RESEARCH ARTICLE

Impacts of Lichens and Bryophytes on the Monoliths of Mawphlang Sacred Groves: A Biodeterioration Assessment

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Abstract

Mawphlang Sacred grove, an ancient and culturally significant forest in the Khasi Hills of Meghalaya, India, has remained an undisturbed ecological sanctuary. Historically, it served as a site for religious rituals, coronations, and the gathering of Khasi kings and leaders. This study evaluates the biodeterioration effects of lichen and bryophytes on the monoliths within the grove. The survey conducted in 2024 focused on identifying the species responsible for the biological weathering of these culturally significant stone structures. Due to strict conservation regulations prohibiting sample collection, high-resolution photographic documentation was employed for species identification. Common taxa were identified up to the species level, while others were classified at the genus level. Future research should integrate advanced non-invasive techniques such as remote sensing, hyperspectral imaging and digital microscopy to monitor and assess the extent of biological weathering over time. This study provides a foundation for future research on cryptogamic-induced stone weathering in heritage sites and highlights the need for sustainable conservation approaches.

Highlights

- Lichens and bryophytes produce a wide range of secondary metabolites which cause biodeterioration of monuments.
- Of all lichens studied so far from the study site, foliose and fruticose (*Usnea* sp.) are dominant from the study site.
- The members of Marchantiaceae, Bryaceae and Riccardiaceae are the most dominant bryophytes found growing on the monoliths.
- Effective management of tourism, recreation, and conservation is essential to safeguard Mawphlang's monoliths and sacred forest

Keywords: Biodegradation, bryophytes, lichenized fungi, north-east India, secondary metabolites.

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Introduction

Every entity has a shelf life of its own in this planet, may it be a living organism or a block of wood. In this vicious cycle of life where entities are created or born, thrive and they perish. Degradation is the process that come into play where an entity gets broken down into a simpler form losing its actual form. With advancement of human civilization in the field of science, researchers worked on how the microbes (detritivores) play vital role in degrading substances and they introduced two terminology 'biodegradation' and 'biodeterioration' which used alternately as a synonym to define action of biological agents in breaking down complex substances into simpler form. The term 'biodeterioration' although came into limelight since last few decades but it has been described and discussed way back to 17th century where Linnaeus (1762) brought it into limelight the ability of crustose lichens to colonize on rocks or monuments. Duchafour (1979) classified the phenomenon of weathering of rocks into two broad categories namely (a) geochemical weathering, which takes place under the influence of water and characterized by the crystallization of clay materials and some oxides or hydroxides and (b) biochemical weathering which is predominantly influenced by living organisms (Fig.1). Jones et al., (1981) using scanning electron microscopy and energy dispersive X-ray analysis reported that lichens produce an array of secondary products which causes etching and decomposition of rock minerals which was until this time was believed that weathering of rock was due to physical causes. But it was Hueck (1986) who defined biodeterioration as any undesirable change in the properties of a material caused by the vital activity of the organism. He established a distinct difference between these two terms where he defined biodegradation as the involvement of microbial activities to yield beneficial products. Both of these processes have advantages and disadvantages that could influence how matter is used. Studies on biodeterioration of monuments are being done worldwide and numerous research articles are available till date. In India biodeterioration studies was started in late 19th century. In Indian context, the biodeterioration studies has been carried out from the various region of country mainly from northern, western, eastern and southern region such as Uttar Pradesh, Madhya Pradesh, Odisha, Karnataka and Tamil Nadu but a little study has been conducted

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in North-eastern region which one of the biodiversity hotspots of our country and the seven sister states is inhabited by wide array of tribes and ethnic communities. A brief review of notable works has been included in this present study.

