Assessment of Microbial-Induced Weathering in Heritage Stone Monuments of Warangal: A Culture-Based Analytical Approach

M. Rhema Suhani[1], S. Rejoice[2], P. Joy[3], Dr. G. Renuka[4]

[1,3]Student, B. Sc. Life Science I Year, [2]Student, B. Sc. Life Science II Year, [4]Associate Prof & HOD of Microbiology
[1,2,3,4]Pingle Government College for Women(A), Hanumakonda -T.S
Corresponding Author: Dr. G. Renuka

Abstract:
As microorganisms inhabit these monuments over time, biofilms are formed, and the stone becomes physically weakened and discolored due to microbial metabolites. Cultural legacy is significantly lost as a result of this process, which is called biodeterioration. The most common taxa were found to be closely related to Bacillus species, Arthrobacter species, *Staphylococcus* spp. and *Paenibacillus* species after purification and 16S rDNA sequencing of bacteria living on historical monuments. Apart from bacteria, there have also been reports of some fungal strains belonging to the genera Alternaria, Fusarium, Aspergillus, and Penicillium. to create conservation plans that work in order to repair monuments and stop biodeterioration. This paper provides an overview of some well-known biodeterioration processes that have been seen on various materials, including stone and construction materials, items on display in museums and libraries, human remains, and materials used in burial.

Keywords: Microorganisms, Biodeterioration, Microbial communities, Microbial-Induced Weathering, Heritage Stone Monuments.

Introduction:

In the past, people employed a variety of stones, including marble, granite, and limestone, to create stunning artwork and erect imposing structures. Our heritage is represented by these old structures and pieces of art, which educate us about earlier architectural and artistic trends and infuse us with cultural values. These sculptural monuments were made using naturally occurring sedimentary rocks, which are made up of one or more minerals. The stones used in their construction were extremely resistant and cemented. These landmarks and works of art are now at risk of deterioration due to exposure to corrosive acid rainwater and contaminated air. Intricately crafted paintings and artwork that require payment are being viewed by a variety of bacteria that are currently enjoying their royal stay in historic monuments. The existence of microorganisms on monumental stones and artwork does not necessarily mean that their growth is linked to the biodeterioration. Numerous variables, including mineral composition, nutrient availability, pH, salinity, surface texture, moisture content, porosity, permeability, climate, and microenvironmental circumstances, affect the capacity of microorganisms to colonize stone surfaces [1].

A number of factors influence the biodeterioration phenomenon seen on cultural heritage artifacts, including: (1) the material's chemical makeup and nature; (2) the object's exposure and environment; and (3) how and how frequently surface cleaning and housekeeping are done in museums. Here are a few well-known instances.

The microbial communities—lichens, fungi, and bacteria—that flourish in Warangal's warm, humid climate are mostly responsible for the biodeterioration of stone and construction materials, especially on ancient Kakatiya-era structures. These substances, for instance, produce acid and build biofilms, which seriously weaken the body and cause coloring and structural damage.

The Kakatiyas were renowned for their magnificent constructions, which included the Warangal Fort, the 1000 Pillar temple at Hanamkonda, the Shiva temples at Kotagullu, and the Ramappa Temple, which is a UNESCO World Heritage site. The Kalyani Chalukyas and a combination of Dravidian and Nagara architectural styles had a significant effect on the style. One noteworthy aspect is that the Vimana was built using sandbox technology. With each prop set up atop a sand box, this technique essentially eliminates the arch's centering. The center moves lower as a result of the sand pouring from one box to another after the prop is removed, relieving strain on the arch.

Built in 1213 CE by Recherla Rudra, the general of Ganapati Deva, the magnificent Ramappa Temple is situated in a forest approximately 66 kilometers from Warangal and is now a UNESCO World Heritage site. This temple, which lies adjacent to the enormous Ramappa Lake, which the Kakatiya monarchs constructed as a water supply reservoir, must be the only one named after its architect. India is the brightest star amid a galaxy of temples, according to Marco Polo, who visited the country.

The entire temple is situated on a six-foot-tall star-shaped platform, and the hall directly in front of the sanctum features several carved pillars that provide the impression of light and space. The columns include sizable brackets of black basalt, but the temple is mostly composed of red sandstone.

