Review Article

Nanomaterials in Construction and Architecture: Cross-Scale Performance, Risks, and Implementation Limits

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DOI: 10.14416/j.asep.2026.04.004
Received: 4 December 2025; Revised: 7 January 2026; Accepted: 27 January 2026; Published online: 8 April 2026

Abstract

Nanomaterials are increasingly investigated for their potential to enhance the mechanical performance, durability, energy efficiency, and environmental functionality of construction materials and architectural systems. This paper presents a critical, cross-scale synthesis of nanomaterial applications in structural composites, building envelopes, and urban-scale interventions, examining both reported performance gains and implementation constraints. An evaluative synthesis approach is adopted rather than quantitative ranking, reflecting the heterogeneity of testing protocols and the predominance of laboratory-scale evidence, with comparatively limited validation at pilot or field scales. Reported benefits include improvements in mechanical and structural performance, enhanced durability and material longevity, advances in thermal and energy performance, environmental and air-quality functions, gains in resource efficiency and material optimization, expanded design and system integration potential, and localized urban-scale and system-level contributions. However, these outcomes remain highly context-dependent and are shaped by production pathways, cost structures, durability uncertainties, and potential health and environmental risks across the material lifecycle. By situating nanomaterials within integrated, lifecycle-oriented design and governance frameworks, the findings indicate that their greatest contribution lies in context-sensitive, system-level deployment rather than in isolated technological fixes often associated with techno-solutionism.

Keywords: Antimicrobial surfaces, CO_2 emissions, COVID-19, Eco-compatible architecture, Energy efficiency, Nanotoxicity, Smart coating, Sustainable architecture, Sustainable materials

1 Introduction

The construction sector, in its effort to achieve zero–carbon, resilient, and sustainable built environments, is increasingly shaped by the emergence of green nanotechnology. This shift reflects a growing emphasis on resource conservation and the reduction of the overall environmental footprint. Sustainable construction extends beyond meeting immediate needs; it entails preserving resources for future generations while supporting economic growth, urbanization, and social development.

At the same time, the sector faces persistent challenges, most notably high CO_2 emissions and inefficient energy use. Globally, buildings are the largest energy consumers and account for approximately 39.65% of energy–related carbon emissions [1]. Of these, around 28% arise from operational activities, namely heating and cooling, while 11% are attributed to embodied emissions associated with construction materials and processes [2]. Ordinary Portland Cement (OPC) alone contributes roughly 10% of total global CO_2 emissions [3]–[5].

In this context, nanomaterials (NMs) have gained attention as potentially transformative materials capable of mitigating these impacts. Beyond their potential contribution to carbon–emission reduction, NMs offer functional advantages in thermal performance, mechanical strength, and moisture resistance, as well as non–structural benefits in particular self–cleaning surfaces, energy efficiency, and improved indoor air quality [6]. These properties position NMs not only as emerging technologies, but also as viable candidates for integration into buildings designed to meet environmental objectives and next–generation performance standards.

In addition, several NMs exhibit antimicrobial, antiviral, antibacterial, and antifungal properties, which may contribute to healthier built environments [6]. Their environmental relevance also extends beyond short–term performance gains. Compared with conventional materials, nano–coatings often demonstrate enhanced durability and reduced maintenance requirements, supporting long–term resource efficiency. While such applications have been widely explored in heritage conservation, their relevance increasingly extends to contemporary construction practices [6].

Recent investigations [6]–[10] consistently identify nanotechnology as a key enabling pillar of green construction, with particular emphasis on nanostructured coatings, self–cleaning surfaces, and intelligent materials that reduce environmental impact, improve efficiency, and extend service life. When integrated within broader green building strategies, nanotechnology emerges as a promising approach for architectural and urban design, offering pathways for carbon–emission mitigation while enhancing material performance and sustainability.

Most existing studies on NMs in the built environment focus on individual materials or specific applications, resulting in a fragmented body of knowledge and relatively few comparative overviews of the main nanomaterial families discussed in construction–related research. Consequently, the literature offers a limited synthesis of how different NMs are positioned, compared, and evaluated across the built environment.

This review addresses this gap through a structured synthesis of published studies from engineering, architecture, and health–related fields. It provides an overview of the most frequently reported NMs applied in the built environment, summarizes empirically reported functional and sustainability–related benefits, and examines the technical, environmental, economic, and regulatory considerations identified in the literature as influencing their scalability and broader adoption.

The review is guided by the following research questions:

a. How are NMs currently discussed and applied in the built environment, and which material categories and construction domains are most frequently addressed in the literature?

b. What functional and sustainability–related benefits are consistently reported, and under what material and application conditions are these benefits described as relevant for construction practice?

c. What technical, environmental, economic, and regulatory factors are identified in the literature as constraints on the scalability and long–term implementation of nanomaterial–based solutions?

The novelty of this paper lies in its comparative and system–oriented synthesis. By moving beyond single–material analyses, it offers a consolidated overview of the most important NMs discussed in relation to the built environment and frames them as conditional performance enablers rather than universal substitutes, thereby clarifying the opportunities and limitations highlighted in current research.

2 Nanotechnology and the Built Environment

Table 1 summarizes the principal NMs used in construction and architectural applications; however, meaningful cross–comparison of reported performance is constrained by non–standardized measurement protocols, heterogeneous testing conditions, and inconsistent consideration of durability, scalability, and health–related constraints. Accordingly, the table should be read as an evaluative synthesis rather than a quantitative ranking, with reported values indicating general performance trends derived predominantly from laboratory studies, and to a lesser extent from pilot–scale and early field applications.

The predominance of laboratory–scale investigations (Table 1) reveals a structural imbalance in the field, wherein material performance is extensively characterized under controlled conditions, while validation through pilot–scale or operational architectural deployment remains comparatively underdeveloped.

Table 1: Most Key applications of nanomaterials in construction and architecture.