Lichen biodeterioration studies in India

Biodeterioration studies in India with regard to lichens and monuments was first pioneered by Gayathri (1980) who described the effects of lichens on the Indian monuments made up of granite. Singh & Upreti (1991) gave detailed expositions of lichens growing on different monuments of Lucknow city where they recorded the presence of 11 species of lichens. Singh & Dhawan (1991) studied the detrimental effects of lichens and qualitative assessment of the damage caused by three lichen species growing on the Yogarsimha Swami temple of Karnataka state which dated back to 16th century. Singh and Sinha (1993) explained the weathering of natural and monumental stone with special references to lichens, the kind of rock damage along with the list of certain lichen secondary metabolites responsible for biodeterioration. Chatterjee et al., (1995) studied the lichen diversity on various monuments of Karnataka and Odisha, reported 40 species belonging to 18 genera with their detailed taxonomic accounts along with key for their identification. They also inferred that the monuments exhibit a distributional pattern of lichens based on the microclimate at different niches by their architecture. Garg et al., (1995) in their work suggested that usage of agricultural fungicides such as Butachlor, Calixin, Simazine and Zebtane can be used to check the growth of lichens, mosses and others biodeteriorants on the monuments as a conservation measure.

Singh et al., (1999) enumerated 40 lichen species belonging to 18 genera and 14 families which they have reported growing on the monuments of Karnataka and Orissa (now Odisha). They have also enlisted the details of the herbicides (chemicals) that can be brought in for the eradication of lichens. Jain (2001) in a short communication, enlisted four species of algae and lichens growing on the Gwalior Fort of Madhya Pradesh. Upreti (2002) explored the lichen flora growing on the Khajuraho group of temples and rock structures present in the temple premises and reported ten lichen taxa. From his study he concluded that, along with the climatic factors type of stones and architectural designs determine the composition of lichen flora. It was observed from his study that walls and artifacts near the ground level gets more shade and moisture, which results in the luxuriant growth of hydrophilic lichen species such as *Peltula*, *Buellia*, *Endocarpon* etc.

Upreti et al., (2004) studied the lichen activity over the rock shelters of Bhimbetka world heritage site at Madhya Pradesh and reported total number of 14 lichen taxa along with their taxonomic details and secondary metabolites they produced. Saxena et al., (2004) gave the detail accounts of the distributional and ecological patterns of the lichen species growing on the different monuments of Indian subcontinent namely Karnataka, Tamil Nadu, Uttar Pradesh and Madhya Pradesh which includes facing of the monuments i.e., wall facing different directions receives varying degree of wind velocity, sunlight, rain showers which results in differing in microclimatic scenarios which affects the spore dispersal and overall diversity of lichens inhabiting. Ayub (2005) worked on the lichens growth on monuments and old buildings of colonial period in Agra, Allahabad (Prayagraj), Faizabad, Kanpur, Lucknow and Varanasi districts of Uttar Pradesh and reported around 14 species distributed under six genera belonging to six families. Bajpai (2007) studied the monuments of Bhimbetka caves of Raisen district of Madhya Pradesh and reported 42 species of lichens belonging to 17

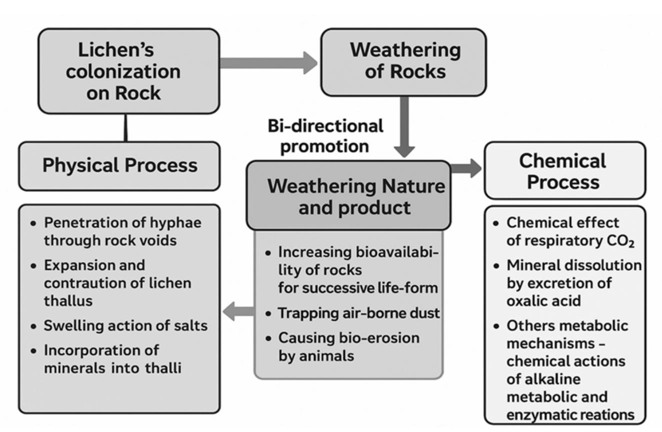

Fig. 1: Schematic representation of physical and chemical processes in lichen-induced weathering

