

Cybersecurity and Material Pathology: An Integrated Approach to Protect Cultural Heritage from Digital Threats and Chemical–Biological Degradation

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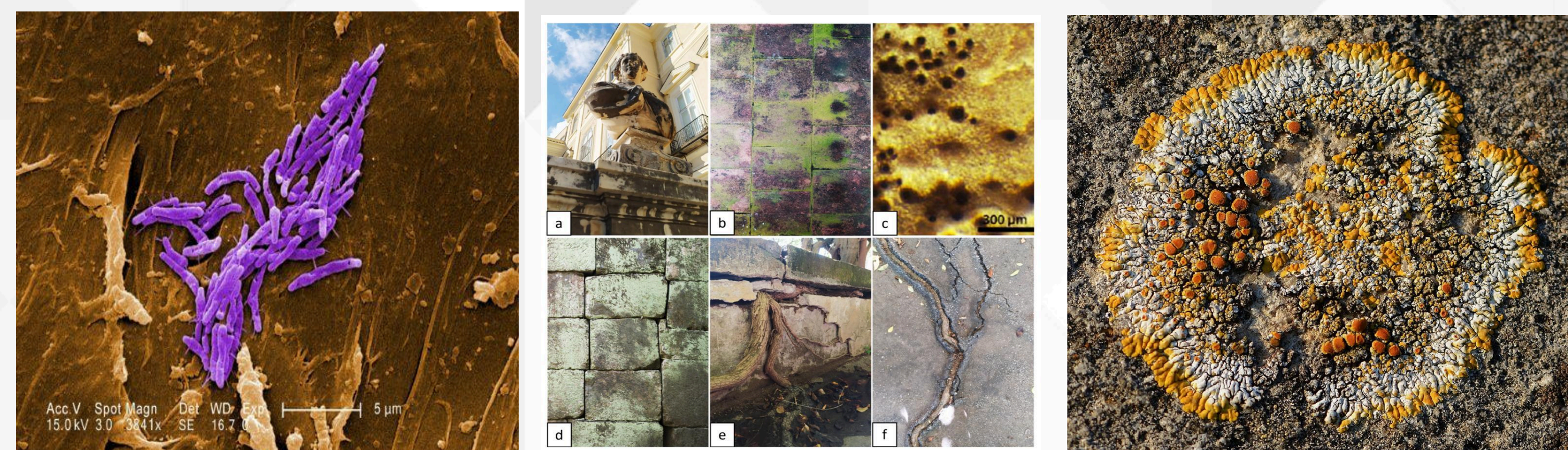
INTRODUCTION

Cultural heritage (monuments, archaeological sites, frescoes, and historic structures) constitutes an irreplaceable testimony to humanity's history, identity, and collective memory. Unfortunately, these assets are continuously exposed to a wide range of degradation processes that threaten their integrity and longevity. Among these, biodeterioration plays a significant role in the chemical, physical, and aesthetic alteration of heritage materials [1].

In recent decades, conservation science has made significant progress in understanding and mitigating this process, particularly through the development of biocidal treatments and protective materials [2]. However, conventional approaches often present limitations, including short-term efficacy and adverse interactions with sensitive substrates [3]. This has fueled a growing interest in advanced material-based solutions, such as controlled-release systems, which aim to improve the durability, efficiency, and environmental compatibility of treatment [4].

At the same time, the cultural heritage conservation sector is undergoing a digital transformation that, thanks to the Internet of Things (IoT), environmental sensors, and automated processing systems, is enabling the development of more precise monitoring and intervention strategies [5-6]. These innovations offer significant opportunities for preventative conservation, providing real-time data and control mechanisms tailored to specific site conditions.

