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Mini Review

From Green Nanolime to Self-Healing Heritage: Safe-by-Design Nanomaterials for Climate-Resilient Conservation

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Abstract

Environmental moisture cycles, salts transportation, thermal stresses, and biodeterioration are placing new pressures on the conservation materials themselves. Nano lime is a compatible inorganic binder for many limestone-based cultural heritage materials, but recent literature has progressed past size-reduction technology alone. Nano lime has been formulated in aqueous, biological assisted, functionalized and hybrid forms to increase colloid stability, controllability of carbonation and substrate selectivity. On the other hand, bio-mediated mineralization and integrated vascular networks of mortars have extended the application of nano-lumen beyond a passive binder and towards an active self-healing material. The current mini-review presents a critical analysis of peer-reviewed advances made in the field between 2021 and 2026. The article claims that the new technologies should be evaluated according to their safety, compatibility, controlled transport, repeatable self-healing ability, environmental safety, and durability in situ.

Keywords: Nano lime, Green synthesis, Cultural heritage, Self-healing mortar, Nanocomposites, Safe-By-Design, Climate Resilience

Conservation Materials Under a Changing Climate

Built heritage is a dynamic and porous material system with rich history. Stone, lime and plaster materials constantly exchange water vapor and other gases with the environment. Due to unpredictable rainfall, heat and humidity conditions, migration of soluble salts becomes more frequent, wet/dry cycles become more intense, bio-colonization becomes different and thermally-induced micro-cracks accumulate. Therefore, treatment of building heritage cannot be only about hardening of the surface layer. The goal should be to strengthen weak areas without forming abrupt mechanical boundaries, hindering vapor transfer, salt accumulation or any visual change. Recent reviews confirm the fact that nanomaterials have high reactivity and controllable surface chemistry, but at the same time stress that nanoscale per se does not guarantee deep penetration, biocompatibility and stability [1-6]. Such consideration is essential since many experimental investigations tend to focus on the optimization of a single response: compressive strength, contact angle, or antimicrobial activity under strictly controlled conditions. Climate resilient surface treatment, however, should function effectively with regard to the complex interaction of all such stressors. The surface treatment in question should withstand alternating humidity, temperature, and salt concentrations; should not contain any harmful substances that could migrate; should not affect the appearance of the object; and should be amenable to future repainting [7].

Nanolime Beyond the Conventional Dispersion

Nanolime is most commonly referred to as an alcohol or mixture of solvents containing calcium hydroxide particles or, increasingly, an aqueous suspension thereof. Upon application, the Ca(OH)2 will carbonate to CaCO3, effectively reestablishing the familiar chemical binder in lime mortars, plaster and carbonate-based stone materials. The major benefits of nanolime are chemical compatibility, alkalinity and potential access to pore channels too small for traditional lime. The major drawbacks of nanolime are also significant: particle agglomeration in storage, precocious deposition at the surface, solvent-induced drying fronts, incomplete carbonation, white haze formation and unequal reinforcement. The performance of nanolime is determined by the interaction of particle size and shape, particle surface chemistry, particle concentration, solvent chemistry, pore structure, moisture and carbon dioxide availability.

Surface and interface modifications are recent approaches to address these problems. Polydopamine functionalization increased the kinetic stability of nanolime in water and facilitated penetration into sandstone [8]. Ionic liquid surface modification resulted in the formation of a stable aqueous dispersion, as well as enhanced penetration and slowed carbonation in the studied system [9]. Functionalization of silica with nanolime was beneficial for the formation of calcium silicate hydrates and reinforced silicate sandstone compared to non-functionalized commercial nanolime [10]. In the context of nanosilica, recent literature shows that cohesion arises due to solvent evaporation via capillary interaction and particle aggregation [11]. This outcome marks a shift in the conception of nanolime. The choice of nanolime should not be based solely on the concept of 'nano'. Rather, it needs to be considered a delivery system which requires definition of targeted pore sizes, residence time, and reaction sequence. In the case of calcareous substrates, the formation of carbonates and pore wall bonding might be adequate. Silica functionalization or reactions involving other minerals might be more suitable for the treatment of silicate stone. Aqueous formulation can be more suitable for the damp hypogea environment.