Fig. 3: A. *Parmotrema praesorediosum* (Nyl.) Hale; B. *Usnea* sp.; C. *Parmotrema* sp.; D. Monolith surface having luxuriant growth of lichens; E, F, G H, I and J. Monoliths of Mawphlang Sacred Grove and Entry point of Sacred Grove

Fig. 4: A. *Marchantia polymorpha* L.; B. *Riccardia* sp.; C. *Rhodobryum roseum* (Hedw.) Limpr.; D. Intermixed population of mosses; E. *Stereophyllum* sp.; F. *Marchantia papillata* Steph.) Bischl.; G. *Thuidium* sp.

genera under 11 families out of which 32 lichens were reported to have lichen metabolites with chelating properties. Bajpai et al., (2007) reported the diversity of saxicolous lichens in some districts of Madhya Pradesh and inferred that the maximum diversity of lichen species was observed on sandstone monuments, followed by siliceous artifacts, bauxite and calcareous substrates.

Bajpai et al., (2008) discussed the distribution of lichens on the monuments of Madhya Pradesh and also studied the chelation activities of lichens growing on those monuments. Upreti et al., (2010) studied the lichen growing on the monuments of Central India (Dhar, Katni and Raisen districts of Madhya Pradesh) and reported two unique lichens, namely *Dimelaena tenuis* (Müll. Arg.) H. Mayrhofer and Wippel and *Peltula placodizans* (Zahlbr.) Wetmore for the first time from the Indian sub-continent. Bajpai and Upreti (2014) published a book where they discussed the methodology to assess the lichen diversity, pollution biomonitoring using lichens, damage caused and conservational aspects. Choudhury et al., (2016a) studied the lichen diversity of historical sites, Bamuni Hills of Tezpur district of Assam and reported 16 species belonging 10 genera under eight families out of which three lichen species, namely *Caloplaca capilifera*, *Lecanora pseudistera* and *Lecanora subimmersa,* were new distributional records for Assam. Choudhury et al., (2016b) worked on few ancient monuments of Sonitpur district of Assam and reported 38 lichen species distributed among 21 genera under 15 families, out of which members of the Physciaceae family showed the dominance with 11 species, followed by members of Teloschistaceae with four members and Lecanoraceae and Verrucariaceae each with three species. Upadhyaya (2016) studied the diversity and distributional patterns of lichens growing on the monuments of Gwalior division of Madhya Pradesh and reported 28 lichens species under 16 genera and nine families. From the study, it was inferred that crustose lichens were most dominant growth form, followed by squamulose and foliose, as per the substrate preference was concerned maximum number of lichens was reported growing on sandstones, followed by concrete, igneous granite, calcareous and clay. They have also calculated the rock porosity to measure the water retention capacity and correlated it with lichen growth which resulting in lichens are squamulose lichens with thick medullary zones that grows on the rocks, which bears maximum water holding capacity. Deshmukh et al., (2017) studied the lichen growth on the Gwalior fort of Melghat forest and reported 27 lichen species under 21 genera and 12 families, out of which 13 lichen species were reported to produce secondary metabolites, thereby actively participating in the biodegradation process.

Nayak et al., (2017) studied the lichen growth on the Sun temple of Puri district, Odisha and reported 15 species under 14 genera belonging to 11 families out of which ten species are crustose and reported for producing secondary metabolites dominating the study sites followed by four foliose lichen species and one squamulose lichen taxa was reported from their study. Nayak et al., (2018) assessed the lichen bio-deterioration on Ratnagiri and Udayagiri Buddhist excavation sites in Jajpur district of Odisha, made up of Khondalite stone and burnt bricks. From their study, they observed that the dominating growth form was crustose lichens with genera such as *Lecidella*, *Buellia*, *Lecanora* and *Lepraria*. They also recommended few measures for the restoration of monuments in India. Behera et al., (2020) studied the lichen diversity and their potential role in causing biodeterioration of various monuments of temple city Bhubaneswar, where they listed 18 lichen species with family, growth forms, along with the names of secondary metabolites they produce. They have also listed a brief review of the earlier works done by the state with historical data of the monuments studied as well as the information regarding the construction materials and lichen species reported. Pradhan et al., (2020) surveyed the ancient caves of Khandagiri and Udayagiri of Khordha district of Odisha where they reported 16 species under eight genera belonging to six families, members of the families such as Caliciaceae, Teloschistaceae, Lecanoraceae, Peltulaceae, and Thelotremataceae, were dominant at the study sites which were mostly of crustose growth form.

