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A Review of Nanotechnology in Self-Healing of Ancient and Heritage Buildings

Lana Roshen Tariq 1[a*], Ali Mohsen Jafaar 2[a]

[a] *Architectural Engineering Department, University of Technology, Baghdad, 10066, Iraq.*
∗ *Corresponding author. Tel.: 00964 7708944426; e-mail: ae.20.13@grad.uotechnology.edu.iq*

ABSTRACT

The field of nanotechnology has revolutionized the architectural sector, particularly in the domain of preserving cultural heritage. The gradual deterioration and degradation of ancient and heritage buildings pose significant challenges for the conservation of our cultural legacy. This review aims to emphasize the crucial role of nanotechnology in extending the lifespan of archaeological materials and artefacts, which are essential components of our cultural heritage. Archaeology encompasses both theoretical and applied methods, with applied archaeology involving activities such as excavation, restoration, and monument conservation. These practices heavily rely on the integration of novel findings from various disciplines including physics, chemistry, and geology. Nanotechnology has emerged as a promising approach within the realm of applied archaeology, offering innovative solutions for the preservation of organic and inorganic archaeological materials. This research focuses specifically on the applications of nanotechnology in conserving and restoring inorganic archaeological materials, particularly stone artefacts and buildings constructed from materials such as limestone or sandstone. By exploring the potential benefits and highlighting the significance of nanotechnology, this study seeks to underscore its role in safeguarding our cultural heritage and promoting sustainable construction practices.

Keywords: *Heritage buildings, Nanomaterial, Nano architecture, Nanotechnology in construction.*

1. INTRODUCTION

Nanotechnology enables us to create a new materials on a nanoscale level [1]. The produced nanoparticles (NPs) always appear in an unbounds state or in an aggregate groups of particles or randomly distributed in a range of particle sized from 1-100 nm [2]. Because of the unique characteristics of nanosized materials [3], nanomaterials have been incorporated into a wide range of disciplines and applications over the past 50 years, including energy, environmental safety, construction, architecture and so on [4]. The industrial sectors started from the last decades to develop and manufacture advanced nanomaterials, especially those that benefit construction materials [5]. The science of nanomaterials allows the manufacturers to improve and increase the durability of concrete, glass, steel, and buffers materials, e.g. self-healing concrete that protects monuments from destruction [6]. Due to the higher energy amount required to produce construction materials, the environmental pollutants are increasing. Additionally, the industrial implants and urban site factors produce an environmental pollution due to the long period of exposing to the atmosphere [7]. Environmental pollution represented by higher carbon content can be limited by improving the construction materials by nanotechnology as well as the use of thermal insulation may lead to efficient energy usage for air conditioning [8]. The Iraqi construction materials industry is not particularly interested in nanotechnology from the perspective of architecture or civil engineering. However, the expertise of these technical branches should be considered. Future civil engineers must have a broad perspective and develop higher-order thinking skills, [9], which allow them to handle multiple technologies and create creative solutions to the challenging problems [10]. The construction industry has a tremendous deal of potential for utilizing nanotechnology, and there are many uses for it, including cutting-edge building materials and sophisticated building systems [11].

Globally, the high costs of maintaining archaeological sites pose challenges for civilized nations. This problem obliges those countries to adhere to plans to monitor the problems facing historical sites, for the purpose of preserving and rehabilitating them and to identify potential risks as shown in Figure 1. In order to strengthen construction project management, it is crucial to have a clear knowledge of the obstacles that nanotechnology applications in Iraqi projects face. This review article examines the current state of the construction industry, utilizing findings from a literature analysis and the most recent global research, to demonstrate the fundamentals of nanotechnology in the industry. To highlight the potential advantages of adopting more sustainable construction practices, various developments are also discussed. The results of this study are anticipated to assist nanotechnology in building materials and architecture, either directly or indirectly increasing their appropriateness and current materials use.

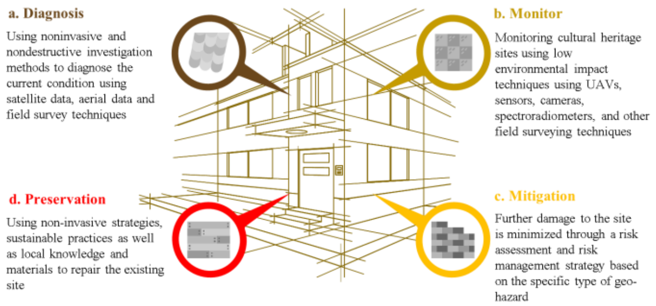

Figure 1. Best practical practices in different countries with archaeological civilizations to preserve archaeological sites, by diagnosing and monitoring the state of cultural heritage.

