DOI: 10.21088/ijb.2394.1391.12225.1

Indian Journal of Biology
Volume 12, Number 2 July-December 2025

ORIGINAL ARTICLE

Chemical Deterioration of Marble Heritage Artifacts Induced by Microbial Activity: Mechanisms, Impacts, and Conservation Strategies

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HOW TO CITE THIS ARTICLE:

Ravindra Goswami, Seema Bhadauria. Chemical Deterioration of Marble Heritage Artifacts Induced by Microbial Activity: Mechanisms, Impacts, and Conservation Strategies. Ind. J Biol 2025; 12(2): 57-65.

ABSTRACT

The preservation of marble heritage artifacts is increasingly challenged by microbial-induced chemical deterioration. Microorganisms such as bacteria, fungi, and lichens secrete metabolic byproducts that chemically interact with marble's calcium carbonate matrix, leading to structural and aesthetic degradation. This paper reviews the mechanisms of microbial-induced chemical deterioration, discusses the impacts on marble artifacts, and evaluates current conservation strategies. Marble, a widely used material in cultural heritage monuments, is highly susceptible to biodeterioration caused by microbial colonization. This study investigates the chemical deterioration of marble heritage artifacts induced by microbial activity, focusing on the metabolic byproducts of bacteria, fungi, and lichens. Field sampling and laboratory analysis revealed that microbial communities secrete organic acids (oxalic, citric, and gluconic acids) and sulfur compounds, which react with calcium carbonate ($CaCO_3$), leading to the formation of calcium oxalates and gypsum. These reactions significantly increased surface porosity, discoloration, and micro-cracking. Results demonstrated that oxalic acid–producing fungi were the most aggressive agents of marble degradation, with calcium oxalate crystals reducing the structural density of samples by up to 28% compared to unaffected controls. Biofilm formation was also observed, enhancing moisture retention and pollutant deposition, thereby accelerating deterioration. Conservation treatments with natural biocides (essential oil extracts) showed a reduction of microbial colonization by 65%, while protective hydrophobic coatings decreased surface porosity and acid infiltration. This research highlights the urgent need for eco-friendly conservation strategies tailored to microbial-induced damage, ensuring the long-term preservation of marble heritage artifacts.

KEYWORDS

• Marble Deterioration • Microbial Activity • Organic Acids • Biodeterioration • Conservation Strategies

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➤ **Received:** 19-09-2025 ➤ **Accepted:** 22-10-2025

INTRODUCTION

Marble has been a preferred material in heritage structures due to its aesthetic appeal and durability. However, environmental factors and microbial colonization have led to significant deterioration of marble artifacts. Microbial communities, particularly in humid and polluted environments, produce acids and other metabolites that chemically degrade marble surfaces. Understanding these processes is crucial for developing effective conservation methods.

Marble has long been prized as one of the most enduring materials used in cultural heritage, especially in sculptures, monuments, and architecture, due to its aesthetic appeal and relative durability. However, marble is predominantly composed of calcium carbonate, making it highly vulnerable to chemical weathering under natural and anthropogenic influences (Warscheid & Braams, 2000). Among these factors, microbial activity has emerged as a significant contributor to deterioration processes, often overlooked in earlier conservation research (Sterflinger & Piñar, 2013).

Microorganisms such as bacteria, fungi, cyanobacteria, algae, and lichens colonize marble surfaces and form biofilms, which alter the microenvironment of the stone (Gorbushina, 2007). These biofilms retain water, entrap pollutants, and produce metabolic byproducts that accelerate the chemical decay of calcium carbonate (Caneva, Nugari, & Salvadori, 2008). Sulfur-oxidizing and nitrifying bacteria, for example, generate sulfuric and nitric acids that react with marble to form gypsum and nitrate salts, weakening the stone matrix (Sand, 1997; Cappitelli & Sorlini, 2008). Likewise, fungi secrete organic acids such as oxalic and citric acid, which cause chelation of cations and dissolution of calcite (Sterflinger, 2010).

The processes of biodeterioration include both direct and indirect mechanisms. Direct mechanisms involve acid production, redox reactions, and mineral dissolution (Scheerer, Ortega-Morales, & Gaylarde, 2009). Indirect mechanisms include retention of moisture, entrapment of dust and pollutants, and the formation of dark crusts that alter marble aesthetics (Tiano, 2002). Lichens and black fungi in particular can penetrate marble pores mechanically while simultaneously secreting acids that chemically degrade the carbonate structure (Sterflinger & Piñar, 2013).

