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Exploration of the Innovative Application of Biological Enzyme Dyes in the Minimally Invasive Restoration of Chinese and Foreign Cultural Relics

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Abstract

The global application of biological enzymes in cultural relics has long been limited to the dimension of "subtractive restoration" for cleaning and decontamination, while traditional inpainting materials have such problems as irreversibility, strong corrosiveness, and obvious color difference. This paper proposes introducing biological melanin dyes synthesized by enzyme catalysis into the field of cultural relic conservation, and constructs a new path of "reversible additive restoration" to break fixed disciplinary thinking. This scheme has safety, authenticity, reversibility, and controllability, fits the restoration scenarios of ancient Chinese and foreign paintings and murals, and designs a complete reversibility verification system, providing an interdisciplinary innovative technical idea for international cultural relic conservation.

Keywords

biological enzyme, dye, cultural relic, restoration

1. Introduction

With the development of green biotechnology, biological enzymes, because of their mild, safe, and non-secondary-damage characteristics, have been tried in such fields as hair dyeing, tattooing, and fabric dyeing. However, in the field of cultural relic restoration, enzyme technology applications worldwide are all concentrated on the "subtractive restoration" of cleaning, decontamination, and scale removal [1]. European and American restoration teams have long used enzyme-based gels to treat stains on classical murals and ancient silk, and the Capital Museum in China has also successfully developed a biological enzyme uncovering agent for mounting and remounting calligraphy and paintings. The academic consensus is that biological enzymes are reliable tools for cleaning cultural relics.

In the process of systematically reviewing relevant literature, this paper finds that current enzyme-based technical methods cannot meet the practical restoration needs of faded areas of cultural relics, local defect completion, and mottled color coordination. Traditional inpainting schemes also have two problems that are difficult to balance at the same time [2]. On the one hand, industrially synthesized pigments contain heavy-metal components, which not only corrode the fiber carrier of cultural relics and accelerate the aging process of cultural relics, but are also difficult to remove after coloring, contrary to the concept of minimum

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intervention advocated in the field of cultural relic conservation. On the other hand, natural pigments from minerals and plants have limited color options, making it difficult to reproduce the unique colors formed after hundreds of years of oxidation of cultural relics. The restoration traces produced are relatively obvious, and the adjustable space in practical operation is very small.

Therefore, this paper further explores a new idea. Based on the characteristic that biological enzymes can act mildly on the surface of cultural relics, it attempts to explore the application of biological melanin dyes synthesized by enzyme catalysis to the inpainting of cultural relics, and to expand enzyme technology from traditional subtractive cleaning to reversible additive restoration, while the latter is still an undeveloped research field worldwide.

2. Core Innovation: Interdisciplinary Technology Transfer

The core value of this paper does not lie in creating new materials, but in breaking through the fixed cognition that "biological enzymes are only used for decontamination," and realizing reverse technology transfer and dimensional upgrading. By independently transferring enzyme-catalyzed synthesis technology in bioengineering to the field of cultural relic conservation, this paper constructs a new restoration logic of "reversible inpainting with enzyme-synthesized biological dyes," upgrading biomaterials from "decontamination tools" to "precision restoration tools," and completing path innovation from subtraction to addition.

This paper uses controllable and quantifiable experimental thinking from science and engineering to solve the humanistic bottleneck in which traditional restoration relies on experience and has a low fault-tolerance rate. Traditional cultural relic conservation relies on aesthetics and manual techniques, while the controllability and reversibility of biomaterials enable inpainting to retain authentic aesthetics and also have scientific norms. Under the premise of absolutely not damaging cultural relics and being removable at any time, the final scheme realizes high-precision minimally invasive inpainting and provides new technical thinking for international cultural relic conservation.

3. Adapted Application Scenarios

Enzyme-synthesized melanin naturally presents a brownish-red tone, with a warm color and a texture highly close to that formed by the oxidation of cultural relics over hundreds of years. This feature brings advantages for inpainting that are difficult for other materials to have [3]. Based on this, this paper selects two types of application scenarios with relatively high adaptability, covering classic Chinese and foreign cultural relics respectively.

The first type is aimed at Tang-dynasty silk paintings and Ming- and Qing-dynasty Xuan paper. After hundreds of years of oxidation, such carriers often form a unified brownish-red aged ground, but they are often accompanied by local fading, whitening, and mottling. Traditional inpainting methods are difficult to balance here: synthetic pigments have stiff colors and are disconnected from the aged ground, while natural pigments may corrode fibers. Enzyme-synthesized melanin naturally fits the aged ground in hue, and it contains no heavy metals, is non-corrosive, and does not accelerate aging, so it is suitable for undertaking traceless inpainting.