2. INNOVATION IN BUILDING TECHNOLOGY

The growing nanotechnology research efforts span a variety of fields, along with the elements of sustainable building in the fields of architectural, civil, and environmental engineering [12]. There have been some incredible advancements in the use of nanotechnology in sustainable building, but there is still so much more to develop [13]. Enhancing the rheological characteristics, strength, and durability features of nanoscopic features dependent concrete, is one of the breakthroughs in the application of nanotechnology to sustainable construction [14]. Any alteration to concrete and its constituents at the nanoscopic level affects its behavior, along with the qualities. Therefore, it is anticipated nanotechnology adoption to modify concrete atoms and molecules and sustainable construction materials and their constituents at the nanoscale would significantly improve their performance in the future [15].

By using protective polymer coatings to reduce the surface energy of mineral substrates utilised in many stone monuments of cultural heritage and simultaneously increasing the roughness of their surface, they can significantly improve their ability to repel water [16]. The mineral substrates were either handmade calcium carbonate blocks or pieces of natural marble. By chemically etching minerals or by depositing a nanoscale binary composition coating on the substrate surface, the roughness was increased. The polymers used were poly (methyl methacrylate) (PMMA) and perfluoropolyether (PFPE), and silica NPs of various sizes were used to create the nanocomposite films. Surface roughness clearly influences water repellency, as demonstrated by measurements of water contact angles, profilometry, and Atomic Force Microscopy (AFM) on coated and uncoated surfaces. Surfaces become extremely hydrophobic, particularly in the case of nanocomposite coatings.

Giorgi et al. in 2010 developed a system for the preservation of Maya wall murals in situ at the Calakmul archaeological area in Mexico [17]. The most cutting-edge technologies for consolidating wall murals have been developed thanks to the creation of revolutionary, customized NP-based materials. When created as a nanomaterial, simple calcium hydroxide particles can be elevated to a noble substance with exceptional consolidation agent properties [18]. The degradation of wall paintings, which is mostly caused by the transformation of calcium carbonate into gypsum, has been remedied by the authors through the use of calcium hydroxide NPs. The cohesiveness of the paint layer is restored when calcium hydroxide NPs effectively interact with carbon dioxide to reconstruct calcium carbonate and replace the original ligand, which had been destroyed. When there are significant concentrations of sulphates present, the supplementary usage of barium hydroxide NPs enhances the consolidation action of calcium hydroxide and results in the creation of the completely insoluble and inert barium sulphate. Each formulation requires a different set of synthetic steps.

Cultural heritage can be preserved by alternative methods such as the self-cleaning method. In this case, light-absorbing nanomaterials are selected to power chemical reactions. Sierra-Fernandez et al. in 2017 applied a mixture of magnesium oxides with zinc (ZnMgO NPs) to Laspra dolostone from Spain and conchuela limestone from Mexico to treat them [19]. ZnMgO NPs are photocatalytic active nanomaterial when absorbing UV rays (see Figure 2). This adsorption produces effective molecules containing oxygen atoms that degrade pollutants on the surfaces of stones or historical buildings.

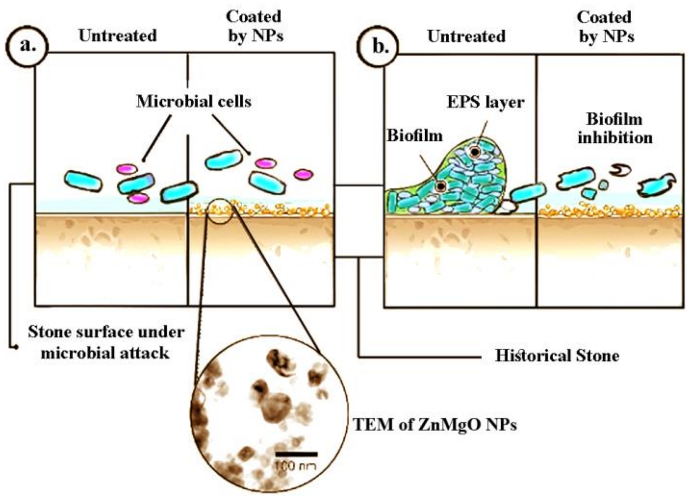

Figure 2. A schematic diagram showing the formation of biofilms on a heritage surface once and uncoated with ZnMgO NPs. a. before microbial attack, and b. After the microbial attack.

