in the country. Further surveys of undocumented areas of Sri Lanka will reveal new records and species to confirm Sri Lanka as a hotspot for tropical lichens, highlighting the contribution to global lichen diversity. Also, medicinal properties of lichens and their use as bioindicators have been explored in recent years. Several chemical compounds extracted from lichens have shown antibiotic, antibacterial, anti-microbial, antioxidant, anti-diabetic, anti-inflammatory, and anti-cancer properties. These chemicals compounds could be used in the pharmaceutical industry to generate income and provide benefits for human health. Further, lichens have been used as bioindicators to monitor air quality in Sri Lanka responding to atmospheric NO_2, SO_2, and metal levels in different parts of the country, especially in urban areas. Ongoing studies can be used as baseline information for proposing critical levels of air pollutants, such as NH_3, for tropical regions. Also, sensitive and tolerant lichen species to changes in air quality can be proposed based on current studies. Critical levels of NH_3 are already established in countries in temperate regions, where citizen monitoring programs have been conducted to increase community engagement on monitoring air quality using bioindicators. Public awareness and engagement on lichen biomonitoring and lichen conservation should be another future direction in lichen studies in Sri Lanka.

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