Nanomaterial	Chemical Formula	Type	Main Use in Systems	Typical Area of Application	% Addition	Numerical Value (Results)	Key Technical Merits	Advantages	Disadvantages	Ref.
Nano-silica	SiO_2	Oxide Nanoparticle	Nanofiller and binding agent in cementitious matrices	Concrete, cement mortar, and self-healing systems	0.25% to 6% by cement weight	Up to 150% increase in early strength; 27% increase at 28 days	Rapid hydration, reduced porosity, and enhanced particle packing	Improves compressive/flexural strength and durability	Higher water demand reduces workability/slump	[8], [27]–[29]
Nano-titania	TiO_2	Oxide Nanoparticle	Photocatalytic coating and self-disinfecting film; Nanofiller and binding agent in cementitious matrices	Concrete facades, glass, and road surfaces; Concrete, cement mortar,	1 wt% to 5 wt% (wt: by weight)	60% reduction of NOx on roads; 99.9% dye degradation; 19.3% strength increase at 0.75% by cement weight	Decomposes pollutants (NO_x, SO_2) and microorganisms	Self-cleaning, air purification, and UV protection; Improves compressive/flexural strength and durability	Efficiency reduces over time due to carbonation/dust	[6], [16], [29], [30]. [31]
Doped TiO_2	Doped TiO_2 (Hf, Zr, Ce, Dy)	Doped Oxide	Hybrid self-cleaning and hydrophobic modifier	Wood, red clay brick, and aerated concrete facades	2 wt% concentration in solution	Water contact angle of 140–145°; 99.9% dye removal	Extends photocatalytic activity into visible light	Superhydrophobicity and moisture resistance	Requires specialized synthesis, like ultrasonic hydrolysis	[30]
Carbon Nanotubes	CNT / MWCNT	Carbon Nanostructure	Structural reinforcement and conductive filler	High-performance concrete and smart infrastructure	0.05 wt% to 3 wt%	150% increase in beam ductility; flexural strength doubled	Crack prevention, increased ductility, and conductivity	Provides self-sensing/piezoresistive abilities	High cost; difficult to disperse (agglomeration)	[27]–[29]
MXenes	$Ti_3C_2T_x$/ Ti_2CT_x/ Nb_2CT_x	2D Transition Metal Carbide	Electromagnetic Interference (EMI) shielding	Smart building envelopes	8 wt% to 24 wt% within the polymer matrix or total composite	EMI shielding efficiency up to 116 dB; 99.9999% waves blocked	Exceptional shielding effectiveness and flexibility	Lightweight and high metallic conductivity	Oxidative degradation in humid environments	[32]–[34]
Nano-alumina	Al_2O_3	Oxide Nanoparticle	Heat transfer enhancer and structural modifier	Asphalt concrete, timber, and MDF panels	0.25 wt% to 5 wt%	Compressive strength improved by up to 30%	Resistance to high temperatures; accelerates C-S-H formation	Increases serviceability and resistance to biological attack	Dosages >5% do not linearly improve mechanicals	[6], [8], [27]
Nano-ferric oxide	Fe_2O_3 / Fe_3O_4	Oxide Nanoparticle	Structural modifier and self-monitoring component	Concrete, mortars, and anti-corrosive paints	0.5 wt% to 10 wt%	Compressive strength increased up to 69.76% at 14 days	Increased abrasion resistance and microstructural density	Enhances magnetism and compressive strength	High dosages reduce workability	[6], [27], [29]
Nanometakaolin (NMK)	$Al_2Si_2O_7$	Aluminosilicate	Partial cement substitute and filler material; secondary C-S-H gel generator; micro/nano-filler	High-strength concrete, recycled aggregate concrete (RAC), geopolymer binders	5% to 20% by cement weight; optimal range 10% to 12.5%	63% compressive strength increase; 46.8% flexural increase; 62.4% ITZ thickness reduction; 29.6% lower crack rate; 20.87% reduction in water absorption	Reacts with $Ca(OH)_2$ to form additional C-S-H and C-A-S-H; fills micro-voids; refines the interfacial transition zone (ITZ) improves impermeability	Increases early and long-term compressive, flexural, and tensile strength; enhances fire and acid resistance; white color ideal for aesthetics; reduces footprint by up to 43%; enhances fire resistance (stable to 250–800°C)	High fineness increases water demand/ workability/flowability; energy-intensive production (650–850°C calcination); agglomeration at high dosages	[16], [28], [31], [35]–[38]

Nanomaterial	Chemical Formula	Type	Main Use in Systems	Typical Area of Application	% Addition	Numerical Value (Results)	Key Technical Merits	Advantages	Disadvantages	Ref.
Graphene / Graphene Oxide	G / GO / rGO	Carbon Nanostructure	Reinforcing agent and piezoresistive filler	Smart concrete and oil-well cement	0.02% to 1.0% by cement weight	Flexural strength improved by 52%; compressive by 33%	Extreme mechanical strength (Young's modulus 1 TPa)	Improves impermeability; enables structural health monitoring	Agglomeration in basic cement environments	[27], [39]
Vanadium Dioxide	VO_2	Phase-Change Material	Thermochromic glass coating for heat regulation	Smart windows and building envelopes	Doping levels 1 at% to 8 at% (at%: atomic percent)	20 µm coating reduces indoor temp increment by 58%	Metal-to-insulator transition (MIT) to regulate heat	Reduces cooling costs by blocking up to 90% of IR	Prone to oxidation; high MIT temperature 68°C	[6], [27], [40]
Tungsten Trioxide	WO_3	Transition Metal Oxide	Electrochromic electrode for light modulation	Smart windows and energy storage systems	1 wt% to 6 wt% (doping)	Specific capacitance of 1897.8 F/g; optical contrast >74%	Reversible light modulation via voltage application	Lowers air conditioning loads by blocking sunlight	Low intrinsic electrical conductivity	[41]
Nanoclays	-	Silicate Layer	Structural reinforcement and barrier coating	Bricks, mortar, and foundations	1 wt% to 7 wt%	Compressive strength increased 4.8 times in earth bricks	Improved gas-barrier properties and tensile strength	Reduces water uptake and spalling in bricks	Hydrophilic nature requires careful water control	[6], [8], [29]
Silver Nanoparticles	Ag	Metallic Nanoparticle	Biocidal additive (antibacterial/viral/fungal); early nucleation catalyst for C-S-H; conductive filler for self-sensing	Healthcare facilities (switches, floors, HVAC); smart cementitious composites; geopolymer mortars	0.5 wt% to 6.0 wt% (Optimized at 0.5 wt% for co-doped systems; 2 wt% for powders).	33% increase in 28d compressive strength (at 0.5%); 68% increase in geopolymer strength (at 6%); volume resistivity reduced by 1–2 orders; 99.9% microbial block.	High specific surface area facilitates C-S-H nucleation and blocks capillary pores; extreme electrical/thermal conductivity; disrupts microbial cell membranes via Reactive Oxygen Species (ROS) generation.	Significant increase in compressive/tensile strength; provides dual-functionality (durability + conductivity); prevents disease transmission; smaller particle sizes yield higher thermal conductivity.	High processing costs (7 times higher than raw silver); strong agglomeration tendency in powder form >2%; environmental toxicity (lethal to zebrafish at >0.190 nM); can penetrate human skin.	[6], [8], [38], [42]
Copper Nanoparticles	Cu	Metallic Nanoparticle	Modifier for protective coatings on carbon steel	Steel structures and anti-corrosion paints	0.5 wt% in solution	Reaches maximum inhibition efficiency for steel protection	Superior surface coverage and anticorrosive effects	Improves weldability and formability of steel	Environmental toxicity concerns if leached	[8], [29]
Calcium Hydroxide	$Ca(OH)_2$	Metallic Hydroxide	Consolidation agent via "micro-grouting"; alkaline activator for slag and solid wastes; cement nanofiller.	Heritage conservation; alkali-activated slag (GGBFS) binders; multi-component solid waste materials.	0.5% to 10% (by mass of precursor); optimized at 1–4%.	52.0 MPa 28d strength in solid waste systems; reduces setting time from 2940 to 330 min in Na_2SO_4 systems.	Provides OH^- ions to enhance system alkalinity; promotes C-S-H gel and ettringite precipitation; forms a $CaCO_3$ crystalline network within inner cracks.	Significantly shortens setting times; improves early-age compressive strength; compatible with historical stone ("breathing" effect); synergistic with gypsum for long-term stability.	Efficacy depends on pore system and moisture; excessive amounts >1–2.5% may lead to a more porous microstructure or fragile structures at later ages.	[6], [29], [43], [44]
Zinc Oxide	ZnO	Oxide Nanoparticle	Self-cleaning and UV-protective agent	Façades, and wood coatings	3.5 to 7.5 mg/mL loading	UV blocking performance up to 95%	Provides UV radiation protection and antimicrobial effects	Water and oil repellency on wood surfaces	Dermal exposure hazards; potential cell toxicity	[6], [8], [45]