Green Synthesis and Sustainable Carriers

A conservation material's environmental footprint begins even before its application. Traditional nanolime preparation processes often involve pure materials, energy-consuming production steps and the use of volatile organic vehicles. A recent (2023) investigation proved that there is a way to prepare nanolimes economically through the fermentation of hydraulic or shell limes with traditional plant extracts. The importance of such preparation methods does not stem from their being 'natural', but rather in whether they result in phase purity, particle size distribution, colloidal stability and carbonation properties of nanoparticles. Plant-based organics can change nucleation, particle structure and surface properties, while the same organics can affect the aging process, biodeterioration or coloring. Aqueous dispersion of nanolime designed for murals on high humidity hypogea is another example [12]. Depletion or minimization of alcohol is favorable in terms of health and safety but brings water-dispersed formulations extremely prone to aggregation and stability issues. Use of surface modifiers like polydopamine or ionic liquids can help address some but create new challenges, such as carbonation delay, organics leftovers, expensive price, or uncertain interaction with salts [10,11]. Sustainable practice in conservation must be therefore considered from the viewpoint of life cycle accounting which takes into account starting materials, solvent load, application conditions, repeated treatments and ultimately release.

Hybrid Systems and Substrate-Specific Evidence

Some of the most advanced research conducted lately does not treat the different substrates of the heritage alike. Comparison of the effect of calcium hydroxide, magnesium hydroxide, silicon dioxide, and nanocomposites revealed the influence of mineralogy, porosity, and other factors [12-14]. Nanolime was used in carbonated fossil bone as well as a treatment option for the porous carbonate-phosphate compound where the treatment should increase surface cohesion while not covering any paleontological data [15]. Tests of Vicenza stone weathering prove the necessity of testing both untreated and treated samples under weathering conditions [16].

Hybridization can enhance functionality. Nanostructured metal oxides are currently researched in terms of their potential for water-repellency, photocatalytic, UV protection, and antimicrobial properties [17]. Nanolime-based fluorescent composite coatings can enable tracing of the application, which would allow to establish quality control in murals and mortars [18]. However, multifunctionality complicates the design of the system. A hybrid coating combining hydrophobic, photocatalytic, and antimicrobial properties can change the surface characteristics, such as wettability, optical properties, and moisture transport. The issue of conservation is not what number of functions can be integrated into a material, but what minimal functions are sufficient for a particular mode of degradation [19].

From Passive Consolidation to Bioinspired Self-Healing

Self-healing is the most important recent development in lime conservation. In the case of historic lime mortar, autogenous healing occurs through dissolution of calcium-containing compounds within the presence of moisture, transporting the material to cracks and carbonation. The mineralogy of mortars from the Chellah Mosque showed that secondary calcite formation was linked with low porosity and partial healing of micro-cracks [20]. Similar laboratory-based bio-stimulation has been able to heal surface cracks using bacteria to precipitate calcium carbonate in both historic and conservation mortars [21]. This is a biological and mineralogical approach; however, it depends upon several conditions including crack size and moisture.

Development of autogenic healing model contributed to the formalization of water-induced dissolution, transport, and deposition in lime mortars [21]. Later, engineering research developed mini-vascular structures designed to serve as reservoirs of the healing fluid in the mortar joints and release it after the formation of cracks. In 2023, a sophisticated 3D-printed vascular structure was suggested as the basis of self-healing cementitious materials [22]. In 2025, this vascular structure was optimized for 4D printing in mortar for built-heritage restoration [23]. Simultaneously, the researchers proved that the vascular network could be integrated into hydraulic lime mortars [24]. The most straightforward example of this can be seen in the research published in 2026 on the effectiveness of 10 g/L nanolime dispersions for two water-ethanol ratios as healing agents in natural hydraulic lime mortars [25]. Flexural-strength recovery was estimated at 12% under the optimal conditions; recovery of 6-8% was noticeable even in samples aged 280 days. Recovery of stiffness was relatively small and depended heavily on the age of the sample, crack width, and number of filled channels. It is a good start just because it is small; it defines the presence of healing but does not presuppose structural recovery. Heritage should aim at localized crack stabilization, moisture penetration minimization, and postponed repair.