The urban core of historic cities is made up of archaeological structures that support both individual identity and urban social life. Due to its theological and spiritual significance in the Islamic world, Old Najaf City may be the most significant city in Iraq; as a result, its archaeological structures exhibit the characteristics of both communal memory and the private reality of cultural heritage. Alhilo et al. in 2020 investigated the usage of nanomaterials in terms of helping to preserve ancient brick buildings in Najaf City specifically and Iraq in general [20]. Based on the supposition that some nanomaterials can shield these structures from damaging environmental variables or stop them from suffering more harm, the researchers came up with ways to use NPs to extend the life of these structures.

As such treatments do not alter the physical or chemical characteristics of heritage buildings, they would enable a high level of environmental efficiency and aid in their preservation [21]. The findings implied that nano-treated bricks can be successfully employed as a novel building material for the supporting components of archaeological structures, providing access to structures with great environmental efficiency.

The utilization of nanotechnology in Egypt has been recently limited to specific categories of buildings within city centers, including office, commercial, educational, healthcare, recreational, and residential structures. These buildings are considered ideal candidates for implementing nanotechnology to meet safety, security, and functional efficiency requirements, thereby greatly advancing urban development. However, it is noteworthy that nanotechnology has not been prioritized for crucial structures like nuclear power plants [22].

Considering this perspective, multiple studies have proposed that nuclear power plants should incorporate nanotechnology to ensure construction safety, reduce energy consumption, conserve economic resources, and minimize pollution. Establishing sustainable nuclear power plants necessitates adopting efficient techniques, as highlighted by Rehan N. in 2021 through several case studies. The author provides a comprehensive set of guidelines for the implementation and construction of the Dabaa plant in Egypt [23].

To foster the development of urban cities and facilitate their transformation into smart and sustainable environments, reliant on nanotechnology advancements, the research objective revolves around adopting nanotechnology in various applications [24]. This applies not only to city centers but also to the outskirts of cities, aiming to achieve a new sustainability paradigm aligned with sustainability objectives, facilitated by advanced technology. Enhancing the envelope of urban typologies through nanotechnology materials on facades, roofs, and exterior renovations, with suitable construction systems, can significantly bolster the progress of urban development in Egypt.

Another survey is based on the most recent invention in the technological area that required maintaining current with the most recent updates with this innovation that had inspired nanotechnology. While the management of materials at the ultra-small scale of the nanoscale represents a revolution in contemporary technology in all spheres of life, especially in material design, construction processes, and architectural perceptions, it also depends on the fabrication of many products on the market [25]. El Alfy et al. addressed the definition of nanotechnologies and their applications in the field of building in 2021 by using nanomaterials [26], which resulted in a positive assessment of environmentally friendly, sustainable structures. Mansoura University's Faculty of Engineering's Specific Programs Building was chosen as the case study for applying nano-insulation materials to enhance building performance and lower energy consumption, particularly during building cooling operations.

In their 2021 research, Ghosal and Chakraborty explore the realm of advanced nanomaterials and examine their influence on the construction industry and built environment both in India and internationally [27]. While previous industrial revolutions have contributed to various global issues, including the emergence of the Covid-19 virus, the fourth industrial revolution holds the promise of a sustainable future through the utilization of advanced materials such as Nanotechnology. The use of this disruptive technology is not a recent development and can be traced back to significant historical examples like the Ajanta Paintings and Damascus Sword. Among the nanotechnology-based building products, Nano Titanium dioxide (TiO_2 NPs) (58%) and Nano silica (21%) are the most widely employed advanced materials. China, in Asia, and Germany, in Europe, stand out as the leading countries in the production of nanomaterials for the building industry. Notably, India ranks among the top five countries globally in terms of technical publications on nanoscience's and technology, as evidenced by various scholarly sources [28].

3. NANOTECHNOLOGY AND ARCHITECTURAL DESIGNS

Nanotechnology emerged as a result of the rapid advancement in science and technology in the latter half of the 20th century, and its uses in construction involved enhancing the qualities of raw materials. It makes surfaces scratch-resistant or keeps debris and dust from clinging to them, as well as a concrete additive for self-healing fissures [29]. As a result, it is a tool for sustainability and the creation of architectural designs that adhere to the fundamentals of construction because it gives buildings the ability to last five times as long as they would naturally, without exhausting resources or polluting the environment, and it also makes operations more efficient [30]. One of the most effective contemporary approaches for achieving sustainable buildings with high functional efficiency is the use of nanotechnology [22]. Durability of concrete and its resistance allowed it to enter the manufacture of the so-called "nano-concrete". These emerging materials bear unique properties in the field of construction and architecture as shown in Figure 3. Small amounts of nano-materials are usually used to be mixed with cement and building materials, which gives the character of hardness and durability to these mixtures.