Nanomaterial	Chemical Formula	Type	Main Use in Systems	Typical Area of Application	% Addition	Numerical Value (Results)	Key Technical Merits	Advantages	Disadvantages	Ref.
Magnesium Oxide	MgO	Oxide Nanoparticle	Expansive agent to offset shrinkage; antibacterial/antibiofilm agent; cementitious admixture	Large-volume concrete (dams); non-shrink cement composites; self-healing concrete; high-performance mortars	1.0% to 10% by cement weight	103% increase in 7-day compressive strength (at 1%); 17.6% increase in flexural strength (at 4%)	Volumetric expansion via $Mg(OH)_2$ crystal formation; reduces autogenous and drying shrinkage; refines microstructure	Significantly increases compressive and flexural strength; seals cracks up to 500 µm; provides long-term stability in fly ash systems	Reduces workability (fluidity and consistency); high dosages >10% risk excessive expansion and micro-cracking	[6], [8], [46]-[48]
Graphite Nanoplatelets	xGNP	Carbon Nanoplatelet	Asphalt modifier for temperature stability	Road paving and asphalt binders	1% to 2% by cement weight	Absorbed light ratio of 0.93 for NIR radiation	High optical absorption and thermal conductivity	Improved low-temperature cracking and rutting resistance	High content increases mixing/compaction temperatures	[49]
Silicon / Titanium Carbide	SiC / TiC	Carbide Nanoparticle	Structural admixture for microstructural refinement	Cement pastes and mortars	Optimal at 5% by cement weight	Max mechanical improvement at 28 days curing	Produces a highly homogeneous C-S-H microstructure	Increases splitting tensile and compressive strength	Dosages >5% lead to "slumped" properties	[50]
Lignin Nanoparticles	LNP	Bio-based Nanomaterial	Solar energy-harvesting additive	Photothermal films and smart glass	10 wt% to 40 wt% in films	99% UVA blocking; significant reduction in heat gain	Selective UV absorption (97–99%) and photothermal effect	Passive cooling of indoor environments; non-toxic	Yellowish-brown color may impact aesthetics	[45], [47], [51]
Nanocellulose / CNF	$(C_6H_{10}O_5)n$	Bio-based Nanomaterial	Fiber reinforcement and photocatalytic carrier	Concrete reinforcement and smart windows	0.10% by cement weight	Improves NOx degradation rate over 1000 times via freeze-casting	High elastic modulus and bending strength	Non-toxic, renewable, and biodegradable	Poor water resistance; difficult large-scale isolation	[31], [45], [51], [52]
Carbon Black	CB	Carbon-based Waste	Asphalt modifier	Discarded tires are recycled into asphalt binders	2% by binder weight; 2.6 µm particle size	Optimal recommended content for best performance	Increases rutting and cracking resistance performance	Improves softening point and storage modulus	Large particles (270 µm) show less obvious SE increase	[53]
Biochar	-	Carbon-based Waste	Soil amendment and anti-aging modifier	Weak sandy foundations and asphalt binders	0.2 wt% to 4 wt%	Compressive strength increased 2.79 times at 28 days	Improves resistance to unconfined compression	Sustainable carbon sequestration removes pollutants	Efficiency varies with soil contamination levels	[28], [51]
Metal Organic Frameworks	Zr-MOFs	Hybrid Structure	Nucleation catalyst for C-S-H gel	High-performance cement pastes	0.15 wt% by cement weight	25.53% increase in 7d compressive strength; 13.03% increase at 28d; Tdecomp= 540 °C	Molecular-scale porosity	Exceptional thermal and chemical stability	Undergoes a phase transition from crystalline to amorphous in cement pore solutions; delays initial hydration and reduces hydration heat	[54], [55]

2.1 *Structural and mechanical enhancement*

NMs exert their most pronounced effects in cement–based composites, where they simultaneously enhance mechanical performance, durability, and environmental efficiency [11]. At the microstructural level, silicon dioxide nanoparticles (SiO_2NPs) act as highly reactive pozzolans, consuming calcium hydroxide ($Ca(OH)_2$) and generating additional calcium silicate hydrate (C–S–H), as shown in Equation (1):

$$SiO_2NPs + Ca(OH)_2 \rightarrow C\text{-}S\text{-}H \quad (1)$$

This reaction densifies the cement matrix, refines pore structure, and reduces permeability, thereby strengthening the load–bearing framework and improving long–term durability [11]:

The performance gains observed with silica are not isolated. Carbon nanotubes (CNTs) and aluminum oxide nanoparticles (Al_2O_3NPs) further enhance flexural strength and fracture toughness by bridging microcracks and improving stress transfer across the cementitious matrix, demonstrating the versatility of NMs in reinforcing both compressive and tensile load paths within structural elements [12]. Beyond mechanical enhancement, nanotechnology contributes directly to sustainability objectives through nano–modified recycled materials. For example, the incorporation of nano granite waste into cement mortar improves compressive strength while achieving approximately 10% reductions in both material consumption and energy use, illustrating that ecological benefits can be realized without compromising structural performance [13].

These micro–scale mechanisms underpin the development of Ultra–High–Performance Concrete (UHPC), where NPs promote ultra–dense microstructures with minimal microporosity. The resulting improvements in durability and mechanical efficiency extend service life and reduce lifecycle material demand, aligning UHPC with long–term sustainability and resilience goals in the built environment [9]. In parallel, nanotechnology is reshaping building energy systems through nano–phase–change materials (nano–PCMs) and nanocomposite aerogels integrated into envelopes. These materials enable effective thermal energy storage and release, significantly enhancing indoor thermal stability and reducing reliance on mechanical HVAC systems [6]. Ultra–thin nano–aerogel coatings provide high insulation performance at minimal thickness, expanding architectural design flexibility [14], while graphene–and CNT–reinforced structural nanocomposites achieve exceptional strength–to–weight ratios, enabling lighter components, thinner sections, and more efficient construction systems [9].

