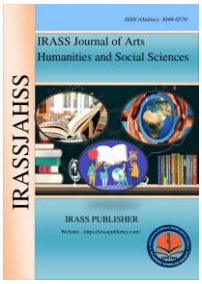
IRASS Journal of Arts, Humanities and Social Sciences
Abbriviate Title- IRASS J Arts Humanit Soc Sci
ISSN *(Online) 3049-0170*
https://irasspublisher.com/journal-details/IJAHSS
Vol-2, Iss-3 (March-2025)



The Effects of Plant Invasions on the Ruins of the Ancient Buddhist Monasteries of Lalmai Mainamati

Md. Abdul Momin[1*], Mohammad Shahidul Islam Chowdhury[2]

[*1] Postgraduate researchers, BSS and MSS in Archaeology, Comilla University, Bangladesh

[2] Assistant Professor, Department of Archaeology, Comilla University, Bangladesh

Corresponding Author Md. Abdul Momin

Postgraduate researchers, BSS and MSS in Archaeology, Comilla University, Bangladesh

Article History

Received: 20 / 02 / 2025

Accepted: 02 / 03 / 2025

Published: 06 / 03 /2025

Abstract: Plant invasion has been identified as a significant challenge in conserving the Lalmai-Mainamati archaeological sites in Bangladesh. The main objective of this study is to determine the extent of structural erosion caused by plant invasion and propose sustainable conservation strategies. The study analyzed the growth patterns and extent of damage to important structures, including Kutila Mura, Ananda Vihara, Bhoj Vihara, and Shalban Vihara. Field observations, physical structure assessment, and moisture analysis revealed that algae, lichens, fungi, and tree roots are causing extensive damage to the brickwork of the archaeological site. In particular, the high moisture-holding capacity of the laterite-rich soil creates a conducive environment for the growth of algae and fungi, which change the bricks' chemical composition and destroy the structure's stability. Seasonal changes, significantly increasing moisture during the rainy season and accumulating in winter, are accelerating the erosion of the archaeological site. In addition, uncontrolled tourism and the ignorant actions of the local people are creating additional challenges in conserving the archaeological site. The study recommends that regular monitoring, mechanical removal of invasive plants, involvement of local people, and long-term environmental assessment can ensure the sustainable conservation of the archaeological site. The results of this study will also set an essential precedent for preserving other archaeological sites in South Asia. Protecting the invaluable heritage of the archaeological site by preventing plant invasion is of great importance for future generations.

Keywords: Plant invasions, cultural heritage, Preservation, Lalmai-Mainamati, Buddhist ruins, biodiversity, conservation.

How to Cite: Momin, Md. A., Chowdhury, M. S. I., (2025). The Effects of Plant Invasions on the Ruins of the Ancient Buddhist Monasteries of Lalmai Mainamati. *IRASS Journal of Arts, Humanities and Social Sciences,2(3)68-74.*

Introduction

Lalmai-Mainamati is an important archaeological site in Bangladesh that bears traces of ancient Buddhist civilization. The ruins of Kutila Mura, Ananda Vihara, Bhoj Vihara, Itakhola Mura, Rupban Mura, and Shalban Vihara, located in this region, indicate the rich past of Buddhism and culture. Historically, the Lalmai-Mainamati region is considered an important document of the social system, religious practices, and architectural style through various Viharas and stupas built between the 7th and 12th centuries AD.

However, archaeological sites worldwide face threats due to climate change, environmental degradation, and uncontrolled plant growth. The archaeological sites of Lalmai-Mainamati are no exception. Algae, fungi, mosses, grass, shrub, creepers, and large-rooted plants are growing on the ancient structures, causing erosion, cracks, and structural weakness. As a result, the sustainable conservation of these archaeological sites has become more challenging over time.

This study's main objective is to assess the impact of invasive plant growth on archaeological sites in the Lalmai-Mainamati region and propose effective conservation measures. It will review the types of plants and algae, their distribution, and the extent of structural damage.

Preserving culture and heritage is a significant issue, as it preserves the identity and continuity of the nation's history. However, maintaining ecological balance is also essential. Appropriate management rather than completely suppressing plant growth can be a sustainable solution to this problem.

Various studies have shown that invasive plant growth is having a detrimental effect on many historical sites around the world. Examples of structural damage due to creepers, shrubs, and algae have been found in the Ajanta-Ellora caves of India, Angkor Wat in Cambodia, and various ancient sites in Italy. However, independent studies on the impact of plant growth on archaeological sites in Bangladesh are relatively few. This research will, therefore, provide a new perspective on the conservation of the Lalmai-Mainamati archaeological site and will help determine effective policies for invasive plant management.