More recently, Saraswat et al., (2023a) surveyed the monuments of Jaipur, Udaipur and Bharatpur districts of Rajasthan and from their study, it was inferred that most of the monuments surveyed were made up of limestone, which shows luxuriant growth of lichen species. The members of the Lichinaceae family, which was dominated by four genera consisting of 19 species under six families, highlight the fact that there is very low species diversity due to semi-arid climatic conditions. From their study, it was also observed that squamulose growth form was predominant in the study sites, followed by the leprose and crustose lichens. Saraswat et al., (2023b) did extensive surveys on 51 historical sites distributed in different districts of Rajasthan, namely Bharatpur, Udaipur and

Jaipur and inferred those 19 species belonging nine genera under six families, out of which eight species were new distributional records for Rajasthan, in addition to it a cyano-lichen, namely *Lichinella iodopulchra* (Cauderc ex Croz.) P.P. Moreno and Egea were reported for the first time from India. Saraswat et al., (2024) studied the effects of lichen biodeterioration on the monuments of Rajasthan where two species namely *Phylliscum indicum* and *Leprocaulon coriense* were used for SEM-EDX studies and *Endocarpon subrosettum* along with one endolithic lichen *Naetrocymbe saxicola* was used for petrographic studies. Petrographic slides and peaks of mineral particles and various elements were observed from SEM-EDX analysis which showed the presence of Al Si and Mg traces, which suggests that there is a positive correlation between the lichen colonization and silica-rich substratum. Along with silica, traces of Ti and S were also observed during the analysis, which implies anthropogenic activities in the near vicinity.

Biodeterioration studies on Bryophytes in India

Barukial (2011) conducted an extensive investigation into the bryological diversity of Assam, documenting approximately 162 taxa. Among these, only two liverworts, *Porella gracillima* and *Marchantia polymorpha*, and seven mosses, *Ceratodon stenocarpus*, *Fissidens pulchellus*, *Hydrogonium arcuatum*, *Hyophila inflexum*, *Hyophila revoluta*, *Bryum hemisphericarpum*, and *Vesicularia reticulata*, were found growing on historical temples and monuments. The presence of these bryophytes on ancient structures is particularly significant, as they contribute to the process of biodeterioration. Bryophytes colonize stone surfaces due to their ability to survive in harsh environmental conditions, including extreme temperatures, high humidity, and exposure to sunlight. Their growth leads to the physical and chemical weathering of building materials. For instance, the rhizoids of mosses can penetrate the microcracks in stone surfaces, causing mechanical stress and exacerbating structural damage over time. Furthermore, the retention of moisture by bryophytes creates a microenvironment conducive to the growth of other bio-deteriorative organisms, such as fungi, bacteria, and algae. The acids secreted by these organisms, along with those produced by the bryophytes themselves, can chemically degrade stone materials, accelerating the deterioration process. The findings underscore the dual significance of bryophytes in this context: as indicators of ecological diversity and as agents of biodeterioration. While their presence highlights the resilience of these plants and their ability to thrive on man-made structures, it also emphasizes the need for conservation strategies to protect historically significant monuments from their damaging effects.