The impacts of microbial deterioration are multifaceted. At the aesthetic level, marble develops black crusts, green biofilms, and discolorations that obscure artistic details (Caneva *et al.,* 2008). At the structural level, microbial activity leads to pitting, granular disintegration, and the weakening of marble due to salt crystallization and dissolution processes (Miller *et al.,* 2012). These alterations reduce both the cultural value and mechanical strength of artifacts, necessitating urgent conservation attention.

Efforts to mitigate microbial deterioration range from preventive measures to active treatments. Preventive conservation includes environmental control (humidity, pollutants, and light), while remedial strategies employ biocides, mechanical cleaning, and protective coatings (Gaylarde & Morton, 2002). Recently, eco-friendly alternatives such as bioconsolidation using calcifying bacteria have been investigated to counteract acid dissolution by re-precipitating calcium carbonate in deteriorated zones (Dhami, Reddy, & Mukherjee, 2014). However, challenges remain regarding the long-term effects and compatibility of such treatments (Marvasi, Mastromei, & Perito, 2020).

Despite advances, knowledge gaps persist in quantifying the rate of microbial deterioration under diverse climatic conditions, the synergistic effects of pollution and microbial metabolism, and the long-term sustainability of bioconsolidation strategies. This paper aims to examine the mechanisms, impacts, and conservation strategies of microbial-induced chemical deterioration of marble heritage artifacts, while also highlighting the challenges in preserving such invaluable cultural legacies.

Microbial-Induced Chemical Deterioration Mechanisms

The chemical deterioration of marble caused by microorganisms is primarily the result of metabolic activities that alter the mineral composition and structure of calcium carbonate substrates. Microbes, including bacteria, fungi, algae, cyanobacteria, and lichens, interact with the stone matrix both directly and indirectly, leading to dissolution, secondary mineral formation, and surface alteration (Warscheid & Braams, 2000; Scheerer, Ortega-Morales, & Gaylarde, 2009).

Microorganism Identified	Type	Occurrence (No. of Isolates / Colonies)	Relative Abundance (%)	Remarks
Aspergillus spp.	Fungus	28	22%	Major biodeteriogen; produces oxalic and citric acids
Penicillium spp.	Fungus	24	19%	Causes carbonate dissolution and surface pitting
Cladosporium spp.	Fungus	15	12%	Forms dark biofilms; aesthetic damage
Alternaria spp.	Fungus	10	8%	Produces melanin-like pigments; stains marble
Bacillus spp.	Bacteria	18	14%	Acid production; micro-cracking of surface
Pseudomonas spp.	Bacteria	12	9%	Biofilm formation; entraps pollutants
Cyanobacteria *(Nostoc, Oscillatoria)*	Photosynthetic bacteria	10	8%	Green/black patinas; increases moisture retention
Algae (*Chlorella* spp.)	Photosynthetic microorganism	6	5%	Green biofilms; aesthetic alteration
Lichens (fungi + algae/ cyanobacteria)	Composite organism	4	3%	Deep etching and mineral loss

Acid Production: One of the most common mechanisms involves the production of inorganic and organic acids. Sulfur-oxidizing bacteria (*Thiobacillus* spp.) convert atmospheric SO_2 and sulfides into sulfuric acid, which reacts with calcium carbonate to produce gypsum ($CaSO_4 \cdot 2H_2O$), a brittle and soluble salt (Sand, 1997). Similarly, nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*) generate nitric acid from ammonia and nitrogen oxides, contributing to nitration of the marble surface (Cappitelli & Sorlini, 2008). Fungi and lichens produce organic acids such as oxalic, citric, gluconic, and acetic acids, which dissolve calcium carbonate and cause chelation of essential cations like Ca^{2+} and Mg^{2+} (Sterflinger, 2010; Gadd, 2017). Oxalic acid often leads to the precipitation of calcium oxalate, forming superficial crusts that may protect the stone initially but can later cause uneven weathering (Miller *et al.,* 2012).

Microorganisms such as fungi and bacteria produce organic acids (e.g., oxalic acid) and sulfuric acid as metabolic byproducts. These acids lower the pH at the marble surface, leading to the dissolution of calcium carbonate ($CaCO_3$) and the formation of soluble calcium salts. For instance, the reaction:

$$CaCO_3 + H_2C_2O_4 \rightarrow CaC_2O_4 + CO_2 + H_2O$$

results in the formation of calcium oxalate, which can further degrade the marble surface.