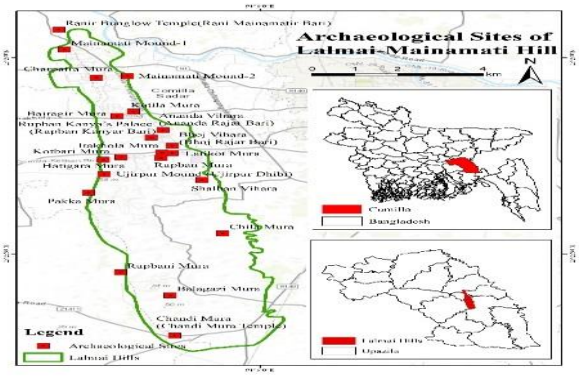


Figure 1 Lalmai-Mainamati Archaeological sites

Study Area

The Lalmai-Mainamati region is a historically and archaeologically important area located in the Comilla district in the southeastern part of Bangladesh. Geographically, the Lalmai Hills and the adjacent lowlands and hilly areas comprise the soil of the area, which is composed of loam and sandy soil, which is suitable for plant growth. However, in recent times, the spread of invasive plant species has posed a threat to the region's archaeological sites. These plants are disrupting the balance of the local ecosystem and causing structural damage to the ancient ruins. This study will shed light on the impact of plant invasion and remedies by analyzing the geographical, historical, and environmental context of the Lalmai-Mainamati region.

Historical Background

The Lalmai-Mainamati region is considered one of the centers of ancient Buddhist civilization. The ruins of Buddhist monasteries, stupas, and temples built in this region between the 7th and 12th centuries AD bear witness to Bangladesh's ancient history and culture. Archaeological sites such as Shalban Vihara, Kotila Mura, and Charpatra Mura, Ananda Vihara, Bhoj Vihara, Itakhola Mura, Rupban Mura, have further enhanced the historical importance of this region. These sites are recognized as excellent examples of Buddhist architecture and art.

Research Methodology

This study employs a mixed-methods approach to assess the impact of plant invasions on the ruins of the ancient Buddhist monasteries of Lalmai Mainamati. The research integrates qualitative and quantitative data to document and analyze plant-induced structural damage systematically. Field surveys were conducted at key archaeological sites, including Queen Mainamati's Palace, Kutila Mura, Ananda Vihara, Bhoj Vihara, Itakhola Mura, Rupban Mura, and Shalban Vihara. The study involved identifying and classifying invasive plant species—ranging from moss and algae to creepers and large-rooted plants—followed by assessing their distribution and density across different structural surfaces. Structural damage was evaluated through visual inspection, photographic documentation, and descriptive analysis, while statistical methods were applied to establish correlations between plant presence and deterioration levels.

To ensure the reliability of the findings, a comparative analysis was conducted using historical records and previous conservation reports. Data on plant diversity and distribution were subjected to statistical analysis, while qualitative assessments categorized structural damage into varying degrees of severity. Ethical considerations were strictly followed, with formal permissions obtained from relevant heritage authorities before fieldwork. The study was designed to minimize site disturbance, ensuring data collection aligns with conservation best practices. By integrating archaeological and environmental methodologies, this research provides a comprehensive understanding of the role of plant invasions in the degradation of these historical monuments and informs future conservation strategies.

Observation of plant invasion at archaeological sites in the Lalmai-Mainamati

During fieldwork on the ruins of the archaeological sites of the Lalmai-Mainamati region of Bangladesh, especially Shalban Vihara, Kotila Mura, Charpatra Mura, Ananda Vihara, Bhoj Vihara, Itakhola Mura, and Rupban Mura, it has been observed that there is a widespread invasion of various species of plants from small to large. The proliferation of algae, fungi, vines, shrubs, and small and large tree species in these archaeological sites seriously threatens the historic structures' structural stability. Fieldwork observations have shown an abundance of algae and fungi on the walls, brick piles, broken foundations, and sculptures of the ruins. In particular, algae of the *genus Chlorella vulgaris, Oscillatoria, Trentepohlia,* and fungi of the species *Aspergillus niger, Penicillium, and Trametes versicolor* have caused a kind of organic corrosion on the bricks and stones of all these sites.