Sundaramoorthy *et al.*, (2010) recorded three mosses (*Barbula indica, Bryum apiculatum, Gymnostomiella vernicosa*) and three liverworts (*Cyathodium acireonitens, Riccia billardieri, Riccia revolute*, *R. grollei*) from temples in Thanjavur district. He highlighted that *Bryum coronatum, Cyathodium cavernarum, Barbula indica, Gymnostomiella vernicosa,* and *Semibarbula orientalis* colonize heritage walls, roofs, and damp surfaces on humus-rich deposits. Detached moss clumps, due to rain or drying, indirectly damage sites by supporting the growth of higher, more destructive plants. Four taxa of mosses, namely, *Barbula indica*, *Bryum coronatum*, *Gymnostomiella vernicosa*, *Semibarbula orientalis,* and one liverwort *Cyathodium cavenarum* was reported by Duraisamy (2012) from cultural heritage sites in Thiruvarur district of Tamil Nadu.

Seven bryophytes (three mosses: *Physcomitrium japonicum*, *Funaria hygrometrica*, *Fissidens* spp. and (four liverworts: *Asterella khasianum*, *Marchantia palmata*, *M. subintegra*, *Plagiochasma rupestre*) were also reported from the archaeological sites of Ahom Dynasty's 'Talatal Ghar' of Sibsagar, Assam by Verma et al., (2014). Bhatnagar et al., (2016) reported several mosses, which include *Aongstroemia orientalis*, *Barbula* sp., *Bryum coronatum*, *Calymperes* sp. *Ectropothecium monumentum*, *Groutiella schlumbergeri*, *Hyophila revoluta*, *Neckeropsis undulata*, *Neohyophila sprengelii*, *Octoblepharum albidum*, *Papillaria nigrescens*, *Rhacomitrium tomentosum*, *Sematophyllum caespitosum*, *Stereophyllum cultilliforme* and *Weisia jamaicensis,* whereas the liverworts include *Eusomolejeunea clausa*, *Frullania* sp., *Haplozia javanica*, *Marchantia chenopoda*, *Mastigolejeunea auriculata* and *Plagiochila distinctifolia* growing on different substrates like stone, limestone and andesite from archaeological sites.

Recently Mehta and Shah (2023) studied bryophyte colonization on monuments of the Champaner-Pavagadh UNESCO World Heritage site caused degradation, with 17 bryophyte species recorded such as, *Anomobryum auratum*, *Fissidens flaccidus*, *Hydrogonium arcuatum*, *Hyophila involuta*, *Semibarbula orientalis*, *Gymnostomiella vernicosa*, nine liverworts viz., *Asterella wallichiana*, *Cyathodium cavernarum*, *Lejeunea aloba*, *Riccia gangetica*, *R. discolor*, *R. grollei*, *R. billardieri*, *Plagiochasma microcephalum*, *P. appendiculatum* and two hornworts viz., *Anthoceros bharadwajii*, *A. subtilis*. Geological analysis revealed the presence of minerals like quartz, calcite, and feldspar. Calcium uptake by *Asterella wallichiana* and *Hyophila involuta* was studied, showing 52 µg/mg and 36 µg/mg, respectively. Bryophytes degraded structures by forming humus, followed by protonema development and rhizoid penetration, causing cracks and damage.

Methodology

The sacred grove of Mawphlang is one of the untouched forest lands which is considered an epitome of Khasi culture

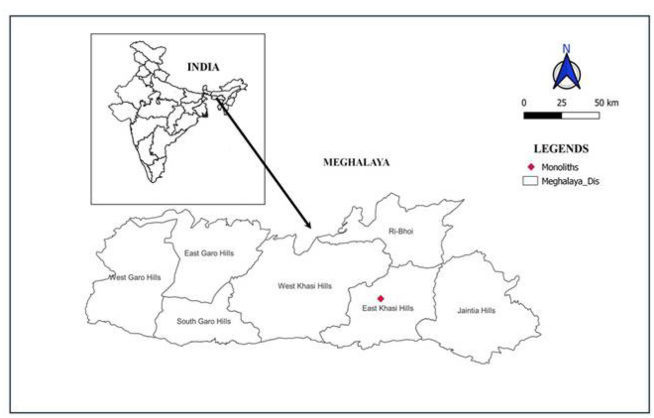

Fig. 2: Map showing the location of Mawphlang Sacred Groves in East Khasi Hills, Meghalaya