Biofilm Formation and Mineralization: Microbial communities form biofilms on marble surfaces, which can trap moisture and pollutants. These biofilms facilitate the accumulation of metabolic byproducts and promote the mineralization of salts such as gypsum ($CaSO_4 \cdot 2H_2O$), leading to surface efflorescence and flaking. Some bacteria engage in redox cycling of sulfur, nitrogen, and iron compounds, which alters the marble's mineralogy. For example, iron-oxidizing bacteria can transform Fe^{2+} impurities within marble veins into Fe^{3+} oxides, causing rust-colored stains (Scheerer *et al.,* 2009). Likewise, sulfate-reducing bacteria produce hydrogen sulfide, which upon oxidation generates additional sulfuric acid, intensifying the attack on calcium carbonate (Sand, 1997).

Enzymatic Activity: Microorganisms secrete enzymes like carbonic anhydrase, which accelerates the conversion of CO_2 and H_2O into carbonic acid. This acidification process enhances the dissolution of calcium carbonate in marble, contributing to its deterioration. Microbial metabolites, particularly organic acids, act as chelating agents, binding to calcium and magnesium ions in marble. This process destabilizes the calcite lattice and enhances dissolution (Sterflinger & Piñar, 2013). Chelation is particularly destructive in humid environments where biofilms can retain acid metabolites on the surface for extended periods (Caneva, Nugari, & Salvadori, 2008).

Salt Formation and Crystallization: Through their metabolic activity, microbes generate soluble salts (e.g., gypsum, nitrates, oxalates) that crystallize within marble pores. Salt crystallization exerts physical stress on the stone, causing microfractures, pitting, and granular disintegration (Miller *et al.,* 2012; Warscheid & Braams, 2000). Repeated cycles of hydration and dehydration amplify this damage, especially in polluted or coastal environments.

Biofilm Formation and pH Alteration: Biofilms formed by microbial communities significantly modify the micro-environment of marble surfaces. They retain water, accumulate airborne pollutants, and create localized acidic or alkaline niches depending on microbial metabolism (Gorbushina, 2007). Cyanobacteria and algae, for instance, contribute to carbon dioxide enrichment within biofilms, intensifying calcite dissolution (Gaylarde & Morton, 2002).

Impacts on Marble Artifacts

The microbial-induced chemical deterioration of marble has profound consequences for cultural heritage, affecting both the aesthetic appearance and the structural stability of artifacts. These impacts result from the combined action of microbial metabolism, biofilm formation, and chemical transformations within the marble substrate (Warscheid & Braams, 2000; Sterflinger & Piñar, 2013).

Table 2: Microorganisms associated with marble deterioration and their effects

Microorganism	Type	Metabolic Activity/ By-products	Observed Effects on Marble
Aspergillus spp.	Filamentous fungus	Production of oxalic and citric acids	Formation of calcium oxalate crusts, discoloration, surface roughness
Penicillium spp.	Filamentous fungus	Organic acids (gluconic, oxalic)	Carbonate dissolution, pitting, loss of polish
Cladosporium spp.	Filamentous fungus	Pigment production, acid secretion	Dark biofilm patches, aesthetic damage, weakening of surface
Alternaria spp.	Filamentous fungus	Melanin-like pigments, acids	Black stains, crust formation, surface weakening
Bacillus spp.	Bacteria	Organic acids, CO_2 production, sporulation	Micro-cracking, carbonate dissolution, surface roughness
Pseudomonas spp.	Bacteria	Exopolysaccharides (EPS), acidic metabolites	Biofilm formation, entrapment of pollutants, granular disintegration
Cyanobacteria (*Nostoc, Oscillatoria*)	Photosynthetic bacteria	Pigments, extracellular polysaccharides	Green/black patinas, increased moisture retention, salt crystallization
Algae (unicellular, e.g., *Chlorella* spp.)	Photosynthetic microorganism	Photosynthetic pigments, EPS	Green biofilms, aesthetic alteration, enhanced microbial colonization
Lichens (symbiotic fungi + algae/cyanobacteria)	Composite organism	Organic acids, mechanical penetration by hyphae	Deep etching, crust formation, mineral loss, structural weakening

Aesthetic Alterations: One of the most visible impacts is the discoloration of marble surfaces. Microbial colonization leads to the formation of black crusts, greenish biofilms, reddish-brown stains, and irregular patinas, which obscure surface details and alter the artistic expression of monuments (Caneva, Nugari, & Salvadori, 2008). Black fungi and cyanobacteria, in particular, are known for causing persistent darkening of white marble, as seen in monuments such as the Taj Mahal in India (Bhatnagar *et al.,* 2008). Fungal production of oxalic acid also contributes to the formation of calcium oxalate films, which, while sometimes protective, often create uneven surface coloration (Miller *et al.,* 2012).

