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Biological Knowledge in Cultural Heritage Conservation: A Global Review

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Abstract. Biological methods are being talked about more and more in the field of cultural heritage conservation, but I think their role is still not very clear. In many papers, these methods are described as "innovative" or "green" solutions, but in real life, how they work depends a lot on the local materials, the weather, and what people used to do in that place. From my reading of many recent studies, I feel that biological methods are not really a complete replacement for old treatments. Instead, they are more like extra tools that help us understand how things break and help us decide if we should touch the heritage or not. In this paper, I look at how biological diagnostics and treatments are used in different parts of the world, like Europe, East Asia, Egypt, and Latin America. I also try to see how these methods are actually limited when you use them in real situations. By comparing these cases and thinking about China's very long experience in conservation, this review shows that biological ways have both good potential and some scary uncertainties, especially for the long-term results and ethical questions.

Keywords: Cultural heritage preservation, Microbial monitoring, Microbial-induced carbonate precipitation (MICP)

1. Introduction

Cultural heritage is often discussed for its historical and cultural value [1]. This idea appears in many papers. In real situations, however, it is not always easy to work with. Heritage objects change over time. Murals change. Paintings change. Old buildings also change. This is seen in many conservation cases. Changes come from different reasons. Materials matter. The environment also matters. Human contact adds another factor [2]. Because of this, conservation work is not simple. During treatment, it often becomes more complicated than planned. Many publications describe conservation mainly as a technical process [1]. This explanation alone is often not enough. In real cases, conservation decisions are not always clear. Even similar damage can be treated in different ways. Climate conditions influence conservation decisions. Local traditions also matter [1]. Because of this, conservation practice is often difficult to standardize. In China, conservation practice has been carried out for a long time [3]. Many decisions are made based on experience. Traditional repair methods were already in use before modern scientific tools became common [4]. These methods were used again and again in practice. They helped some fragile objects last for many years [4]. Similar situations can still be found at many heritage sites today. At the same time, experience

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does not solve all problems. Interventions can still introduce risks. This happens more often when material behavior is not fully understood [5]. Similar concerns appear in many studies [1]. Most conservation treatments still rely on chemical or physical methods [1]. These methods are often used first in practice. In some cases, they work well in the short term [6]. However, residues and material changes are reported in several studies [6]. These changes are not easy to reverse. With repeated treatment, original materials may slowly change. Over time, this can affect authenticity [7].

In addition, some studies apply microorganisms directly during treatment [8]. This approach is discussed together with other biological methods.However, biological approaches do not work well in all situations [1]. Many authors suggest using them together with existing practices [1]. Using biological methods alone is often not advised. This paper compares how biological approaches are used in different regions. It also discusses their limitations. Experience from China is given special attention.

2. Results

2.1. Biological diagnostics

In cultural heritage conservation, I think it is not enough to just find microorganisms. We really need to know if they are "awake" and eating the material or not [1]. Many studies show that just knowing the names of microbial species is not enough for making a good decision [1]. For example, scientists used molecular methods like 16S rRNA and ITS sequencing at the Mogao Grottoes in China to see who lives on the mural surfaces [2]. But I feel these results only describe the "names" of the community and cannot really explain the metabolic activity or the real risk of deterioration [2].

Because of this big problem, enzyme assays are used together with the molecular analysis [3]. I read that enzymes like β-glucosidaseand dehydrogenase are measured to see if the microorganisms are actually busy with metabolism, which helps to assess the ongoing damage [3]. But it is still not simple; enzyme levels can change because of the weather or when you take the samples [3]. Also, some studies include site-scale environmental monitoring, like checking the air and how many visitors come [9]. These factors might change how microbes grow, but their influence is not always very clear [9]. Even when we have all this data—molecular identification, enzymes, and weather—the final choice still depends a lot on the professional experience of the experts [1].

2.2. Biocleaning and enzymatic gels

One biological approach discussed in conservation is microbial-induced carbonate precipitation, known as MICP [10]. I think this idea sounds very clever at first. It uses bacteria to form new minerals inside cracks of stone materials. When I looked at scanning electron microscopy images, I saw calcite crystals filling small pores [10]. These crystals sometimes appear to form mineral bridges between stone grains. This seems to improve material strength.

Engineering tests also report that MICP-treated materials become stiffer and less permeable [10]. However, I found that this method has clear limits. It does not work equally well on all materials. In wood or metal, bacteria often cannot form minerals in the same way. Results also depend strongly on nutrient composition [10]. Small changes can affect crystal growth speed. Because of this, a single standard method is difficult to apply. Although MICP is often described as green or natural, I think caution is still needed. New minerals may cause long-term problems if they block airflow or become too rigid [10].