Recent advancements in nanotechnology have revolutionized architectural designs, opening up new possibilities for creating structures with unprecedented functionality and aesthetic appeal [31]. Nanomaterials, such as carbon nanotubes and graphene, are being used to develop ultra-lightweight and incredibly strong building materials [32]. These nanomaterials can be incorporated into architectural elements like facades, roofs, and windows, enabling energy efficiency, self-cleaning surfaces, and even the ability to generate electricity through photovoltaic properties [33]. Furthermore, nanotechnology is enabling the integration of sensors and smart systems into buildings, facilitating real-time monitoring, adaptive control, and improved occupant comfort [34]. With nanotechnology, architects are pushing the boundaries of design, creating environmentally sustainable and technologically advanced structures that blend seamlessly with their surroundings [35].

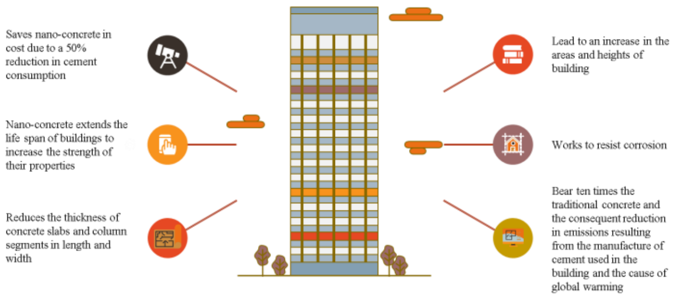

Figure 3. Illustration of the most important unique properties of nano-concrete in advanced nano-architecture.

Nano-architecture is a field that deals with structure and building by using nanomaterials, items, or even nano-shapes. To illustrate the use of technologies in achieving the goals of green architecture computational and executive by introducing the topic of nanomaterials and its applied application in green architecture, Daryoush and Darvish in 2013 deconstructed the conventional structures with green architecture topics [36]. In addition to concentrating on nanomaterials in green architecture, this research demonstrated the significant effects that real-world technological applications in green architecture have on the macroeconomic situation of the nation and the economic well-being of families through statistical calculations and tests. The use of NPs in green architecture has been advocated by researchers as a way to reduce energy loss in industrial and residential buildings and to plan for power production and consumption at the national level [37]. The application of nanotechnology in architecture represents the trend in technology toward improved built environments on a global scale. It focuses on how nanomaterials are used and what they do in architecture. Existing nanotechnology products are numerous, and there are seemingly unlimited potential uses for the technology in the future in fields like energy and material development [38]. Together with architecture, it creates the nano architecture trend, which involves incorporating nanotechnology into architecture through either the use of new, specially made materials or brand-new architectural forms [39]. According to the literature, the most crucial thing is to educate 21st century architects on cutting-edge technology so they are aware of these modern issues and can help keep freshly designed structures current and sustainable.

Restoration of architecture is a discipline of architecture that is rebuilt such that based on the recognition and restoration of historic monuments and locations, leads in reconstruction of historical spaces in terms of body, structure and function [40]. According to Sekularac et al. in 2020, restoring historic buildings is a way of putting into practise a general idea that can be extended in the community and among technical people rather than being restricted to specific locations or special architectural environments [41]. On the other hand, it has become possible to simulate the development and creativity in the field of preserving antiquities in environmentally friendly ways [39]. However, any innovative scientific and technical action needs to pay enough attention to identification. The quality of the advancement of conservation science is fundamentally impacted by human progress toward perfection. At first glance, the discipline of nanotechnology nowadays appears to be focused on energy conservation and environmental friendliness. One of the most successful ways to establish functional features of architecture, such as ensuring the sustainable preservation of the nation's cultural heritage, is to integrate modern technologies like nanotechnology in the building and restoration of historic monuments.