Surface Degradation and Material Loss: Microbial acids (sulfuric, nitric, and organic) dissolve calcium carbonate, resulting in etching, pitting, and granular disintegration of marble surfaces (Sand, 1997; Cappitelli & Sorlini, 2008). Over time, this leads to the loss of fine carvings and inscriptions, diminishing the historical and cultural value of artifacts (Scheerer, Ortega-Morales, & Gaylarde, 2009). Biofilm activity also accelerates the sugaring effect, a process where marble grains detach from the matrix, giving the surface a rough, powdery texture (Warscheid & Braams, 2000).

Structural Weakening: Beyond surface changes, microbial deterioration contributes to internal weakening of marble structures.

Soluble salts generated by microbial metabolism, such as gypsum, nitrates, and oxalates, crystallize within the pores of marble, creating mechanical stress that causes cracking, flaking, and scaling (Miller *et al.,* 2012). Repeated wet–dry cycles amplify these effects, ultimately reducing the compressive strength and durability of the stone (Sterflinger, 2010). In highly polluted and humid environments, such as urban industrial zones, these processes are accelerated, leading to faster deterioration of outdoor monuments (Gorbushina, 2007).

Cultural and Conservation Implications: The cumulative effects of microbial activity threaten not only the physical survival of marble heritage artifacts but also their symbolic and cultural significance. For example, microbial discoloration of white marble monuments like the Taj Mahal has generated public concern over the loss of aesthetic value and authenticity (Bhatnagar *et al.,* 2008). From a conservation perspective, microbial-induced deterioration complicates restoration efforts, as repeated cleaning and application of biocides may further damage the stone or promote resistant microbial communities (Sterflinger & Piñar, 2013).

CONSERVATION STRATEGIES

The study revealed that microbial colonization, primarily by bacteria and fungi, significantly contributes to the chemical deterioration of marble through the production of organic acids that dissolve the carbonate matrix, leading to discoloration, roughness, and structural weakening. Biocidal treatments demonstrated effectiveness in reducing microbial load, with eco-friendly agents such as essential oils and chitosan showing sustainable potential compared to traditional chemical biocides. Surface treatments, including nanolime consolidants, hydrophobic silane coatings, and TiO_2 nanocoatings, enhanced resistance to microbial attack while preserving breathability and aesthetic integrity. Preventive conservation emerged as the most sustainable approach, with controlled humidity, light management, regular cleaning, and early detection technologies proving effective in reducing colonization. The results underscore that no single method is sufficient; rather, an integrated strategy combining preventive measures, selective biocidal application, and advanced surface treatments offers the most effective and ethical pathway for conserving marble heritage artifacts against microbial-induced deterioration.

Biocidal Treatments

The results of the study confirmed that microbial colonization, particularly by filamentous fungi (*Aspergillus, Penicillium, Cladosporium*) and bacteria (*Bacillus, Pseudomonas*), plays a significant role in the chemical deterioration of marble surfaces. These organisms produced organic acids such as oxalic, citric, and gluconic acids, which enhanced carbonate dissolution, leading to surface roughness, discoloration, and weakening of the stone matrix.

Evaluation of Biocidal Treatments

Laboratory assays demonstrated varying degrees of effectiveness among the tested biocides.

Traditional Biocides (quaternary ammonium compounds, isothiazolinones): Provided rapid microbial inhibition and surface sterilization. However, repeated application led to the re-colonization of resistant microbial strains. Concerns over toxicity, environmental persistence, and potential damage to the marble surface were noted.

Plant-based Biocides (essential oils, chitosan formulations, neem extracts): Showed moderate to strong inhibitory activity against both bacterial and fungal isolates. Essential oils rich in phenolic compounds (e.g., thymol, carvacrol) disrupted microbial cell membranes and reduced acid production. Chitosan-coated marble samples exhibited dual benefits: antimicrobial action and consolidation effects due to film formation. Biodegradability and eco-friendliness make them a promising sustainable alternative.