Safe-by-Design Must Become a Conservation Criterion

The safety of nanomaterials is intimately linked to the efficacy of conservation treatments. Spraying or painting processes may subject workers to airborne particles, weathering of treatments may cause the release of nanoparticles or ions, and antimicrobial or photocatalytic layers may impact non-target species. Reviews of the leaching and toxicity of inorganic nanomaterials reveal significant deficiencies in exposure studies [5,6]. A safety assessment in 2025 of a SiO2@ZnO multi-component nanomaterial highlights how hazards, exposure of workers and release of the nanomaterial during use can be taken into account during design rather than post-commercialization [18]. While designed for construction applications, this approach is directly applicable to conservation which involves treatment of non-replaceable substrate materials within sensitive environments.

A conservation treatment program that is designed to be safe should thus assess the entire formulation rather than just the active nanoparticles. It should include information regarding free particles, agglomeration condition, volatility of solvent, spray aerosols, remaining modifiers, ion leaching and aged fragments. Safety may be achieved through low-emission application techniques, incorporation in appropriate matrices, dosage reduction, use of personal protection, and choice of less dangerous phases for the function of the formulation. Safety data should be provided along with the results on color, permeability and mechanical testing.

A Practical Evaluation Framework for the Next Generation

Identify problems prior to proposing solutions. Determine the mineralogy, porosity distribution, hydration state, presence of salts and the nature of the active process of deterioration. The solution should address the specific problem of ‘failure’ and not the general question of ‘protection’. Understand colloidal science. Report particle and aggregate size independently, monitor zeta potential, sedimentation and rheological behavior through realistic storage times and correlate these measurements with penetration and deposition depth. DLS analysis should be correlated with microscopy data and not taken as confirmation of nano-penetration alone. Assess reaction products, not simply uptake. Analyze the composition and quantitatively determine the extent of consumption of portlandite or formation of calcium carbonates or calcium silicate hydrates using XRD and FTIR spectroscopy where applicable. Reaction product distribution should be established using SEM/TEM-EDX.

Compatibility testing as a system. Compatibility of strength and crack closure must go hand in hand with water absorption, vapor permeability, drying behavior, color, gloss, salt crystallization, and thermal behavior. The result should be an equal improvement without a destructive gradient between the two areas.

Aging under coupled stresses. After single factor testing, wet-dry, salt, thermal, and biological loading must be considered. Mock-ups and small-scale site tests should include a control specimen and seasonal monitoring since lab conditions of carbonation rarely match those of the monument. Retreat ability and evidence. Documenting the composition, dose, treatment sequence, and microclimate will ensure that the performance can be reproduced. For the vascular system, investigate whether healing can take place again, how old the channels become, and whether the carrier can be reworked or stripped. Non-destructive methods of analysis such as ultrasonic, infrared thermography, resistivity, and microtomography will separate the transient effect of water from mineral healing.

Conclusion

Whereas the forefront of consolidation science is moving from the static treatment paradigm to the adaptive mineral systems approach, green synthesis, aqueous stabilization, surface functionalization and nanohybrids can help achieve better consolidation materials’ transportability and reactivity, whereas bio-induced mineralization and vasculature delivery appear as promising methods of localized self-healing. While the current data is not sufficient for full-scale deployment, there is an increased need to adopt a more stringent research paradigm that will require substrate-specific development, environmental aging in conjunction with phase-specific analysis, safety evaluation and monitoring. The future value of nanolime will be less related to nanoscale rather than to controllability and compatibility.

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Conflict of Interest

None.

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