4. NANOMATERIALS-BASED CONSTRUCTION AND HERITAGE BUILDING

The application of nanotechnology including nano-coating in archaeological sites offers novel solutions for the conservation and restoration of artifacts, providing valuable insights into ancient civilizations while ensuring their long-term preservation [42]. There are many reasons that require attention to archaeological sites and the preservation of cultural heritage, some of which are illustrated in Figure 4. Conservation science is considered as one of the most challenging in areas of materials science, requiring knowledge ranging from advanced analytical and physical chemistry to the history of art and archaeology [43]. Nanomaterials have revolutionized the field of archaeology by offering non-invasive and efficient solutions for artifact cleaning, structural stabilization, and imaging. As researchers continue to explore the potential of nanotechnology, one can anticipate further advancements in the preservation and study of archaeological sites, allowing us to uncover and appreciate the rich cultural heritage of our past [44]. However, recent developments have revealed technical and precise solutions using nanotechnology to preserve cultural heritage [45]. Due to their enhanced mechanical characteristics, compatibility as consolidating materials, and adherence to the idea of authenticity of historical structures, nanomaterials are now a viable choice in the preservation of architecture. Nanomaterials also play a crucial role in the stabilization and consolidation of deteriorating archaeological structures. For instance, carbon nanotubes or nanoparticles can be incorporated into mortar or other binding materials to enhance their mechanical properties and increase their resistance to weathering. This approach helps to prevent further decay and structural damage, ensuring the longevity of architectural elements and ancient structures. In 2006, Baglioni focused on the method of preparation that may benefit from construction materials that had been functionalized in order to enhance the quality of urban surfaces, with a focus on cultural heritage [18].

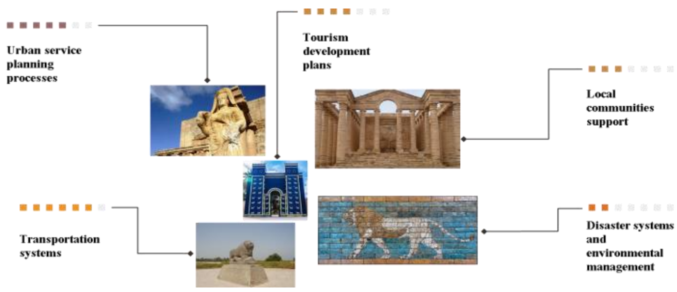

Figure 4. Some of the reasons why scholars and researchers address the issue of protecting and preserving cultural heritage.

Due to the conversion of lime into calcium carbonate, water and milk of lime are frequently used for conservative surface treatments. Since calcium carbonate's qualities closely resemble those of the materials to be repaired, it is actually quite compatible with many carbonatic lithotypes and architectural surfaces [46]. The lower penetration depth, the binder concentration, and the inadequate carbonization process are some factors that limit the effectiveness of the treatments. $C_a(OH)_2$ nanolimes, which have submicrometric dimensions, have lately been used in cultural heritage conservation to enhance lime treatments. Typically, a chemical precipitation process in supersaturated aqueous solutions of the reactants results in lime NPs (calcium chloride and sodium hydroxide).

In 2008, Daniele et al. examined the relationship between the Nano lime carbonization process and various variables, including time and relative humidity conditions [47]. Exploring the possibility of enhancing the Nano lime carbonization process, an alcoholic suspension is employed, while a baking soda solution is added to the suspension. This combination serves to enhance the CO_2 content and disaggregate the suspended particles. Additionally, this process supports the creation of water-repellent materials and techniques for the consolidation and protection of stones in historic building conservation [48]. In 2011, De Ferri et al. focused on composites of hybrid silicone or siloxane polymers and inorganic oxide NPs [49]. The scientists discussed a study on the water repellency of a thin protective coating made using the sol-gel method, commencing with Glymo and Dynasylan 40®, and filling the silicate matrix with nano-sized silica particles (Aeroxide LE1® -Degussa-Evonik). Samples of granite, sandstone, and limestone all received the coatings. Even after four months of exposure to ambient conditions, NPs at the right concentration produced high values for the static contact angle (up to 150°) for all stone species. Even though prolonged direct water contact decreases hydrophobicity, the coatings only respond as expected for granite in the water capillary absorption tests.

Self-cleaning surfaces can be made with photoactive materials containing TiO_2, which lowers maintenance costs and speeds up the deterioration of polluting agents [7]. For the restoration of building stone materials from our cultural heritage, TiO_2 disseminated in polymeric matrix can serve as a coating technique with hydrophobic, consolidating, and biocidal qualities. On limestone and marble substrates, mixtures were tested. In 2015, Ion et al. assessed the performance of hydroxyapatite NPs (HAp) after using chalk samples taken from the Basarabi monument [50].

Marzi in 2015, assessed the efficacy of inorganic compatible therapies based on NPs as consolidates for wood and stone materials damaged by various types of deterioration [51]. The author demonstrated scientific accomplishments contribution in relation to the realization of projects involving nanomaterials, notably those using silicon and titanium sesquioxide (Ti_2O_3). and nanostructured inorganic oxides (Si_2O_3). All of the findings pointed to these NPs as a cutting-edge, highly biocompatible, and innovative material for the consolidation of architectural wood and stone surfaces. Concrete is widely acknowledged as the best material for structural applications because of its superior stiffness, strength, and affordability [52]. The most efficient nano-additives that quickly enhance the qualities of concrete, according to Silvestre et al. study in 2016, are nanosilica and silica fume, TiO_2 NPs, iron oxide, chromium oxide, nanoclay, $CaCO_3$, Al_2O_3, carbon nanotubes (CNTs), and graphene oxide [29].