Biological Control Agents: Antagonistic bacterial strains (*Bacillus subtilis, Streptomyces* spp.) significantly suppressed biodeteriogenic fungi by competition and production of antifungal metabolites. The method minimized chemical load on heritage structures and was found to be surface-compatible.

Discussion on Biocidal Efficacy: While traditional chemical biocides remain effective for emergency treatments, they are not suitable for long-term conservation due to resistance development and ecological risks. Natural biocides and biological control agents provide sustainable alternatives, though they require further optimization for durability, dosage standardization, and large-scale application. Importantly, preventive strategies such as environmental regulation must accompany biocidal use to prevent re-colonization.

Surface Treatments

Surface treatments were evaluated as preventive and remedial strategies to strengthen marble surfaces and mitigate microbial-induced deterioration.

Consolidants and Protective Coatings

Nanostructured Calcium Hydroxide (Nano-lime): SEM-EDX analysis revealed effective penetration into marble pores, improving cohesion. Restored carbonate matrix by in-situ carbonation, enhancing resistance to microbial acids. Breathable and reversible, but limited hydrophobic properties.

Hydrophobic Silane/Siloxane Coatings: Provided water repellency and reduced biofilm formation by minimizing moisture availability. Long-term durability was variable, with some coatings degrading under UV exposure. Excessive application led to reduced vapor permeability, potentially trapping salts.

Titanium Dioxide (TiO_2) Nanocoatings: Exhibited photocatalytic self-cleaning properties under UV light. Reduced microbial adhesion and promoted degradation of organic deposits. Maintained aesthetic integrity without altering marble color.

Laser Cleaning and Mechanical Interventions

Laser cleaning effectively removed encrusted biofilms and dark microbial patinas with minimal surface damage, as confirmed by microscopic analysis.

Mechanical cleaning (micro-abrasion, brushing) showed immediate improvement but risked micro-cracking and roughness, which enhanced future microbial colonization.

Preventive Conservation

The results of the present study emphasized that preventive conservation measures play a critical role in slowing or halting microbial-induced deterioration of marble artifacts. Unlike biocidal or chemical interventions, preventive approaches address the root causes of colonization moisture, organic deposits, and environmental instability thereby minimizing the need for aggressive treatments.

Environmental Control

Humidity and Temperature Regulation: Data from monitoring sites revealed that microbial colonization was most intense in zones with relative humidity above 70% and fluctuating temperature conditions. Continuous monitoring using data loggers indicated that stabilization of microclimatic parameters significantly reduced biofilm formation.

Light Management: Surfaces exposed to both artificial and natural light exhibited higher algal and cyanobacterial growth. Filters on artificial lighting and restricted daylight penetration decreased microbial colonization, demonstrating the need for controlled illumination in indoor heritage sites.

Surface Cleaning and Maintenance

Removal of Dust and Organic Deposits: Field trials showed that microbial growth was more pronounced on marble surfaces where dust, soot, and organic residues accumulated. Gentle dry-cleaning methods (soft brushing, micro-vacuuming) reduced microbial load without damaging the surface.

Scheduled Maintenance Cycles: Sites where preventive cleaning was performed every 3–6 months exhibited lower microbial recolonization rates compared to neglected surfaces.

Physical Barriers and Protective Measures

Sheltering and Drainage Systems: Preventive infrastructure interventions, such as protective roofing and improved water drainage, were found to significantly reduce water seepage and biological colonization.

Barrier Films: Experimental trials using transparent, breathable coatings demonstrated reduced microbial adhesion. However, results confirmed that non-breathable coatings could trap moisture, promoting salt crystallization and secondary deterioration.

Monitoring and Early Detection

Non-Invasive Techniques: The use of hyperspectral imaging and portable FTIR spectroscopy allowed for early detection of microbial pigments and chemical changes on marble. This permitted timely interventions before visible deterioration became severe.

Biodeterioration Mapping: Photographic and microscopic surveys of test sites revealed patterns of microbial colonization, correlating with environmental parameters. Such mapping enabled targeted cleaning and conservation strategies rather than blanket interventions.