Quantitatively, the incorporation of NMs into cementitious composites consistently reduces void spaces and reinforces the internal microstructure, yielding substantial strength gains. Reported increases in compressive strength range from 12% to 50% in normal concrete and from 16% to 58% in lightweight concrete [15]. Specifically, a 3% replacement with nano–silica (nano–SiO_2) produces a 20%–33% strength increase [16]; graphene oxide (GO) at an ultra–low dosage of 0.10% increases compressive strength by approximately 25%, reaching values near 50 MPa [17]; CNTs at 0.5% in self–compacting concrete raise compressive strength by 38.6% [16]; and nanometakaolin (NMK) at 10% yields compressive strength gains of up to 63% [16].

Improvements extend beyond compression to tensile and flexural behavior, with enhancements typically ranging from 16% to 55% [16]. GO at 0.04 wt% increases splitting tensile strength by 31.0% [18], while at 0.10% it delivers a 40% increase in flexural strength to approximately 7.0 MPa [17]. Nano–alumina (NA, nano-Al_2O_3) at 1% further increases flexural capacity by 16.7% [16]. Importantly, GO also alters deformation mechanics: Poisson's ratio decreases to 0.21 (a 12.5% reduction relative to conventional mixes), volumetric strain is reduced by 33.7%, and lateral strain decreases by up to 76% compared to OPC, indicating enhanced stiffness and crack–resistance under multi–axial loading conditions [18].

2.2 *Durability, insulation, and energy performance*

Nano–enabled concretes demonstrate significantly enhanced durability due to nanoparticle–induced densification of the cement matrix, which limits the transport of aggressive agents, including chlorides (Cl^-), water (H_2O), and sulfates (SO_4^{2-}). By refining pore size distribution and disrupting capillary continuity, NMs function as both physical barriers and chemical stabilizers, thereby slowing degradation processes. This effect is clearly evidenced in Rapid Chloride Penetration Tests (RCPT): concretes incorporating 2% nano–silica (NS) exhibit a reduction in charge passed from 3000 Coulombs in control mixes to 1000 C, corresponding to a 67% decrease in chloride permeability, while graphene oxide (GO) at 0.10% achieves a comparable reduction to 1200 C (60%) [17].

Moisture resistance follows a similar trend. The inclusion of 2% NS reduces water absorption by 40% (from 5.0% to 3.0% by weight) in one investigation [17], while another study reports reductions as high as 85% for 2% NS and 74% for 4% nano iron oxide (Fe_2O_3), underscoring the role of NMs in sealing pore networks and limiting fluid ingress [15]. Chemical durability is likewise improved: concrete modified with 0.10% GO retains 97% of its compressive strength after 56 days of exposure to a 5% sodium sulfate (Na_2SO_4) solution, indicating strong resistance to sulfate–induced expansion and softening [17].

At the scale of the building envelope, nanoparticle–based coatings and insulation systems extend these durability and efficiency gains beyond structural materials. Metal–oxide nanoparticle window coatings selectively filter solar radiation, blocking up to 99.9% of ultraviolet (UV) radiation and 70%–90% of infrared (IR) wavelengths, thereby reducing solar heat gain while protecting occupants and interior materials [6]. Aerogel–and nanogel–based insulators further enhance thermal performance through extremely low thermal conductivity; commercial aerogels reach values as low as 0.014 W/mK, substantially outperforming conventional insulation materials, which typically range from 0.025 to 0.040 W/mK [19].

These material advantages translate into measurable building–scale energy savings. A 5 mm fiber–reinforced aerogel blanket reduces total building energy consumption by 2.17% and cooling energy demand by 3.15%, while a nanogel glazing system (Lumira) alone achieves reductions of 4.93% in total energy use and 7.41% in cooling loads [19]. When combined, aerogel insulation and nanogel glazing produce synergistic effects, lowering total energy consumption by 7.42% (216,479 kWh) and cooling loads by 10.78% (137,544 kWh) [19]. Climate–specific assessments further confirm these benefits: nano–aerogel glazing systems applied in Egypt yield approximately 19% annual building energy savings under hot-arid conditions [20].

In addition to thermal regulation, NMs enable precise control over optical performance. Incorporating 7.5% hollow silica powder into glazing reduces solar and visible light transmittance to 0.48 and 0.45, respectively (on a 0–1 scale), while increasing solar and light reflectance to 0.49 and 0.46. This tunability supports optimized daylighting strategies and controlled solar gains, balancing visual comfort with energy efficiency [21].

2.3 *Urban air quality*

At the urban scale, photocatalytic titanium dioxide (TiO_2)–based materials illustrate how nanoscale surface reactions can translate into measurable environmental effects when deployed over large areas of the built environment. When applied to pavements and façades, these materials operate as passive systems that continuously interact with ambient pollutants under natural solar irradiation, positioning photocatalysis as a distributed, low–energy supplement to urban air–quality management. A representative example is a 7,000 m² TiO_2–coated roadway in Milan, which reported a 60% reduction in nitrogen oxides (NO_x), demonstrating the potential effectiveness of large-area photocatalytic infrastructures in dense urban contexts [6].

At the material scale, photocatalytic performance is typically quantified using standardized laboratory indicators that capture photoactivity and self–cleaning capacity under controlled conditions. Dye degradation tests employing rhodamine B as a model organic compound remain a common proxy for photocatalytic efficiency. TiO_2–containing mortars achieve approximately 38% rhodamine B discoloration after 4 hours and 64% after 26 hours of artificial solar exposure, corresponding to the R_4 and R_{26} indices, respectively [22]. According to the UNI 11259 standard, materials are classified as photoactive when R_4 exceeds 20% and R_{26} exceeds 50%, confirming that these mortars meet established thresholds for effective self-cleaning behavior. While such metrics provide essential benchmarks for material qualification and comparison, they primarily reflect idealized exposure conditions and do not fully capture long–term in situ performance.

Beyond direct pollutant abatement, photocatalytic and protective nanocoatings applied to façades contribute to urban livability through secondary but strategically important effects. By reducing surface soiling, inhibiting graffiti adhesion, and limiting biodeterioration, these coatings help preserve aesthetic quality, lower maintenance requirements, and support the conservation of both historic and contemporary buildings. In addition, their optical and radiative properties can attenuate ultraviolet and infrared radiation, contributing to reduced cooling energy demand and improved indoor and outdoor thermal comfort. Collectively, these benefits extend the relevance of photocatalytic technologies beyond air purification, linking them to broader objectives in urban comfort, public health, and post–COVID resilience strategies [6].