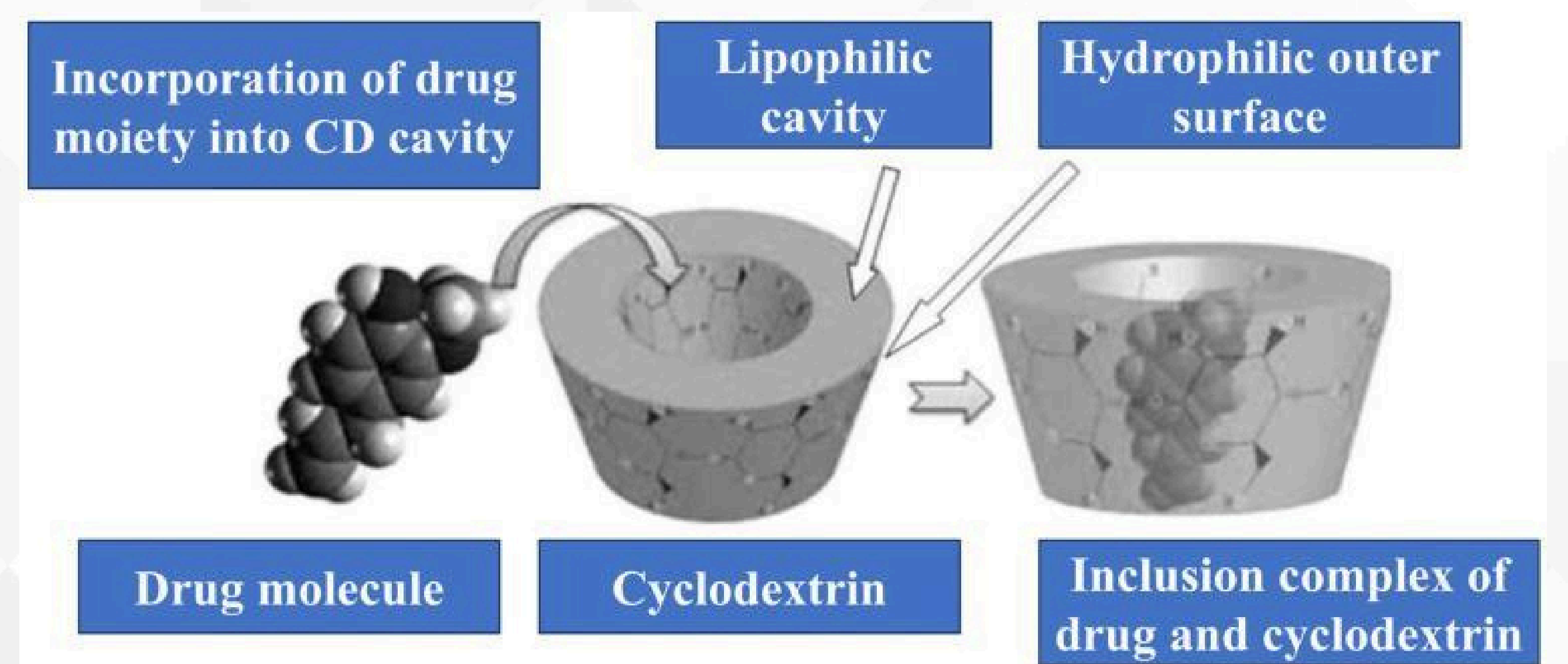
This research proposes an integrated interdisciplinary approach for the protection of cultural heritage.



METHODS

The study adopts an interdisciplinary experimental approach that combines systems design, laboratory materials development, and cybersecurity analysis. The methodology follows a structured path from controlled-condition experimentation to subsequent in vivo validation. The first operational phase involves the identification of sites of historical and artistic interest and related artifacts, followed by the characterization of the substrates, monitoring of environmental parameters, and diagnosis of degradation phenomena (chemical, physical, and biological). Following the selection of biocides and the development of controlled-release systems, the antimicrobial performance will be evaluated and a predictive analysis of the results on the different substrates will be performed, focusing on:

- Correlation between environmental parameters and biodeterioration;
- Relationship between release kinetics and treatment efficacy



Controlled-Release Systems in Conservation Science

Recent advances in material science have introduced controlled-release technologies as promising alternatives to conventional treatments. Systems such as hydrogels, cyclodextrin inclusion complexes, halloysite nanotubes, and polymeric microcapsules enable the gradual and sustained release of biocidal agents.

Studies show that these systems can:

- Prolong the activity of biocides
- Reduce environmental exposure and toxicity
- Improve penetration into porous substrates
- Enhance resistance to environmental stressors such as UV radiation and rainfall

However, research in this area remains fragmented, with limited comparative studies and insufficient integration into real-world conservation workflows. Additionally, long-term performance and compatibility with diverse heritage materials require further investigation.

RESULTS

The research activity aims to achieve tangible objectives in terms of knowledge and technological innovation, but above all, it introduces a paradigm shift in restoration management through:

- the definition of an integrated methodological framework that merges materials science with cybersecurity, creating a bridge between physical conservation and digital protection.
 - predictive modeling: useful for predicting degradation phenomena and optimizing intervention times.
- The identified solutions will translate into direct benefits for the sector, namely:
- drafting operational guidelines for conservators and curators for the scientific and rational management of sites,
 - validation of modular technological solutions that can be easily exported and applied in various real-world contexts,
 - reduction of costs and environmental impact thanks to reduced treatment frequency and optimized resource use.

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