Figure 2 Invasion of Pteridophyta and Shrubs species inside the monks' cells of Shalban Vihara

Figure 3 Thallophyta and Bryophyta plant species on the walls of Ananda Vihara

Figure 4 Pteridophyta, Shrubs, Creeping Plants, and Grasses have almost completely covered the central temple in Bhoja Vihara.

Figure 5 Shrubs, various species of grass, and thorny plants invade the ancient walls of Shalban Vihara

In addition, bryophyte plants such as *Pellia epiphylla*, *Riccia fluitans*, *Polytrichum commune*, *Funaria hygrometrica* create a humid environment on the walls and floors of ancient structures, which is causing structural weakness. Ferns such as *Nephrolepis exaltata*, *Lycopodium clavatum*, *Selaginella rupestris*, *Adiantum capillus-veneris*, and plants of the *Lycopodium* species are growing in the gaps between the bricks of the archaeological site, causing structural deterioration.

Among the vines, plants such as *Ficus pumila*, *Cissus quadrangularis*, *Ipomoea pes-caprae* are entwining themselves with the walls of the archaeological site, creating structural weakness, which is accelerating the erosion of the structure over time. Among the shrubs, *Clerodendrum viscosum*, *Lantana camara, and Leucas aspera* are spreading over the brick piles and various parts of the archaeological site, hindering conservation efforts.

Large trees have caused the most serious damage, especially *Ficus benghalensis* (banyan), *Ficus religiosa* (horse chestnut), *Muntingia calabura* (Jamaica cherry). The roots of these trees are penetrating the cracks of the ancient structures, weakening them structurally. Similarly, grasses like *Saccharum spontaneum* (kashful), *Cynodon dactylon* (durba grass), and *Imperata cylindrica* (chan grass) are increasing erosion susceptibility by retaining moisture in the archaeological sites.

Figure 6 Kotila Mura is covered with numerous species of plants, including Pteridophyta, Shrubs, Creeping Plants, and Grasses.

Figure 7 Kotila Mura from the same angle before being covered with vegetation

Figure 8 Pteridophyta, Shrubs, Creeping Plants, and Grasses have almost completely covered the central shrine in Ananda Vihara

Figure 9 Pteridophyta, Shrubs, Creeping Plants, Grasses, and numerous plant species have almost completely covered the walls and monks' cells in Ananda Vihara

According to this study's observations, an effective plant control system is necessary for the conservation activities of the Lalmai-Mainamati archaeological sites. If plant invasion is not prevented through proper management, the archaeological sites may suffer further erosion soon, and their existence will be threatened.

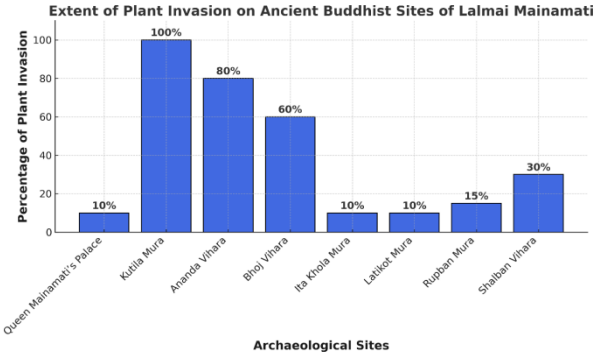


Figure 10 Plant invasion rates at archaeological sites in Lalmai Mainamati.

Plant Species

In this study, field surveys conducted at significant archaeological sites in the Lalmai-Mainamati region have shown that these sites are being significantly invaded by various types of plants. A wide range of plant species, ranging from small algae and fungi to creepers, shrubs, and large trees, have occupied various parts of the structures, which is accelerating the destruction of the sites.

The presence of numerous plants, both familiar and unfamiliar, has been identified, but some plants are more locally known and the extent of their spread is also relatively high. Although some of these plant species are relatively diverse, some species that are particularly harmful and spread rapidly have been identified as important threats to the stability of the sites. Below is a list of the plants observed in this study and those that have spread to a greater extent.