The goal of the Norwegian State-funded initiative Saving Oseberg, according to Andriulo et al. in 2016, is to preserve the wooden Viking Age artefacts from the Oseberg burial mound [53]. They were discovered in 1904 close to Tnsberg, Norway, and several of them had already undergone alum salt treatment ($KAl(SO_4)_2.12H_2O$). Early in the 20th century, alum was frequently applied to ancient wood in order to strengthen it and prevent shrinking [54]. Conservators noticed an alarming state of the artefacts in the 1990s. Initial examinations revealed that the wood has been deteriorating for more than 100 years as a result of the alum treatment, which started a sluggish but continuous process. Alkaline NP dispersions were used to treat alum-treated archaeological wood samples from Oseberg that had a pH of less than 2.

In order to maintain the originality of historical monuments, nanotechnology makes it possible to monitor intrinsic qualities like melting temperature, magnetic properties, and load capacity [55]. By creating certain patterns at the nanoscale scale, the colour of materials may even remain constant despite changes in their chemical nature. This implies that for a given purpose, fewer materials of higher quality will be needed. In 2016, Kazemi et al. attempted to repair defects and damage of historical monuments with the use of nanotechnology and insulators made with this technology [56]. Although the present insulators stop humidity from entering, they also stop adobe and stone surfaces from breathing, which leads to other issues. One of the valuable artefacts from the Garagounlu era is the religious monument of the Blue Mosque. The amazing and innovative architecture, mosaic, combination of adobe and tile, and solid themes that embellished the monument's interior and exterior surfaces are what give this mosque its unique feature and notoriety. Based on the materials employed and the environment of the area, the writers looked into how well the nanotechnology performed in this monument.

In 2017, Bakhoum et al. conducted a study that explored various methods of utilizing nanomaterials to improve the characteristics of cement-based materials. They also introduced a novel application of nanotechnology in pollution control to promote the concept of sustainable construction [3]. The study presented a specific case where nano-granite waste particles were substituted for cement and fine aggregate in the production of mortar. The results revealed that incorporating nano-granite waste, replacing 5% of cement and 10% of sand, increased the compressive strength of the environmentally friendly mortar by 41% compared to the control mix (CM). Scanning Electron Microscope (SEM) images supported these findings, demonstrating that the green mortar mixture had the highest density and the least number of microcracks and voids. The study further assessed the environmental and social implications, revealing a 10% reduction in resource utilization, as well as 5% reductions in energy consumption and CO_2 emissions. Additionally, positive progress in the sustainable construction sector was indicated by a 6.5% savings in the economic domain.

Within self-cleaning or antifouling stone protection area, adding inorganic NPs like TiO_2, ZnO, and Ag to polymeric blends can increase the protective effect of pristine treatments and bestow additional qualities (photocatalytic, antifouling, and antibacterial) [57]. In 2018, Gherardi et al. created nanostructured photocatalytic protective treatments as part of the "Nano-Cathedral" European project by blending several silane/siloxane systems, solvents, and TiO_2 NPs [58]. The nanocomposites outperformed a commercially available reference siloxane-based protective treatment, but they performed differently when applied to various carbonate substrates with varying levels of open porosity, demonstrating the importance of precisely matching the properties of the stone material to the protective formulations. Particularly, the active surface area and the quantity of accessible NPs are directly correlated with the TiO_2 photocatalytic behavior. While the solvent-based and small size monomeric formulation performed better for Apuan marble, offering a good covering of the pores, the alkyl silane oligomers of the water-based formulation had a good penetration into the microstructure of Ajarte limestone.

According to a study conducted by David and colleagues in 2020, it was found that carbonated versions of hydroxyapatite and tubular nanomaterials like CNTs could be utilized in the conservation of cultural artifacts [44]. Tubular nanomaterials have attracted attention across various industries due to their unique structures and ability to possess multiple walls. These nanotubes possess the necessary attributes for preserving cultural heritage, including exceptional mechanical and elastic strength (even surpassing that of steel), high hydrophobicity (with a contact angle reaching 140 degrees), optical properties (offering substantial photodegradation protection), significant specific surface area (ranging from 50 to 1315 m^2/g, depending on the number of walls) for absorbing other nanomaterials, and relatively good biocompatibility.