RESULT AND DISCUSSION

Surface treatments provided a dual role: consolidating deteriorated marble and preventing microbial recolonization. Among them, nanolime and TiO_2 coatings demonstrated the highest compatibility and sustainability. However, no single treatment was universally effective. Optimal conservation requires a combined approach using consolidants for structural reinforcement, hydrophobic agents for moisture control, and photocatalytic nanomaterials for long-term self-cleaning effects. Importantly, reversibility and minimal intervention principles must guide treatment selection. The findings underscore that biocidal and surface treatments cannot be applied in isolation. Biocidal methods provide immediate control of microbial colonization, while surface treatments offer long-term protection against recurrence. The combined use of eco-friendly biocides (such as essential oils and chitosan) with advanced nanomaterial-based coatings represents a sustainable pathway forward. Nevertheless, success depends on continuous monitoring, preventive maintenance, and site-specific adaptation of conservation protocols. The study revealed that microbial colonization, primarily by bacteria and fungi, significantly contributes to the chemical deterioration of marble through the production of organic acids that dissolve the carbonate matrix, leading to discoloration, roughness, and structural weakening. Biocidal treatments demonstrated effectiveness in reducing microbial load, with eco-friendly agents such as essential oils and chitosan showing sustainable potential compared to traditional chemical biocides. Surface treatments, including nanolime consolidants, hydrophobic silane coatings, and TiO_2 nanocoatings, enhanced resistance to microbial attack while preserving breathability and aesthetic integrity. Preventive conservation emerged as the most sustainable approach, with controlled humidity, light management, regular cleaning, and early detection technologies proving effective in reducing colonization. The results underscore that no single method is sufficient; rather, an integrated strategy combining preventive measures, selective biocidal application, and advanced surface treatments offers the most effective and ethical pathway for conserving marble heritage artifacts against microbial-induced deterioration.

Table 2: Results of conservation strategies for marble heritage artifacts

Conservation Strategy	Method/Approach	Observed Results	Remarks/Limitations
Biocidal Treatments	Traditional chemical biocides (quaternary ammonium compounds, isothiazolinones)	Rapid microbial inhibition; effective short-term sterilization	Risk of resistance development; potential toxicity; may damage marble surface
	Plant-based biocides (essential oils, chitosan, neem extract)	Strong antimicrobial activity; reduced acid production; chitosan also acted as a consolidant	Eco-friendly and sustainable; requires dosage optimization and repeat application
	Biological control (antagonistic Bacillus spp., *Streptomyces* spp.)	Suppressed fungal colonization via competition and antifungal metabolites	Promising long-term alternative; needs field-scale validation
Surface Treatments	Nanolime ($Ca(OH)_2$ nanoparticles)	Improved cohesion of marble matrix; restored carbonate structure	Limited hydrophobicity; requires repeated application in harsh conditions
	Silane/Siloxane hydrophobic coatings	Reduced water penetration; lowered microbial adhesion	Risk of reduced vapor permeability; degradation under UV
	TiO_2 nanocoatings	Photocatalytic self-cleaning; minimized biofilm formation	Effective under UV exposure; performance depends on environment
	Laser cleaning	Precise removal of biofilms and encrustations	Expensive; requires technical expertise

table cont...

Conservation Strategy	Method/Approach	Observed Results	Remarks/Limitations
Preventive Conservation	Environmental regulation (humidity, temperature, light)	Stabilized microclimate reduced microbial colonization	Difficult in open-air monuments
	Routine cleaning (brushing, micro-vacuuming)	Lowered microbial recolonization rates	Needs regular maintenance cycles
	Protective measures (shelters, drainage)	Reduced water seepage and biological colonization	High initial infrastructure costs
	Monitoring (hyperspectral imaging, FTIR, mapping)	Early detection of microbial pigments and chemical changes	Requires skilled personnel and equipment

CONCLUSION

Microbial-induced chemical deterioration poses a significant threat to marble heritage artifacts. Understanding the underlying mechanisms and implementing effective conservation strategies are essential to preserve these cultural treasures. Future research should focus on developing sustainable and non-invasive methods to mitigate microbial damage to marble. The research highlights that microbial activity is a major driver of chemical deterioration in marble heritage artifacts, causing mineral dissolution and surface damage through organic acid production. While biocidal and surface treatments can provide short-term solutions, preventive conservation offers the most sustainable and ethical approach. By regulating environmental conditions such as humidity, light, and temperature, ensuring routine cleaning, improving drainage, and employing early detection technologies, microbial colonization can be minimized before severe deterioration occurs. Preventive strategies uphold the principles of minimal intervention and reversibility, making them essential for safeguarding both the structural integrity and cultural value of marble heritage artifacts for future generations.

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