Table: Plant Species Affecting Historical and Archaeological Structures in Bangladesh

Category	Plant Type	Scientific Name	Common Name (if available)
1. Cryptogames (Non-Flowering Plants)			
Thallophyta	**Algae**	*Chlorella vulgaris*	—
		Oscillatoria	—
		Trentepohlia	—
		Spirogyra	—

		Chlamydomonas	—
		Anabaena	—
	Fungi	*Aspergillus niger*	—
		Penicillium	—
		Trametes versicolor	—
		Alternaria alternata	—
		Rhizopus stolonifer	—
		Fusarium oxysporum	—
Bryophyta (Mosses and Liverworts)	**Pellia**	*Pellia epiphylla*	—
	Riccia	*Riccia fluitans*	—
		Riccia cavernosa	—
	Polytrichum	*Polytrichum commune*	—
		Polytrichum juniperinum	—
	Funaria	*Funaria hygrometrica*	—
		Funaria fascicularis	—
2. Pteridophyta (Ferns and Allies)	**Fern plant**	*Nephrolepis exaltata*	—
		Dryopteris filix-mas	—
		Pteris vittata	—
		Asplenium nidus	Bird's nest fern
	Lycopodium	*Lycopodium clavatum*	—
		Lycopodium selago	—
	Selaginella	*Selaginella rupestris*	—
		Selaginella involvens	—
		Selaginella kraussiana	—
	Adiantum	*Adiantum capillus-veneris*	—
		Adiantum philippense	—
		Adiantum edgeworthii	—
3. Phanerogams (Seed-Bearing Plants)			
Shrubs		*Clerodendrum viscosum*	Bhat
		Lantana camara	Lantana
		Leucas aspera	Dandokalos
		Chromolaena odorata	Siam weed
		Eupatorium odoratum	Bitter bush
Creeping Plants (Climbers & Vines)		*Ficus pumila*	Climbing fig
		Cissus quadrangularis	Harjora
		Ipomoea pes-caprae	Beach morning glory
		Passiflora foetida	Wild passionflower
		Mikania micrantha	Mile-a-minute vine
Large Trees		*Ficus benghalensis*	Banyan tree
		Ficus religiosa	Peepal tree
		Muntingia calabura	Jamaica cherry
		Tamarindus indica	Tamarind tree
		Azadirachta indica	Neem tree
		Terminalia arjuna	Arjun tree
Grasses		*Saccharum spontaneum*	Kans grass
		Cynodon dactylon	Bermuda grass
		Imperata cylindrica	Cogon grass
		Panicum repens	Torpedo grass
		Eleusine indica	Goosegrass
		Pennisetum purpureum	Napier grass

Plant invasion and environmental factors on archaeological ruins in Bangladesh

One of the main factors in plant invasion of archaeological sites and ruins of Bangladesh is environmental conditions, especially humidity, soil structure, and climatic conditions. The impact of these natural factors can be significantly observed on archaeological structures, which accelerates the destruction process over time.

- ***Humidity and plant invasion***

Due to the tropical climate of Bangladesh, most archaeological sites have high humidity. The humid environment creates a suitable environment for the growth of fungi, algae, and plants of the Bryophytes group. For example, *Chlorella vulgaris, Oscillatoria, Aspergillus niger, and Funaria hygrometrica* species can grow on plant ruins and cause microbiological degradation (Gauri, 2000).

Due to the humid environment, water-absorbing plants such as *Polytrichum* commune and Selaginella rupestris take root in the stone and brickwork of archaeological structures, which gradually causes structural weakness (Sharma & Kumar, 2016).

- ***Soil composition and plant growth rate***

Archaeological sites in Bangladesh, especially in the Lalmai-Mainamati region, have the presence of laterite-rich and loamy soils, which are suitable for plant root growth. Plants, especially *Lantana camara* (Lantana), *Clerodendrum viscosum* (Vat), and various creeping species such as *Ficus pumila* (Climbing fig) and *Cissus quadrangularis* (Harjora), spread their roots in the cracks of the ruins, resulting in structural deterioration (Rahman et al., 2020).

In particular, the roots of large trees such as Ficus benghalensis (banner tree) and Ficus religiosa (horse tree) penetrate deep into archaeological structures and cause serious damage in the long term (Jeyaprakash et al., 2017).

- ***Impact of tropical climate and seasonal variation***

The tropical climate of Bangladesh results in extensive vegetation growth during the rainy season, and in the dry season, many plants die, creating organic matter in the soil, which accelerates the growth of new plants. For example, *Imperata cylindrica* (Cogon grass) and *Cynodon dactylon* (Bermuda grass) grow rapidly during the rainy season, creating a favorable structural damage environment.