There are numerous ways to make nanosilica, and each product has a specific use in the market [59]. The morphology of the different nanosilicas is primarily responsible for their individual features [60]. As an illustration, some types of nanosilicas, like nanosilica gels, include significant agglomerates, whilst others, like nanosilica sols, may be created in the monodispersed form [61]. In 2020, Kooshafar et al. looked into the variations in how the morphology of nanosilica's agglomeration state affected the properties of cement composites [62]. The results indicated that nanosilica gel performed better than silica sol and silica fume in improving certain properties such as early-age compressive strength, despite the presence of clumped particles. It was observed that the uniform form of nanosilica sol could not provide higher levels of nucleation sites in the mixture, meaning that the coagulation of nanoparticles is inevitable in cement-based materials. Furthermore, when compared to concrete containing monodispersed nanosilica sol, the inclusion of nanosilica gel in concrete exhibited enhanced durability in terms of resistance to chloride penetration and water absorption.

Stone has served as a construction material since ancient times. Over the years, these stone structures have suffered damage due to natural degradation [63]. In recent times, novel approaches utilizing NPs have emerged for the preservation of stone. These approaches involve the use of biocides or consolidants. In a study by Becerra et al. in 2021, the significance of maintaining stone, whether it is part of historical or modern buildings, was emphasized [64]. Nanotechnology-based treatments offer certain advantages that meet the requirements of preserving cultural heritage, including effectiveness, compatibility with the stone's aesthetic characteristics, and long-lasting durability. Moreover, these treatments overcome the disadvantages associated with conventional products like limewater used for consolidation or quaternary ammonium salts used as biocides.

In 2021, Saleem et al. discussed the numerous emerging applications of NPs in concrete as well as the associated health and environmental dangers [65]. By enhancing their mechanical and thermal qualities, nanomaterials including nanosilica, TiO_2 NPs, CNTs, ferric oxides, polycarboxylates, and nanocellulose have the potential to prolong the useful life of structures. This might result in a tangential decrease in the concrete industry's overall costs and energy consumption. However, some nanosized materials may be detrimental to the environment and public health due to the uncertainties and inconsistencies in size, shape, and chemical compositions. When seeking advancement in the coming years, it will be crucial to be aware of both the potential positive effects and unintended environmental concerns of these nanosized materials.

5. NANO-COATING IN ARCHITECTURE AND BUILDING APPLICATIONS

Nano-coating in architecture and building applications refers to the utilization of nanotechnology-based coatings to enhance the performance and functionality of various surfaces and materials employed in the construction industry [66-72]. These coatings are formulated to bestow unique properties and enhance the durability, aesthetics, energy efficiency, and sustainability of buildings. Nano-coatings, being thin films applied to surfaces, offer several advantages due to their distinctive characteristics at this scale. Some key advantages of nano-coatings in architecture and building applications are as follows:

1. Waterproofing and Corrosion Resistance: Nano-coatings can establish a protective barrier that renders surfaces water-repellent and resilient against corrosion. By obstructing water infiltration, they can augment structure longevity, avert moisture-induced harm, and prolong the lifespan of construction materials.
2. Self-Cleaning and Easy Maintenance: Nano-coatings can possess self-cleaning attributes that repel dirt, dust, and other pollutants from

surfaces. This feature diminishes the need for frequent cleaning and upkeep, proving especially beneficial for high-rise structures or challenging-to-access areas.

3. Thermal Insulation and Energy Efficiency: Nano-coatings can be engineered to exhibit enhanced thermal insulation properties. By reflecting heat and blocking UV radiation, they can help regulate indoor temperatures, decrease the burden on heating and cooling systems, and contribute to energy conservation.
4. Anti-Graffiti and Stain Resistance: Nano-coatings can confer resistance to graffiti, thwarting the firm adherence of paint and other markings.
Furthermore, they can repel stains caused by substances like oil, grease, and chemicals, simplifying cleaning and preserving the appearance of buildings.
5. Anti-Microbial and Anti-Fungal Properties: Specific nano-coatings possess inherent anti-microbial and anti-fungal traits. When applied to surfaces in healthcare facilities or areas prone to microbial proliferation, they can hinder the growth and propagation of bacteria, viruses, and fungi, thereby enhancing hygiene and diminishing infection risks.
6. Enhanced Optical Properties: Nano-coatings can modify the optical characteristics of surfaces, such as glass or ceramics. They can diminish glare, heighten light transmission, and even manipulate color and transparency, unlocking innovative design opportunities and enhancing visual comfort in architectural contexts.
7. Environmental Sustainability: Nano-coatings can contribute to sustainability endeavors by curtailing the need for harsh chemical cleaners, conserving water through self-cleaning features, and advancing energy efficiency. Furthermore,
8. select nano-coatings are engineered to be eco-friendly and devoid of harmful substances, ensuring minimal environmental impact.

