tion, and editorial responsibility remain with the author.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Access to Materials and Data

All materials and data analyzed in this study are available within the article and its referenced sources.

consolidants, hydrophobic coatings, corrosion-resistant layers, and environmental sensors suitable for use in conservation practice. Research conducted over the past two decades demonstrates that sol-gel derived materials can improve the cohesion of deteriorated stone substrates, reduce water penetration, and form thin protective coatings on metals, glass, paper, wood, and textiles while maintaining a relatively compatible interaction with historic materials (Wheeler, 2005; Zucchi, 2013; Bescher & Mackenzie, 2017; Coutinho et al., 2020; Trovato et al., 2020; Baglioni et al., 2021; Andriulo et al., 2022; Salazar-Hernández et al., 2023; Sfameni et al., 2023; Centenaro et al., 2025).

This review article aims to introduce the principles of sol-gel technology and examine its major applications in the conservation of cultural heritage. The study particularly focuses on stone consolidation, protective surface coatings, and sol-gel based environmental sensors used in museums and heritage sites. The main research question concerns the capabilities, advantages, and current limitations of sol-gel technology in conservation studies, as reflected in the existing scholarly literature. The article is based on a review and investigation of published studies related to the application of sol-gel materials in cultural heritage conservation.

Results and Discussion

The reviewed studies indicate that the most extensive application of sol-gel technology in conservation has been related to the consolidation of stone and porous historic building materials. Alkoxysilane-based compounds, especially TEOS-derived systems, have been widely investigated because of their ability to penetrate porous structures and form siloxane networks within deteriorated stone matrices. Several studies reported improvements in cohesion and mechanical stability, as well as reduced water absorption after treatment (Gupta, 2011; Kim et al., 2009). Researchers have also attempted to enhance the flexibility and compatibility of these consolidants through the incorporation of nanoparticles and hybrid organic-inorganic components (Zárraga et al., 2010). Nevertheless, some limitations remain unresolved, including cracking during gel formation, uneven penetration, and uncertainties regarding long-term durability under outdoor environmental conditions (Brus & Kotlík, 1996).

Another major area of application concerns protective coatings for historical surfaces. Sol-gel coatings have been examined for the protection of metals against corrosion, particularly copper alloys exposed to polluted or humid environments (Bescher & Mackenzie, 2003; Zucchi, 2013). Comparable approaches have been developed for historic glass and glazed surfaces, where silica-based thin films demonstrated promising resistance against weathering and biological colonization (Bianco & Bertoncello, 2008; Coutinho et al., 2020). Studies on paper, wood, and textile conservation further suggest that sol-gel derived coatings may provide hydrophobic and antimicrobial properties while preserving the visual appearance of delicate organic materials (Kiuberis et al., 2005; Trovato et al., 2020; Andriulo et al., 2022).

In addition to direct conservation treatments, sol-gel chemistry has also contributed to preventive conservation through the development of optical and chemical sensors. These sensors have been designed to monitor environmental humidity, acidity, pollutants, and light exposure in museums and storage environments (Carmona et al., 2007; Herrero et al., 2007). Such applications demonstrate that the role of sol-gel technology has expanded beyond material treatment into broader conservation management strategies.

The surveyed literature collectively shows that sol-gel technology offers considerable potential for conservation practice because of its adaptability and relatively broad compatibility with historic substrates. However, many studies remain experimental and laboratory-based. Questions concerning reversibility, aging behavior, retreatability, and long-term interaction with original materials continue to require systematic investigation before these materials can be fully adopted in routine conservation practice.

Conclusion

The studies reviewed in this article demonstrate that sol-gel technology has become one of the significant material-based approaches in contemporary cultural heritage conservation. Its applications range from stone consolidation and protective coatings to environmental sensing systems for preventive conservation. The versatility of sol-gel derived materials, combined with their tunable chemical and structural properties, has encouraged their use in the conservation of stone, metal, glass, paper, wood, and textile artefacts.

Despite the promising results reported in many studies, the long-term performance and stability of these materials still require further evaluation under real environmental conditions. Future interdisciplinary research will therefore be essential, particularly in relation to compatibility, durability, and ethical conservation standards. Greater familiarity with these emerging technologies may also help conservation students and professionals in Iran engage more effectively with current international research and develop locally adapted conservation strategies.

Use of Artificial Intelligence Tools

Artificial intelligence tools were used as supportive instruments in the preparation, linguistic editing, and revision of the extended English abstract and conclusion of this article. Final scientific evaluation, content verifica-

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Extended Abstract

Application of Sol-Gel Technology in the Conservation and Restoration of Cultural Heritage

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In recent decades, sol-gel technology has attracted considerable attention in the conservation and restoration of cultural heritage as a nanotechnology-based approach. Features such as the production of organic-inorganic nanocomposites, suitable penetration into porous substrates, formation of thin protective coatings, and resistance to moisture and ultraviolet radiation have expanded its applications in conservation studies. This review examines the capabilities and limitations of sol-gel technology in stone consolidation, protective coatings for historical materials, and environmental monitoring sensors. The reviewed studies indicate that alkoxysilane-based compounds improve the structural cohesion of historical stones and reduce moisture penetration. In addition, sol-gel coatings have shown promising results in protecting metals, glass, tiles, and paper against corrosion, weathering, and microbial growth. Sol-gel-based sensors have also been applied for monitoring humidity, acidity, pollutants, and light in museum environments. Despite these advances, further long-term studies remain necessary.

Keywords: Conservation and Restoration, Sol-Gel Technology, Stone Consolidation, Protective Coatings, Environmental Sensors.

Introduction

In recent decades, the introduction of emerging technologies into the field of cultural heritage conservation has significantly transformed approaches to the preservation of historical materials. One of the turning points in this process was the 1966 flood in Florence and Venice, which revealed the limitations of conventional restoration methods when confronted with large-scale damage to artworks and historic structures. Since then, increasing attention has been directed toward interdisciplinary scientific approaches capable of improving the efficiency, compatibility, and durability of conservation treatments (Baglioni et al., 2009). Within this context, nanotechnology and advanced material sciences have opened new possibilities for the stabilization and protection of cultural heritage objects (Giorgi et al., 2010).

Among these developments, sol-gel technology has gained particular importance because of its ability to produce organic-inorganic hybrid materials with controllable physical and chemical properties. The versatility of this process has enabled the development of