Table 1: List of lichens with their families, growth form and secondary metabolites they produce

Sl.No.	Lichen Taxa	Family	G.F.	Secondary metabolites
1.	*Buellia* sp.	Caliciaceae	Cr.	Atranorin, Confluentic acid, Norstictic acid, Stictic acid
2.	*Dirinaria aegialita* (Afzel ex. Ach.) Moore	Caliciaceae	Cr.	Divaricatic acid and Triterpenoids
3.	*Diploschistes* sp.	Graphidaceae	Cr.	Diploschistasic acid and Lecanoric acid
4.	*Lecanora* sp.	Lecanoraceae	Cr.	Atranorin, Lecanoric acid, Zeorin, 2-O- 2-O-methylperlatolic acid
5.	*Lecidella enteroleucella* (Nyl.) Hertel	Lecanoraceae	Cr.	Lecanoric acid and Xanthone
6.	*Parmotrema praesorediosum* (Nyl.) Hale	Parmeliaceae	Fo.	Atranorin and Praesorediosic acid
7.	*Parmotrema* sp.	Parmeliaceae	Fo.	Atranorin and Lecanoric acid
8.	*Pyxine cocoes* (Sw.) Nyl.	Caliciaceae	Fo.	Lichexanthone and Triterpenes
9.	*Usnea* sp.	Parmeliaceae	Fr.	Usnic acid

Abbreviations: **G.F.** = Growth form; **Cr** = Crustose; **Fo**= Foliose; **Fr**= Fruticose and **sp.**= species

Table 2: List of bryophytes with their families, growth form and secondary metabolites they produce

Sl.No.	Bryophyte Taxa	Family	Secondary metabolites
1.	*Marchantia papillata* (Steph.) Bischl.	Marchantiaceae	Riccardin C
2.	*Marchantia polymorpha* L.	Marchantiaceae	Marchantin A
3.	*Rhodobryum roseum* (Hedw.) Limpr.	Bryaceae	Piperine and Kaempferol
4.	*Riccardia* sp.	Riccardiaceae	Neophytadiene
5.	*Stereophyllum* sp.	Stereophyllaceae	No chemicals
6.	*Thuidium* sp.	Thuidiaceae	Trichoderolactone F

approximately 800 years old. The monolith in the sacred forest was selected for the study as it is one of the oldest monoliths in Meghalaya and in whole northeast region. Secondly, the monoliths bearing immense historical significance have suffered considerable deterioration due to geo-weathering and biological factors. It is imperative that the local tourism authorities recognize this issue and implement effective conservation measures. This sacred forest was one of the places of congregation for the then Khasi kings and leaders (called as Ki Lyngdoh), where they held meetings, coronation, religious rituals and sacrifices. The forest has monoliths in the memory of great kings and warriors of the Khasi tribe. The sacred forest is situated on the Khasi Hills, 15 kms away from Mawphlang town bearing co-ordinates: 25º 26' 46'' N, 91º 44' 57'' E at an altitude of 1,841m (Fig.2). A survey was conducted to evaluate the biodeterioration effects of lichens and bryophytes on the monoliths during the year 2024. The sacred forest is highly protected by the locals, and one has to take permission and a local guide to explore the areas so, it is prohibited to collect samples or even a twig from the forest premises hence, high quality photographs of the lichen and bryophytes growing on the monoliths were taken for the study. The common species have been identified up to the species level whereas others were identified up to the genus level and the photographs were validated by subject experts.