At the city scale, however, the effectiveness of TiO_2–based photocatalytic applications is strongly influenced by contextual and operational factors. Reported NO_x reductions are often derived from pilot or demonstration projects and may vary significantly under real urban conditions due to traffic density, atmospheric dispersion, surface aging, and progressive efficiency losses caused by soiling and weathering. Long–term performance depends on exposure conditions, maintenance regimes, and integration within existing urban infrastructures. From this perspective, photocatalytic surfaces should be understood not as standalone solutions capable of transforming urban air quality, but as complementary interventions that can deliver incremental environmental benefits when embedded within comprehensive emission–reduction, planning, and policy frameworks.

In this light, photocatalytic urban surfaces are unlikely to achieve city–wide air–quality transformation in the short term; their value lies instead in their capacity to contribute measurably, though modestly, to integrated mitigation strategies targeting healthier and more resilient urban environments.

3 Nanoscale Mechanisms

3.1 *Nano–reinforcement*

The enhanced performance of nanomaterial–modified cementitious systems arises from the combined action of chemical reactions and physical reinforcement mechanisms operating at the micro– and nanoscale. Chemically, nano–silica (NS) participates in pozzolanic reactions with calcium hydroxide (CH) released during cement hydration, generating additional calcium silicate hydrate (C–S–H) gel, which is the primary phase governing strength and durability in hardened cement paste [17]. This reaction not only increases the volume of load-bearing C–S–H but also reduces the presence of less desirable hydration by–products.

Thermogravimetric analysis (TGA) provides direct evidence of this transformation, showing that NS–modified mixes contain approximately 35–40% less portlandite than control mixes, confirming more extensive CH consumption and enhanced C–S–H formation [15], [17]. These chemical effects are complemented by physical mechanisms. NPs act as highly efficient microfillers, occupying capillary pores and refining pore size distribution, which increases matrix density and reduces water absorption. Simultaneously, their high specific surface area provides abundant nucleation sites that accelerate cement hydration and promote a more homogeneous microstructure [17].

Beyond matrix densification, carbon–based NMs, namely graphene oxide (GO) and carbon nanotubes (CNTs), introduce a distinct reinforcement mechanism. Owing to their high aspect ratios and exceptional mechanical properties, these NMs bridge microcracks, restrict crack initiation and propagation, and enhance stress transfer across the cementitious matrix. This crack–bridging behavior improves not only compressive strength but also tensile strength and fracture toughness, contributing to a more damage–tolerant and resilient composite material [17].

3.2 *Photocatalysis*

Under visible–light irradiation, N/Li_2MoO_4 co–doped TiO_2NPs exhibit markedly enhanced photocatalytic activity, achieving 74% degradation of methylene blue within 4 h. This performance is directly linked to bandgap narrowing to 2.82 eV, an increased density of crystal defects, and effective suppression of electron–hole recombination. Together, these modifications shift TiO_2 photoactivity from the ultraviolet into the visible spectrum, significantly expanding its applicability to indoor environments and low–light environmental remediation scenarios where conventional TiO_2 is ineffective [23].

In air–purification applications, photocatalytic cementitious composites demonstrate comparable functional gains. Cement–based materials incorporating 5% TiO_2 and 2% nano–silica achieve approximately 30% reduction and adsorption of airborne nitrogen oxides (NO_x, including NO and NO_2) [24]. Under controlled laboratory conditions, ppm–level NO_x concentrations and UV–A irradiation at 10 W/m^2, such materials remove up to 8.95 μmol of NO_x per 10 cm^2 over a 3–hour period [25], with nitric oxide removal rates reaching 14.33 $mg/m^2{\cdot}h$ in unweathered states [24]. These results highlight the coupling of photocatalytic efficiency with surface condition and exposure parameters (Figure 1).

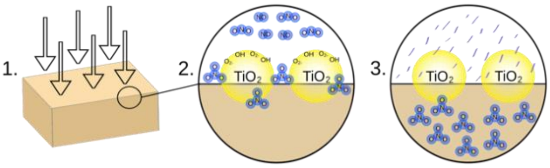

Figure 1: Mechanism of NO_x Abatement : (1) UV Activation: Sunlight activates the titanium dioxide (TiO_2) coating on the block's surface, generating reactive radicals (like hydroxyl and superoxide ions); (2) Pollutant Conversion: These radicals react with airborne nitrogen oxides (NO_x), transforming them into harmless nitrate ions (NO_3^-); (3) Storage & Stability: The nitrate ions are absorbed into the porous structure of the concrete block, where they form stable compounds, effectively removing pollution from the air [26].

At the mechanistic level, photocatalytic oxidation is initiated when TiO_2 absorbs photons in the UV range (approximately 350–380 nm), generating electron–hole pairs according to Equation (2):

$$\mathrm{TiO_2 + h\nu \rightarrow e^- + h^+} \tag{2}$$

where hν denotes photon energy (h is Planck's constant and ν the frequency), e^- represents the excited electron, and h^+ the photogenerated hole [22], [25]. The holes oxidize adsorbed water molecules or hydroxyl ions to form highly reactive hydroxyl radicals, Equation (3):

$$\mathrm{h^+ + H_2O \rightarrow \cdot OH + H^+} \tag{3}$$

while the electrons reduce molecular oxygen to superoxide radical anions, Equation (4):

$$\mathrm{e^- + O_2 \rightarrow O_2^{\cdot -}} \tag{4}$$

These reactive oxygen species drive the oxidation of both organic and inorganic pollutants, including nitrogen oxides, converting them into stable and environmentally benign products, for instance, nitrates and water [22], [25]. In parallel, hydroxyl radicals attack and decompose organic chromophores in compounds, namely rhodamine B, soot, and surface grime, leading to molecular fragmentation and visible discoloration. This observable color loss provides direct evidence of active, light–driven self–cleaning behavior rather than passive surface dirt removal [22].

Through these coupled photochemical pathways, TiO_2–based NMs integrate structural functionality with environmental remediation, enabling cementitious and coating systems to serve simultaneously as construction materials and reactive environmental interfaces [22], [25].

4 Nanomaterials Production

4.1 *Conventional fabrication challenges*

The use of conventional nanomaterial production methods, particularly in the building and architecture industries, generates substantial environmental and economic concerns. These methods predominantly involve energy–demanding processes and harmful chemicals, resulting in excessive energy consumption, toxic waste generation, and reliance on expensive raw materials [56]. As NMs applications expand across sectors, developing greener, cost–effective production processes aligned with economic and environmental sustainability principles becomes urgently necessary [57], [58].

4.2 *Green and low–impact synthesis strategies*

Efforts to mitigate the economic and environmental drawbacks of traditional nanomaterial production have spurred diverse, eco–friendly methods that minimize pollutant and hazardous chemical use, conserve energy, and leverage abundant renewable feedstocks like plant extracts and agricultural wastes. These approaches enable scalable, sustainable practices poised to dominate construction and allied industries, where NPs bolster material strength, durability, and self–healing properties [59], [60].