The temple is particularly well-known for its finely carved Nagini sculptures, which depict the dancers. The temple's bricks, which are so light that they float on water, are another characteristic. The Perini Sivatandavam, which was performed by troops before to the conflict, was revived by renowned dance instructor Nataraja Ramakrishna thanks to these sculptures of dancers.
The process of weathering is brought on by microbial communities secreting metal-binding ligands and corrosive organic and inorganic acids, which causes the rock's superficial mineral surface to gradually weather or dissolve. Studying the involvement of microbes in the geochemical change of monumental stones and artworks can be done effectively through microbial-mineral interaction. This interaction illustrates the various strategies that microorganisms employ to draw nutrients from the surface of minerals. [2–3]

Microorganisms involved in biodeterioration
Bacteria
Three nutritional types comprise the majority of the bacteria that cause monument and artwork deterioration: photoautotrophs, chemoautotrophs, and chemomoorganotrophs. The majority of phototrophs and chemolithoautotrophs are cyanobacteria, and nitrifying and sulfur-oxidizing bacteria have been identified at heritage sites. These bacteria readily grow on outdoor monuments because of their simpler nutritional (such as inorganic minerals, atmospheric ammonia, etc.) and ecological requirements (such as the availability of light, CO2, and water). Cyanobacteria are among these species that can endure the frequent drying and rehydrating that occurs on exposed monument surfaces. They can also defend themselves against the damaging UV rays by creating pigments that shield them from the sun's rays.

By analyzing the correlation between the relative bioprotection rate of biofilms and environmental circumstances, this study assessed the dual functions of biofilms at cultural heritage sites. In particular, 16S rRNA data from 91 sampling locations from 10 World Heritage Sites in various East and South Asian climates were examined. We investigated the effects of climate on the dominating species, diversity, and network structure of microbial communities by evaluating the microbial community structures under various climatic situations. The pace of biofilm protection was also expected to be determined by metabolic processes engaged in degradation and functional genes linked to biofilm protection. The effect of biological preservation and degradation on cultural resources was then assessed using this rate. In order to clarify the main ways that climatic gradients impact biofilm function, the relationship between biofilm protection rate and climate circumstances was finally examined. By reducing microbial deterioration and developing creative biointervention techniques, the study's findings offer fresh perspectives on the climate-driven shift in biofilm functions and support the long-term preservation of stone cultural heritage sites.

Review of Literature:

Monuments and other cultural landmarks draw large numbers of tourists, which has a big economic impact. Stones and other man-made materials are among the materials used to construct many historical structures. Historical monuments use a variety of stones, including granite, marble, sandstone, limestone, slate, and quartzite, which are derived from volcanic, metamorphic, and sedimentary rocks. Numerous minerals, such as Cu, Ni, Ca, Na, Mg, Fe, and Al, are present in many of these stones. India's stone industry presently includes the manufacturing and building of blocks, structural slabs, flooring slabs, monuments, tombstones, sculptures, cobblestones, pebble stones, and landscape garden stones. However, microbial activity, environmental causes, and man-made elements can cause monuments to deteriorate. For instance, the material structure may be harmed by environmental processes such temperature changes, wind, water, capillary action, and sun radiation (Branysova et al., 2022). [4]

Microorganisms and their extracellular polymeric materials (environmental DNA, proteins, and polysaccharides) form biofilms. Research has indicated that the development of biofilms on the stone surfaces of historical sites is significantly influenced by microbes, especially bacteria. However, it has been discovered that biofilms have two different impacts on stone: bioprotection and biodeterioration. Cultural heritage places may lose their historical and aesthetic value due to biodeterioration, which can range from material discoloration to structural degradation. Through physical penetration, corrosion from organic and inorganic acids, and redox reactions of mineral cations, this process can harm the rock formations. On the other hand, bioprotection describes how biofilms benefit cultural heritage by forming protective layers on stone surfaces through biomineralization, such as precipitation of calcium carbonate and calcium oxalate, which increases resilience to environmental stress. Biofilms can serve as physical barriers to shield stone surfaces from UV rays, acid rain, and degradation. However, a variety of multifaceted elements, including the microbial community, environmental circumstances, and rock qualities, influence both microbial protection and deterioration. The creation and development of biointervention techniques is limited by the lack of understanding of the mechanisms behind the functional change of biofilms. [5]

Objectives:

To look into how microbial populations affect the weathering and deterioration of Warangal's stone monuments and to suggest conservation tactics that are supported by science.

Research Methodology:

Study Area: Ramappa Temple, Thousand Pillar Temple, and Warangal Fort

Because **granite, basalt, and sandstone** make up the majority of these monuments' construction, they are vulnerable to **microbial colonization and biodeterioration** in tropical climates. The taxonomic literature about the bacteria that cause biodeterioration was screened using the Google Scholar, Scopus, and Web of Science engines. The terms "biodeterioration," "microorganism," "limestone," "historical buildings," "cultural heritage," and "molecular methods" were employed.

Significant microbial colonization was found to contribute to biodeterioration through physical, chemical, and metabolic pathways in both field and laboratory research.