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2.3. Bioconsolidation

Many studies focus on MICP as a bioconsolidation strategy [6]. The basic idea is that bacteria grow calcium carbonate inside porous materials [6]. In microscopy images, calcite crystals can be seen filling pore spaces. In some cases, these crystals form connections between grains [6]. This appears to reduce porosity and increase mechanical strength compared to untreated samples [6].

Similar effects have also been reported in engineering materials [7]. Treated samples often show reduced permeability and increased stiffness. However, I do not think this effect can be expected everywhere. In dense materials such as wood or metal, mineral deposition is usually limited [6]. This suggests that pore structure and material chemistry strongly influence outcomes [6]. Because different studies use different treatment conditions and evaluation methods, direct comparison is difficult. I found this inconsistency confusing when reading the literature [6].

2.4. Green antimicrobials and biopolymers

Green antimicrobial strategies aim to reduce biodeterioration with limited visual impact. Essential oils, such as thyme oil, show antifungal effects against mural-associated fungi like Aspergillus niger [8]. These oils are sometimes applied in vapor-phase methods to reduce surface contact. Treatment results may vary with exposure time and environment.

Biopolymer-based materials are also explored, especially for organic substrates. Chitosan films are reported to improve mechanical stability and inhibit microbial growth on paper materials [10]. Some composite coatings with calcium-based nanoparticles or zinc oxide show stronger antimicrobial effects in laboratory tests. However, small residues are sometimes observed after application. Colorimetric analysis often reports ΔE^* values below perceptibility thresholds [8]. Long-term behavior under changing environmental conditions remains uncertain.

2.5. Regional practices

After reading many studies, I noticed strong regional differences in biological conservation practices [1]. In Europe, biocleaning of frescoes often emphasizes reversibility and long-term monitoring [1]. In East Asia, biological tools are more often used in preventive conservation, especially for paper heritage [2]. In these cases, microbial ecology is assessed before enzyme treatment [2].

In Egypt, biodeterioration is often linked with salt-related damage, which creates additional challenges [9]. Conservation strategies there usually combine biological and mineral analysis [9]. In Latin America, a study at the Maya site of Copán showed that stimulating local bacteria may strengthen plaster under hot and humid conditions [9]. These examples suggest that biological methods cannot be applied as universal solutions. Instead, they need to be adjusted to local environments and traditions [1].

3. Discussion

Biological approaches are used more and more in recent conservation studies. However, their real role is still not very clear. Different papers show very different results. Some studies report good effects. Others show many problems. This situation makes comparison difficult. Biological approaches are more complex than chemical or physical treatments in real practice. Results often change in different environments. Microorganisms behave differently from place to place. Because of this, results are not stable. It is hard to know what will really happen at real sites. In many cases, biological approaches are not used alone [1]. They are usually added to traditional conservation methods. In most projects, they play a supportive role. They are not the main solution. This is still what can be seen in many current cases. Diagnostic use is usually more stable. Molecular tools such as 16S rRNA and ITS sequencing help identify microorganisms on heritage surfaces [2]. This information is useful in many cases. But it is still limited. Finding microorganisms does not always mean damage. Many microorganisms remain inactive for a long time. To deal with this problem, enzyme tests are often used [3]. These tests try to show whether microorganisms are active or not. However, enzyme values change easily. Temperature and humidity influence results. Sampling time also matters. Because of these reasons, results are not easy to explain. Experience is still important when making decisions [1]. Biocleaning methods are often described as gentle treatments [4,5]. In some indoor cases, they work well. But they need strict control of water and temperature [1]. This makes outdoor use difficult. Similar problems are also found in MICP-based consolidation [6,7]. Some studies show short-term strengthening. Long-term effects are still not very clear. Green antimicrobial methods perform well in laboratory tests [8]. However, real environments are much more complicated. Climate conditions change over time. Surface conditions are also different in each site. Because of this, laboratory results cannot always be directly applied.

Biological approaches provide new options in conservation. At the same time, they bring many uncertainties. These uncertainties should not be ignored in real practice.

4. Conclusion

Biological knowledge is changing how conservation work is done. Its most clear contribution is in diagnostics. Treatment results are more variable. In different regions and for different materials, biological tools are mainly used to help understand deterioration. They are rarely used as the only method. Traditional conservation methods are still used in most cases. At present, the available evidence is still mixed. Some studies show clear results. Other studies are less clear. Long-term performance is not studied enough yet, especially when conditions change over time. Because of these reasons, biological approaches should not be used routinely. More monitoring is needed.

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