Green synthesis, which primarily utilizes plant extracts or crop residues, in particular rice husks and fruit peels, serves as a transformative strategy for reducing the environmental impact of nanotechnology [59], [61]. By replacing hazardous synthetic chemicals with natural reducing and stabilizing agents, these methods minimize the generation of toxic effluents and decrease the reliance on expensive reagents [59], [62]. According to recent 2025 evaluations, these green approaches can lead to a 40% reduction in production costs and a 30% decrease in energy consumption compared to traditional chemical routes, particularly as they often operate under ambient temperatures and pressures [61].

These enhancements position green NMs for construction breakthroughs like CNT–reinforced concrete with 200% tensile strength gains and 50%

lower embodied carbon [60]. Table 2 shows the most important eco–friendly fabrication techniques.

Table 2: Eco–friendly nanomaterials fabrication methods.

Type	Technique	Description
Green Synthesis	Biological Methods	Cost–effective, and eco-friendly [63], [64], it uses biological agents or microorganisms, for example, bacteria, yeast, fungi, algal species, and plant extracts, as natural substrates for nanoparticle formation, eliminating the need for toxic chemicals and complex procedures [65].
	Sol–Gel Method	Involves sol formation, gelation, and drying, offering a scalable and versatile technique [66]. It enables the fabrication of unique nanostructures, including nanowires, nanorods, 3D nanostructures, and nanostructured metal oxides [66].
Physical Methods	Ball Milling	A mechanical technique that grinds materials in a rotating container with milling balls. It is relatively simple and effective for producing a range of NMs, including metal and ceramic NPs [64].
Chemical Methods	Chemical Reduction	Involves reducing metal ions in solution to form nanoparticles. It is widely used for synthesizing metal NPs and is easily scalable [64].

4.3 *Modular Hybrid Plasma Reactor (MHPR): toward scalable manufacturing*

MHPR is a possible breakthrough in cost–effective and scalable nanomaterial production. This technology allows multi–feedstock processing, has precise temperature control, and allows flexible scalability to meet evolving industrial needs [6], [67]. Although the initial capital expense of MHPR systems will probably be substantial, their potential for optimizing processes and making enormous energy savings makes them a cost–effective means for large–scale production of NMs [68].

4.4 *Cost structure and economic barriers*

Despite the latest improvements in sustainable manufacturing processes, the costly nature of NMs is still a significant bottleneck to their widespread application [9]. Their price is determined by many factors including purity, complexity of production, and particular application requirements. Gold NPs may be up to 1,600 times pricier than raw gold and silver NPs up to seven times more than the bulk equivalent [6]. These cost variations highlight the need for continued innovation in low–cost and scalable processes of nanomaterial manufacture.

The US Department of Energy [68] categorizes production processes into: a) Mechanical–physical processes (for example: Milling), which are energy-intensive, and b) Chemico–physical processes (for example: Liquid–phase and gas–phase synthesis), which increase production costs due to complex reaction systems.

The intended application of NMs to be employed also influences the pricing, with medical–grade materials for drug delivery would generally be cheaper than high–purity materials required for applications, particularly cancer diagnosis.

4.5 *Emerging scalable production pathways*

Emerging fabrication methods are being researched to address cost and sustainability concerns:

- Spark Discharge: This energy–efficient fabrication process synthesizes NMs via electrical discharges, saving energy while facilitating manufacturing [69].
- Electrochemical Nano–Imprinting: Based on the coin minting process, this method enables precise, scalable nanostructure production [70]. It is wafer–compatible, supports roll–to–roll production and lowers production costs dramatically.

With the integration of green synthesis, MHPR technology, and the new fabrication technologies, industries can lower the costs with negligible effects on nanomaterial production quality. Efficient use of energy, renewable feedstocks, and scalable processes will be crucial to making NMs economically viable for widespread industrial use.

5 Health and Environmental Risks

5.1 *Human toxicity and systemic health effects of nanoparticles*

Certain NMs, including AgNPs, ZnONPs, and TiO_2NPs, have been reported to interfere with endocrine signaling by mimicking hormonal activity or disrupting hormone regulation, potentially leading to endocrine imbalance [71]. These effects are of particular concern for susceptible populations, including children and pregnant women, due to increased vulnerability during critical developmental periods (Figure 2). Experimental studies have associated AgNPs and ZnONPs with disturbances in reproductive hormone regulation, while TiO_2NPs exposure has been linked to altered thyroid function, including an increased risk of thyroid dysfunction [71].

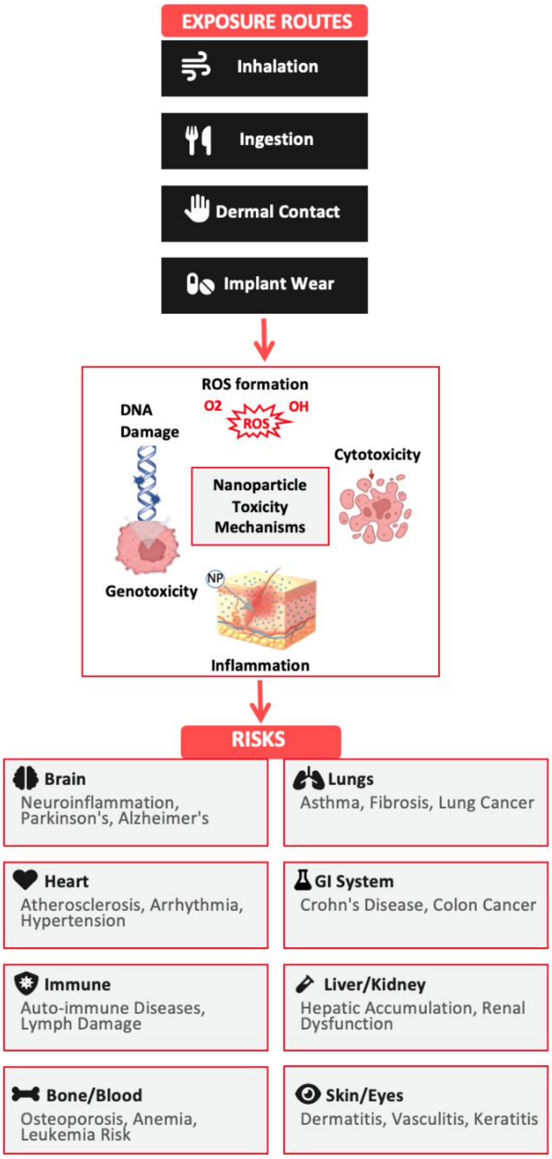

Figure 2: Health risks associated with nanoparticle exposure.

Beyond endocrine effects, NMs may modulate immune responses in a bidirectional manner, resulting in either immune activation or immunosuppression depending on particle composition, size, and exposure context. Carbon black and SiO_2NPs have been shown to induce inflammatory signaling pathways, potentially exacerbating infectious diseases, including tuberculosis, by amplifying the inflammatory burden.