Despite the multitude of benefits, challenges accompany nano-coatings, including production costs, potential toxicity of specific nanoparticles, and the long-term durability of coatings exposed to weathering and wear. Nano-coatings hold substantial potential in architecture and building applications by endowing amplified functionality, durability, energy efficiency, and aesthetics. As the realm of nanotechnology progresses, we anticipate further innovation and the formulation of more sustainable and adaptable coatings that will reshape the construction industry.

While coatings composed of metal nanoparticles and polymers may exhibit satisfactory hydrophilic and hydrophobic traits as well as self-cleaning functionality, their application still poses significant challenges. Given that organic polymer-based coatings lack stability and resilience against the OH radicals generated by metal oxide under UV irradiation, identifying an appropriate host polymer is currently one of the most pertinent concerns [73]. For instance, superhydrophobic coatings containing Lumiflon® 200 and TiO_2 displayed exceptional wettability performance. Nevertheless, prolonged exposure resulted in various adverse effects, including diminished hydrophobicity, coating layer degradation, and polymer loss from the stone surface [74]. In 2018, Petronella et al. optimized the experimental conditions for spray-coating rod-shaped TiO_2 nanocrystals to confer hydrophobic and photocatalytic characteristics to the Lecce stone surface [75]. The comprehensive findings demonstrated the successful and cost-effective treatment of stone samples to impart a photoactive and hydrophobic coating through an appropriate spraying duration. From this perspective, the use of spray-coated TiO_2 NRs n-heptane dispersion holds considerable promise for practical application on buildings and monuments. However, factors like long-term stability, photocatalytic efficiency concerning specific real pollutants, and diverse stony substrates demand careful consideration and resolution. Researchers worldwide have explored the properties of hydrophilic and hydrophobic nano-coatings, as well as their potential integration with nanomaterials for incorporation into building materials. Table 1 provides an overview of some of these studies, highlighting the advantages of each nano-coating in addressing challenges in old/modern buildings and their use as fundamental construction elements. The most prevalent methods for the production and application of these nano-coatings have also been reviewed.

6. CONCLUSION

Constructed cultural heritage deserve to have many innovative research and studies for the purpose of protecting, appreciating and preserving. Architecture, engineering, technology, sociology, economics, urban planning, and legislation must be controlled and organized to function together for cultural heritage conservation efforts to be achieved successfully. The subject of protecting and consolidating historic buildings necessitates a thorough analysis of effective intervention options and a methodology to reach outcomes that are in line with the idea of sustainability. Although the rates of use of nanomaterials seem to be relatively low, they are predicted to rise quickly and self-heal the damages immediately. Other nanomaterials and NPs are thought to be far less dangerous. Some forms of CNTs are known to be possibly toxic. Finally, nano-coatings showed the ability to control self-cleaning of surfaces, making them one of the candidate methods for the protection of cultural heritage in advance. As well as its resistance to fungi or moisture that would destroy archaeological sites, buildings and archaeological structures exposed to environmental factors.

Table 1 A summary of hydrophilic nano-coatings conditional described with their coating method and their resulting features.

Coating material	Coating method	Properties	Year	Ref.
Au-TiO_2	Sol-gel coating	High catalytic activity of chemically stable NPs	2011	[76]
Ag-ZA	Water immersion	Long durability, effective resistivity	2012	[77]
DLC-cotton	Plasma-enhanced chemical vapor deposition	High controlled chemical stability for self-cleaning applications	2013	[78]
TiO_2-Graphene	Spin coating	Self-cleaning active, high photocatalytic properties, indoor potentially usage, low cost	2013	[79]
Ag-SiO_2 Au-SiO_2 Pt-SiO_2	Coating	Eco-friendly, protection coating surface, self-cleaning coating	2014	[80]
TiO_2-ZnO-SiO_2	Sol-gel dip-coating	Photocatalytically active surface, good adhesion properties, high self-cleaning surface	2014	[81]
Polycarbonate-SiO_2	Spray deposition	Self-cleaning activity, and super-wettability coating to control the environmental contamination.	2019	[82]
Travertine-TiO_2	Sol-gel	Good chemical stability, and high self-cleaning effectivity	2019	[83]
PMAA-Ag	NPs growth on cross-linked polymer	Stable NPs growth on polymer, have a profound physicochemical, mechanical and antimicrobial properties to preserve the culture heritage	2021	[84]
OSA/CPO/ZnO	Embedding NPs into OSA	High chemical stability, potent protective coating on heritage sandstone, and long-lasting antimicrobial activity	2021	[85]

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