Result and Discussion:

Biofilms made up of bacteria, fungi, and algae are the primary cause of microbial weathering in Warangal's heritage stone monuments (such as the Kakatiya constructions), which severely degrades their surfaces by physical penetration and acid secretion. The predominant fungi are Aspergillus sp. and Helminthosporium velutinum, which produce organic acids that cause iron-based dissolution and calcium/iron oxalates. [6]

A varied consortia of microorganisms populating the stone surfaces was discovered by microscopic inspection and microbial investigation using culture-dependent techniques. The most common bacterial species were *Bacillus* and *Pseudomonas*, as well as nitrifying bacteria that aid in the biochemical modification of minerals. *Aspergillus niger, Penicillium* spp., and *Cladosporium* spp. were the most common fungi found in the isolates. These species are known to generate organic acids and develop hyphae to enter stone matrices. There were also a lot of phototrophic microbes; cyanobacteria like *Nostoc* and *Oscillatoria* were seen to develop colored layers, especially in areas that were damp and shadowed. Furthermore, it was discovered that green algae were forming cohesive biofilms that improve surface moisture retention. Firmly adhered to exposed stone surfaces were foliose and crustose lichens, which suggested advanced biological colonization phases and made a substantial contribution to chemical and mechanical weathering processes.

Numerous types of physical deterioration linked to microbial colonization were found during field examinations of the historic stone surfaces. One of the most noticeable characteristics was surface discoloration caused by lichen, fungus, and algae growth, which appeared as green, black, and brown spots. Granular disintegration was frequently seen, especially in blocks of sandstone, where the mineral grains gradually became loose and separated. The outer stone layers' flaking and scaling showed that the surface matrix was gradually deteriorating. Through the penetration of fungal hyphal, which created mechanical pressure within the stone fabric, microscopic analysis revealed the enlargement of pre-existing microcracks. Pitting and overall surface roughening were visible in a number of places, which increased vulnerability to environmental stress. By keeping moisture on the stone surface, biofilm growth aided in these processes by speeding up mechanical weathering and intensifying recurring wetting-drying cycles.

Microbial activity caused notable chemical changes in the stone substrates, according to laboratory studies that included pH readings, scanning electron microscopy (SEM), and mineralogical examinations. Because colonizing bacteria produce organic acids such oxalic, citric, and gluconic acids, there was a discernible drop in surface pH. These acids weakened the structural integrity of the stone matrix by aiding in the breakdown of vulnerable minerals, especially mica and feldspar. Degraded surfaces showed signs of secondary mineral production, particularly calcium oxalate crystals, which suggests that microbial metabolites and stone constituents are actively interacting biochemically. Further degradation and internal tension were also caused by increased salt crystallization in the pore spaces. Since they actively secreted organic acids that could chelate metal ions like calcium, magnesium, and iron, fungi were found to be important players in this process. This accelerated chemical weathering and mineral degradation.

Environmental factors that affect the weathering of microorganisms:

Factor	Impact
High temperature (summer >40°C)	increases the thermotolerant bacteria' metabolic rate
Monsoon humidity	encourages the production of biofilms
Air pollution	provides nutrients (sulfates, nitrates)
Tourist activity	introduces a microbial burden from outside

Conclusion:

The study demonstrates that one of the main causes of biodeterioration of Warangal's Kakatiya monuments is microbial weathering. Together with environmental conditions, the cooperative activity of bacteria, fungi, algae, and lichens speeds up chemical and physical deterioration.

Particularly in environments with high humidity and temperatures, the surfaces of granite and sandstone offer ideal habitats for colonization. To protect these culturally significant structures, sustainable conservation measures must combine environmental management with microbiological monitoring.

REFERENCES:

1. Warscheid T, Braams J: Biodeterioration of stone: a review. Int Biod Biodegr 2000, 46: 343–368. 10.1016/S0964-8305(00)00109-8

2. Crispim CA, Gaylarde PM, Gaylarde CC: Algal and cyanobacterial biofilms on calcareous historic buildings. Curr Microbiol 2003, 46: 79–82. 10.1007/s00284-002-3815-5
3. https://historyunderyourfeet.wordpress.com
4. T. Branysova et al. Microbial biodeterioration of cultural heritage and identification of the active agents over the last two decades J. Cult. Herit. (2022)
5. Yang, H., Li, X., Chai, L. et al. Climate-driven transition in microbial deterioration and protection of stone surfaces at cultural heritage sites. Commun Earth Environ 6, 1019 (2025). https://doi.org/10.1038/s43247-025-02993-9
6. Suchy, H., Zalar, P., & Macedo, M. F. (2024). Microbial Diversity of Biodeteriorated Limestone Cultural Heritage Assets Identified Using Molecular Approaches—A Literature Review. Applied Sciences, 14(16), 7429. https://doi.org/10.3390/app14167429