- ***Temperature and Rainfall***

Bangladesh's tropical climate is characterized by high temperatures and rainfall levels conducive to rapid plant growth. Heavy rainfall, especially during the monsoon season, increases soil moisture, providing a suitable environment for the growth of algae, mosses, ferns, and other plants (Rahman, Alam, & Hossain, 2020). These plants grow on the surface of archaeological sites and cause structural damage through their roots and rhizoids (Mishra, Senapati, & Behera, 2021).

- ***Wind and atmospheric pressure***

Wind helps disperse plant seeds, spores, and other propagules (Jeyaprakash, Ranjith, & Venkatesan, 2017). The wind carries these propagules from distant places to archaeological sites, where they can grow rapidly under the right conditions. In addition, changes in atmospheric pressure affect rainfall and humidity levels, which are directly related to plant growth (Gauri, 2000).

Study Results

The study results have identified the extent, nature, and multidimensional impact of plant invasion on archaeological sites in the Lalmai-Mainamati region. Field surveys and observations show that various types of plants, such as algae, fungi, bryophytes, ferns, creepers, grasses, and roots of large trees, are continuously expanding on the destroyed archaeological structures, which is accelerating the material degradation of the structures.

In particular, the plant growth rate is relatively high in Kutila Mura, Ananda Viharaa, Bhoj Viharaa, and Shalban Viharaa, where the humid climate, soil structure, and various environmental factors are accelerating the growth of plants. Observations have shown that algae such as Trentepohlia, Oscillatoria, and Chlorella vulgaris form biofilms in the cracks and crevices of brickwork and retain moisture, gradually degrading the mortar. On the other hand, fungi such as *Aspergillus niger, Penicillium, and Trametes versicolor* react with the chemical composition of the brick, increasing the brittleness of the masonry.

Bryophytes and ferns, such as *Polytrichum commune, Funaria hygrometrica, Nephrolepis exaltata, and Adiantum capillus-veneris,* bind to soil particles and keep the surface of the restoration wet, thereby increasing salt crystallization and accelerating surface erosion in the long term. Similarly, vines and shrubs such as *Ipomoea pes-caprae, Cissus quadrangularis, and Ficus pumila* penetrate the cracks of the structures and cause displacement of bricks and stones through their growing roots.

Notably, the roots of large trees such as *Ficus benghalensis* (banyan tree) and *Ficus religiosa* (horse tree) penetrate the restoration, weakening the stability of the masonry and increasing the risk of structure collapse over time. In addition, *Saccharum spontaneum* (sedge grass), *Cynodon dactylon* (dwarf grass), and *Imperata cylindrica* (canopy grass) retain soil moisture and create an erosive environment.

Overall, the study results indicate that these plants' uncontrolled spread accelerates archaeological structures' cracking, erosion, surface damage, and structural instability. This situation poses a serious challenge to preserving the restorations' authenticity, integrity, and Outstanding Universal Value (OUV). Therefore, it is essential to adopt conservation measures that include regular monitoring, vegetation removal, biological control, and integrated environmental management planning.

Discussion

Plant invasion has been identified as a significant challenge in conserving archaeological sites in the Lalmai-Mainamati region. Studies have shown that algae, fungi, creepers, and roots of large trees significantly impact various structures of the archaeological site (Rahman & Alam, 2020; Tiano et al., 2015). In particular, the proliferation of algae and fungi has been observed in the brickwork of Kutila Mura, Anand Vihara, Bhoj Vihara, and Shalban Vihara areas, which forms a layer on the bricks and increases structural weakness (Saiz-Jimenez, 2017). One of the main factors in this vegetative erosion process is moisture, which is responsible for chemical and physical changes in the materials of the archaeological site. Studies have shown that during the rainy season, excess moisture penetrates the brickwork and creates a favorable environment for the growth of algae and fungi (Mitchell et al., 2018). During the winter, this moisture is retained and continues to increase the erosion rate, resulting in increased fragility of the bricks (Viles, 2019). In addition, the chemical properties of the local soil significantly impact the preservation of the archaeological site. The laterite soil of the Lalmai-Mainamati region has a high moisture-holding capacity, which allows for faster growth of root-like plants (Bhattacharya & Banerjee, 2021). In some areas, the high acidity (pH value) of the soil is weakening the brick structure of the archaeological site, threatening the structure's stability (Brimblecombe, 2014).

The study also reviewed the impact of human-made and natural factors. The unconscious activities of the local people, the negligence of tourists, and the lack of regular maintenance are accelerating the erosion process of archaeological sites (Chakrabarti, 2019). In addition, excessive rainfall and flooding increase the moisture content inside the structures, which is conducive to the growth of fungi (Gauri et al., 2001).