Result and Dscussion

The study revealed that the monolith of Mawphlang sacred grove have faced climatic and anthropogenic pressure. They are made up of sandstone and khondalite which are porous having a good water-holding capacity there by provides a suitable niche for the bryophytes and lichens. A total number of nine species of lichens belonging to eight genera under four families were reported from the study site (Fig. 3). There were total of six species of bryophytes belonging to five genera under five families listed from the study site (Fig. 4). Among the lichens (Table 1), the members of Caliciaceae family were dominant whereas the mosses belonging to families Bryaceae, Riccardiaceae, Stereophyllaceae and Thuidiaceae were growing luxuriantly on the monoliths. The lichens and bryophytes with large thalli dry up and shrink during the summer and retains its original appearance during the rainy season after retaining moisture. This contraction and expansion action causes the thalli to curl up which results in the pulling out surface materials from the monoliths. Moreover, the expansion and contraction of the thalli of these cryptogams causes micro-cracks by the penetration of their rhizines.

According to the studies conducted by Iskandar and Syres (1972), it inferred that secondary metabolite of lichens, namely Atranorin, Lecanoric acid, Stictic acid and Usnic acid, having pH values 3.2, 4.8, 5.3 and 4.5 respectively, are the most prominent compounds that are responsible in the biodeterioration of monuments. Similarly, Dziwak et al., (2022) in their research article has elaborated the wide use and significant array of secondary metabolites from bryophytes which are acidic in nature and might have a similar effect to that of lichen secondary metabolities on the monuments. From the above-discussed facts, it is clear that the monoliths of Mawphlang sacred grove are prone to deterioration by lichens and bryophytes which mostly microlichens or tightly adhered foliose lichens and bryophytes. Secondly most of the lichens and bryophytes reported from the study sites produce secondary metabolites (Table. 1) that are potential chelators and bio-deteriorants. Additionally, the construction materials (sandstone and khondalite), ever-changing climatic conditions and increase in anthropogenic activities like tourisms, forest clearing and increased air pollution in the regions have supported pollution-tolerant lichen species like *Dirinaria* and *Pyxine* there by putting the fate of the monoliths on high risk.

Conclusion

This study highlights the significant impact of climatic and anthropogenic pressures on the monoliths of Mawphlang Sacred Grove, a culturally and historically important site in Meghalaya, India. Composed mainly of porous sandstone and khondalite, the monoliths are particularly vulnerable to biodegradation due to their high-water retention, which facilitates colonization by lichens and bryophytes primary agents of biological weathering. A total of nine lichen species from eight genera (four families) and six bryophyte species from five genera (five families) were documented. Lichens of the *Caliciaceae* family were most prevalent, while mosses from *Bryaceae*, *Riccardiaceae*, *Stereophyllaceae*, and *Thuidiaceae* showed luxuriant growth. The cryptogamic flora plays a crucial role in biodeterioration due to its physiological resilience and biochemical interactions with the stone substrate.

A key mechanism observed was the seasonal shrinkage and expansion of lichen and bryophyte thalli. These cycles impose mechanical stress, leading to gradual surface detachment. Additionally, rhizines and rhizoids penetrate micro-cracks, accelerating stone disintegration over time. Chemical weathering is also driven by lichen-derived secondary metabolites, which are mostly acidic compounds causing stone decay. The presence of such metabolites at Mawphlang suggests their active role in chemical deterioration.

Human activities further exacerbate degradation. Increased tourism, deforestation, and pollution have shifted the cryptogamic community in favor of tolerant species like *Dirinaria* and *Pyxine*, which also act as bioindicators of atmospheric pollutants. The combined effects of biological, chemical, and mechanical weathering, intensified by climate change and human interference, pose a serious threat to the monoliths. This study emphasizes the need for integrated conservation strategies, including non-invasive monitoring, selective removal of colonizers, protective coatings, and sustainable tourism practices.

In conclusion, the research provides a comprehensive overview of the bio-deteriorative role of lichens and bryophytes on Mawphlang's monoliths, calling for urgent and holistic conservation efforts to preserve this heritage site for future generations.

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