Occupational exposure to NPs has also been associated with oxidative stress and immune dysregulation among exposed workers, suggesting systemic health risks under chronic exposure conditions [72].

Several NMs have demonstrated the ability to cross biological barriers, including the placental and blood–testis barriers, thereby enabling systemic distribution. Such translocation has been shown to induce oxidative stress, inflammation, and DNA damage, with potential consequences including reduced sperm count, ovarian impairment, and adverse fetal developmental outcomes. Animal studies implicate AgNPs, gold nanoparticles (AuNPs), and SiO_2NPs in various forms of reproductive toxicity, although interspecies differences and exposure levels limit direct extrapolation to human health risk [71].

Genotoxic effects have been particularly documented for certain metal nanoparticles, notably nickel (Ni) and chromium (Cr), which exhibit the capacity to induce DNA damage through reactive oxygen species (ROS) generation and direct interactions with genetic material. These mechanisms are well established in toxicological studies and are associated with an increased likelihood of carcinogenic outcomes under prolonged or high–dose exposure scenarios [73]. Cardiovascular effects have also been reported following NPs presence in the bloodstream, where inflammatory responses, endothelial dysfunction, and pro-thrombotic processes may collectively elevate the risk of cardiovascular disease [74].

Potential exposure pathways in the built environment include inhalation during material handling and processing, release during surface abrasion or weathering, and dispersion at the end of a building's lifecycle. Figure 2 shows how NPs generate ROS, trigger inflammation and produce multi–organ injury from lung fibrosis to neuro-degeneration, underscoring the need for strict exposure controls in nano–enabled construction.

Toxicological outcomes are strongly material– and context–dependent, and significant uncertainty persists regarding cumulative exposure levels and chronic health effects under realistic use conditions. In the absence of strong exposure quantification and effective mitigation strategies, the large–scale deployment of nanomaterials in occupied buildings warrants cautious evaluation.

Although NMs applications in the built environment are highly promising, their potential adverse effects underscore the need for comprehensive toxicological assessment (Figure 2). Continued research is required to clarify dominant toxic mechanisms and exposure pathways, alongside the implementation of strict safety measures. Particular attention should be given to vulnerable populations and to inhalation exposure in occupational settings, which remains one of the most critical and least controlled routes [73], [75].

5.2 *Environmental contamination and ecosystem disruption*

The environmental risk of NMs is an actual and complex one with various sources of contamination. Among the sources are the spreading of NMs by the wind, surface runoff, discharge of wastewater, and release of aerosols during the production of a material [76], [77]. After they reach water environments, NMs may pollute water bodies and have negative effects on the aquatic organisms. In this respect, the toxicity of AgNPs, TiO_2NPs, and ZnONPs to a number of aquatic organisms has been demonstrated [76], [78]. Likewise, soil ecosystems are affected by the contamination of NPs. Research shows that NMs have a capacity to alter microbial communities, which are essential for soil quality and plant growth [77], [79].

These particles change the soil structure by lowering the surface energy and increasing the water repellency, simultaneously increasing water conductivity and aggregate stability. The transformations that occur in the soil can affect its water cycle and the distribution of nutrients, thus impacting microbial populations in the rhizosphere and changing plant–microbe interactions [79].

Moreover, CNTs suspended in the air are also a significant factor in the degradation of urban air quality, mainly by leading to higher levels of ultrafine particulate matter [77]. Because of their extremely small size, these particles pose a serious threat to human health as they are able to penetrate very deep into the lungs and even penetrate the blood [80].

On top of that, the wrong treatments of products with NMs, namely concrete, coatings, and silica aerogels, not only pollute the environment but also cause serious health problems. NMs released from landfills can contaminate the soil and water sources around them. But the little that is known about the mechanisms of their release makes this a very worrying area [77]. As nanotechnology keeps expanding across industries, such environmental effects are projected to grow [81].

Environmental toxicity of NMs is based on several factors, including their size, morphology, chemical composition, and surface chemistry [80].

Released NPs can generate ROS, generating oxidative stress that leads to damage to cellular components, including lipids, proteins, and DNA [80], [82]. NMs can also disturb the immune system of organisms exposed to them, weakening their defense mechanisms against infection [80], [82].

5.3 *Nano–based remediation and mitigation pathways*

Nanotechnology holds great solutions to environmental remediation and pollution control through engineered NMs. These can effectively detoxify contaminants in various ecosystems, desorb heavy metals from water bodies, biodegrade organic pollutants in soil, and treat industrial effluent [83]–[85]. Amongst these, carbon–based NMs (CBNs). For instance, CNTs, quantum dots, and graphene have been found to have superior adsorption properties and thus are extremely effective in the regulation of diverse industrial waste forms [84].

For use in their safe and responsible environmental contexts, various measures have been used by scientists to reduce potential toxicity.

These include surface engineering of nanoparticle surfaces to inhibit harmful biological interactions, applying less toxic or inert substrates, incorporating chelating agents or antioxidants, and using green synthesis methods [86]. NMs, promising as they are, must be carefully handled due to their behavioral similarities to dangerous substances (e.g., asbestos fibers). It underlines how safety measures that are strictly followed are critical. Adequate ventilation at the workplace, the use of "personal protective equipment" and standardized cleaning procedures so that there are no accidental exposures have been suggested as safe practices [84], [87]–[89].

Good risk management is essential when it comes to the safe development of nanotechnology in the environmental industry. It entails thorough risk assessment, life cycle evaluation, and setting up strong regulatory frameworks to lessen the environmental and health-related effects of NMs [90], [91].

Besides that, different means of discarding, for instance thermal recycling and waste–to–energy burning, are being investigated so as to eliminate pollution of the environment by NMs. Scholars are also researching the use of NMs derived from waste and green production techniques to enhance the overall sustainability of nanomaterial manufacturing [92], [93]. Lastly, by combining innovative remediation processes with precautionary safety measures and eco–friendly production practices, nanotechnology can potentially usher in transformative changes in addressing global environmental requirements. Proper development and utilization of its benefits can be maximally achieved without an unintended increase in risks with it, leading towards a better, safer and sustainable future for environmental cleanup and pollution control.

6 Challenges and Future Directions

Utilization of nanotechnology for sustainable building and historic preservation for buildings holds both significant challenges and huge potential. Whereas it offers new solutions towards the enhancement of material performance, a few hurdles must be addressed in order to make its safe, efficient, and cost–effective deployment in the construction sector.