The second type is aimed at murals, including Dunhuang murals in China and European religious murals from the sixteenth to seventeenth centuries. Both face the common dilemma of surface weathering, peeling, and color loss. Large-scale repainting obviously violates conservation principles, while existing trace inpainting materials also have defects such as irreversibility and easy residue. The dye proposed in this paper can precisely apply trace coloring and control color at fixed points, and it is completely reversible and easy to remove, which is highly consistent with the internationally accepted criteria of "minimum intervention and reversibility."

4. Comparison of Core Advantages

Compared with industrially synthesized pigments and traditional natural pigments, enzyme-synthesized biological melanin dyes have several irreplaceable comprehensive properties. This dye has no heavy metals or

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corrosive components, does not damage the fiber skeleton of cultural relics, and does not induce material aging, so it can avoid permanent damage to cultural relics from the source. In terms of color restoration, the brownish-red tone generated by enzyme catalysis has a warm and antique texture, can approach the color formed by long-term oxidation of ancient cultural relics, produces weak restoration traces, and better maintains the historical aesthetic information carried by the cultural relic itself. Reversibility is the most prominent innovation of this material. Conventional restoration pigments are difficult to remove after curing, and once an operation error occurs, it cannot be remedied. However, by using the oxidation-reduction characteristics of melanin itself, this dye can realize color fading and even complete removal, making the restoration scheme adjustable and correctable and significantly improving the fault-tolerance space of restoration operations. At the same time, enzyme-catalyzed reactions make it convenient to finely regulate the coloring concentration and action area, can respond to the inpainting needs of small areas such as edges, corners, and local mottling of cultural relics, and meet the requirements of contemporary minimally invasive restoration of cultural relics for refined operation.

5. Design of a Reversibility Verification System

To support the practical application value of the research hypothesis, this paper integrates existing research results and constructs an all-round experimental verification system including reversibility, safety, and durability.

The study carries out chemical reversibility tests based on the oxidation-reduction reaction mechanism of melanin [4]. Through multiple-cycle experiments of decolorization by reducing agents and recoloration by oxidants, it verifies the stability of material performance, and combines instrument testing to obtain quantitative data such as absorbance and color difference, providing theoretical support for the reversible restoration characteristics of the material. At the same time, physical removal experiments are carried out. Through mild reagent rinsing, neutral solvent elution, and gentle peeling tests, the optimal decolorization process is screened to ensure that the dye can be completely removed without harmful residue and is suitable for actual cultural relic restoration scenarios.

Through microscopic morphology observation, mechanical performance testing, and long-term constant-temperature and constant-humidity standing tests, the experiment compares the material changes of cultural relic substrates before and after coloring and decolorization, proving that this restoration technology does not damage the structure of the cultural relic body and has no problems such as mold growth or long-term aging damage, so the substrate safety is reliable.

In addition, artificial accelerated aging tests are carried out through simulations of light exposure, friction, and water-stain environments [5] to test the color stability and color fastness of the inpainting layer, and to verify the long-term effectiveness of the restoration effect, which can meet the core requirements for long-term preservation of cultural relics.

6. Conclusion and Academic Reflection

The value of this paper does not lie in complex experiments, but in stepping outside the fixed thinking mode of the industry, and completing an original innovation from zero to one through independent literature comparison, gap discovery, and cross-field association. Existing studies have fixed the idea that “biological enzymes can only remove stains.” Through a critical review of frontier cases, this study breaks disciplinary barriers, deeply integrates bioengineering materials with cultural relic conservation, and for the first time proposes the new idea of “reversible minimally invasive additive restoration with enzyme-based biological dyes,” filling the long-missing inpainting path in international enzyme-based cultural relic conservation.

This exploration shows that real innovation is often born in the blank areas of interdisciplinary integration. The combination of the rigorous controllability of science and engineering technologies and the aesthetic conservation logic of the humanities can generate schemes that are gentler, more scientific, and more consistent with the needs of the inheritance of civilization. In the future, this study will continue to focus on the intersection of green biomaterials and cultural heritage conservation, improve this reversible restoration scheme, and allow a high school student's original thinking to provide new feasible ideas for global green cultural relic conservation.

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Conflicts of Interest

The authors declare no conflict of interest.

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