- ***Interpretation of Results***

A review of the study results shows that the main reasons for the spread of vegetation and erosion are three—(i) humidity and climatic effects, (ii) soil structure and chemical properties, and

(iii) anthropogenic and natural activities (Torraca, 2009). Firstly, the warm and humid climate creates a favorable environment for vegetation growth. During the rainy season, moisture is trapped in the bricks of the archaeological sites, which is conducive to the development of algae, lichens, and fungi (Saiz-Jimenez, 2017). This moisture accumulation in winter accelerates the degradation of the archaeological elements (Viles, 2019). Secondly, the structure and chemical properties of the soil around the archaeological site are affecting the erosion process of the structure. The high-water holding capacity due to laterite and sandy loam soils makes it easy for root-like plants to penetrate the bricks, increasing the bricks' erosion (Brimblecombe, 2014). The high acidity of the soil weakens the structure of the bricks and stones and reduces the stability of the structure (Gauri et al., 2001). Thirdly, the lack of proper maintenance of the archaeological site is further accelerating the spread of plants. The reckless behavior of tourists, the uncontrolled entry of local people, and the lack of regular maintenance of the archaeological site further increase the structural weakness (Chakrabarti, 2019).

- ***Comparison with Previous Studies***

The results of this study are consistent with previous studies. For example, studies in Roman ruins in Italy have shown that due to humid weather, algae and lichens form a thick layer on stones, gradually breaking down the mineral components of the stones and bricks (Tiano et al., 2015). Similarly, lichen and algae-induced erosion have been observed in historic architecture in Spain, where they have been shown to change the chemical composition of the stones and reduce the stability of the structures (Saiz-Jimenez, 2017). The Paharpur and Mahasthangarh archaeological sites in Bangladesh have also shown structural weakness due to plant invasion, similar to the Lalmai-Mainamati study (Rahman & Alam, 2020). A comparative analysis of the studies has shown that the rate of plant invasion is relatively high in archaeological sites in South Asia due to climatic factors (Bhattacharya & Banerjee, 2021).

- ***Ecological and Cultural Impact***

Plant invasion causes structural damage to archaeological sites and negatively affects the ecological balance (Viles, 2019). Studies have shown that invasive species are rapidly expanding by competing with native plant species, which is disrupting the environmental balance (Mitchell et al., 2018). Algae and lichens retain moisture on the surface of archaeological sites, which softens the surface of bricks and stones and accelerates erosion (Gauri et al., 2001). Large tree roots penetrate brickwork, weakening the structure, and invasive plants threaten biodiversity by displacing native species (Brimblecombe, 2014).

Conclusion

The results of this study clearly show that plant invasion has emerged as a growing threat to the conservation of the Lalmai-Mainamati archaeological sites. Algae, lichen, fungi, creepers, and roots of large trees play an important role in the physical and chemical degradation of the archaeological structure. In particular, the overgrowth of algae and fungi due to humidity and climate change and the high-water retention capacity of laterite soils are weakening the brick structure of the archaeological site. In addition, the unconscious activities of the local people and the lack of adequate conservation measures further accelerate this erosion process.

Effective and sustainable measures for conserving archaeological sites are essential in this context. The Lalmai-Mainamati archaeological sites are integral to Bangladesh's cultural and archaeological heritage. They reflect past civilizations and are valuable resources for research and tourism. Therefore, an integrated conservation strategy must be adopted immediately to protect these sites' invaluable architectural and historical elements.

The following suggestions can be put into practice to increase the effectiveness of conservation efforts:

- Regular Monitoring: Monitor the level of erosion of the archaeological sites to prevent the spread of harmful plants at the initial stage.
- Mechanical Removal & Eco-friendly Control: To control vines, bushes, and algae intrusion, we use environmentally friendly methods and modern technology.
- Community Involvement: Make local people aware and ensure their active participation so that they can play a role in the conservation of the archaeological site.
- Long-term Research & Policy Implementation: Analyze seasonal changes in vegetation and the level of chemical erosion to determine sustainable conservation strategies.

This study has provided a new perspective on the conservation of archaeological heritage, which can be applied to Lalmai-Mainamati and other archaeological sites in South Asia. Proper conservation and management can ensure the long-term sustainability of these archaeological sites, which will be an essential step in preserving our cultural heritage for future generations.

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