6.1 *Research & large–scale implementation barriers*

High R&D costs for specialized nanoscale equipment and materials constrain the scale and intensity of construction nanotechnology innovation. A limited pool of experts trained in both architectural design and nanotechnology further restricts interdisciplinary development. Long–term performance and risk profiles of NMs in construction remain poorly characterized; for instance, Al_2O_3NPs enhance concrete properties, but their effects on durability and structural safety over time are still uncertain [94]. This knowledge gap requires large-scale studies on environmental impacts, structural service life, and occupational health hazards of NMs in real construction conditions [95]

6.2 *Regulatory and standardization gaps*

The absence of dedicated testing standards and regulatory guidelines for NMs in construction limits consistent performance assessment, compliance oversight, and verification of the long–term stability of nano–enabled products. Clear and harmonized guidelines, together with sector–specific standards, are therefore essential to support safe nanoparticle application and to enhance public confidence and acceptance [96]. Regulatory frameworks should explicitly balance technological innovation with the protection of human health and the environment, ensuring that NMs meet defined performance expectations while reducing potential risks across their life cycle.

7 Towards a Sustainable and Resilient Built Environment

A sustainable and resilient built environment is unlikely to be achieved through isolated material innovations or incremental efficiency gains alone. Instead, the evidence points to the need for an integrated, lifecycle-oriented framework in which nanotechnology is embedded within established architectural and engineering practices and supported by coherent regulatory structures [60], [97]–[102]. Within this framework, nanotechnology functions as an enabling layer that enhances material efficiency, durability, and adaptability rather than replacing conventional construction systems.

In synthesis, the literature indicates that this integrated approach responds to two coupled pressures: long–term decarbonization aligned with climate-neutrality targets for 2050, and the increasing demand for buildings capable of maintaining performance under environmental, functional, and climatic uncertainty [103], [104]. The contribution of nanotechnology, therefore, lies less in isolated performance breakthroughs than in its capacity to support systemic transitions across material selection, building operation, and lifecycle management.

7.1 *Performance and energy*

At the material and building scale, nanotechnology contributes to sustainability primarily by improving performance at low material intensities, thereby reducing embodied impacts while maintaining structural reliability. Selected nano–additives and coatings enhance resistance to chemical attack, moisture ingress, and mechanical fatigue, extending component lifespan and limiting the need for resource– and carbon–intensive repair and replacement cycles [6]. Self–healing systems incorporating nano–capsules or nanofibers, reported largely at laboratory and pilot scales, provide an additional durability pathway by mitigating micro–scale damage accumulation and reducing maintenance–related emissions [60].

Operational energy consumption remains a critical determinant of environmental impact in buildings. Nano–enabled insulation systems and thermally responsive materials improve envelope efficiency and indoor environmental control [60], [105]. Empirical evidence from educational buildings indicates that, under the reported case–study conditions, the combined use of nano–aerogel insulation panels (Aeropan) and nano–PCMs in glazing systems can reduce energy consumption by approximately 11.8% while maintaining thermal comfort, as measured by the Predicted Mean Vote (PMV), even in demanding climatic contexts [60], [104]. These outcomes are consistent with European policy instruments, namely the EU Renovation Wave and the revised Energy Performance of Buildings Directive (EPBD), which establish Zero–Emission Buildings (ZEB) as a reference benchmark and address the built environment's substantial share of total energy use [6], [104], [106].

From a lifecycle perspective, these operational and durability gains must be assessed alongside production–stage impacts. Lifecycle Analysis (LCA) suggests that although some NMs, particularly CNTs, are energy–intensive to manufacture, their contribution to material reduction, extended service life, and improved operational efficiency can result in net carbon emission reductions reported to reach up to 30% in selected LCA scenarios [60].

7.2 *Safety and governance*

The integration of nanotechnology into the built environment introduces environmental and health uncertainties that require structured governance rather than ad hoc mitigation. NMs may be released from construction matrices through UV exposure, moisture cycling, or mechanical degradation, and certain synthetic NMs exhibit persistence due to limited microbial breakdown, raising concerns regarding accumulation in soils and groundwater [60]. These risks support the adoption of a safe–by–design approach grounded in standardized toxicity testing, exposure assessment, and end–of–life management frameworks, namely EU REACH and ISO/TS 80004 [60].

Responsible deployment therefore, depends on clearly articulated implementation pathways across material choice, system design, and lifecycle management. These pathways include the use of green NMs with reduced environmental burdens; smart building systems integrating nanosensors and responsive materials for adaptive energy management; nano–engineered coatings and additives to enhance durability; and conservation strategies based on compatible and reversible NMs for heritage structures [4]–[6], [107]. Integrated lifecycle assessments capturing durability, recyclability, and carbon impacts remain central, alongside sustained collaboration between nanotechnologists, architects, and engineers to align innovation with constructability and regulatory compliance [97], [101].

The contribution of nanotechnology can be further strengthened through convergence with digital systems. Embedded nanosensors can enable real–time Structural Health Monitoring (SHM), supporting predictive maintenance and improved resilience to extreme events [60]. When combined with AI–driven analytics, Digital Twins, and open building–performance databases, these systems can facilitate Whole Life Carbon (WLC) reporting and evidence–based policy implementation, consistent with the objectives of the EU Building Policy Tracker [60], [103].

Despite demonstrated potential, large–scale adoption remains constrained by cost barriers, fragmented regulatory environments, and uneven professional uptake [4]–[6]. Addressing these challenges will likely require coordinated governance, continued research [108]–[111], targeted economic incentives, and the systematic integration of nanotechnology into architectural education and professional training [112], [113].

8 Conclusion

This review synthesizes evidence indicating that nanotechnology can contribute to the sustainability and resilience of the built environment primarily through system-level effects rather than isolated material improvements. Its relevance emerges at the intersection of material efficiency, operational energy performance, durability, and lifecycle management, where cumulative impacts can outweigh localized performance gains.

Across the reviewed studies, nano-enabled solutions applied at low material dosages demonstrate the capacity to reduce embodied impacts, extend service life, and improve operational efficiency. However, these outcomes are neither automatic nor universally transferable. Their effectiveness depends on careful lifecycle evaluation, contextualized performance assessment, and alignment with architectural practice, regulatory frameworks, and policy objectives.

Environmental and health considerations associated with nanoparticle release, persistence, and end-of-life handling highlight the importance of precautionary governance. Safe-by-design strategies, supported by standardized testing, exposure assessment, and waste-management protocols, remain essential to ensuring that performance benefits are not offset by unintended risks.

The analysis further indicates that the value of nanotechnology is amplified when integrated with digital systems, namely Structural Health Monitoring, Digital Twins, and Whole Life Carbon accounting. When supported by interoperable data infrastructures and regulatory uptake, these tools can enhance performance transparency, predictive maintenance, and evidence-based decision-making across the building lifecycle.

At the same time, persistent barriers, including cost constraints, regulatory fragmentation, and skills gaps, limit large-scale implementation. Addressing these challenges will likely require coordinated advances across technical development, governance structures, professional training, and economic incentives.

Overall, nanotechnology is best understood as a strategic enabler rather than a standalone solution. When embedded within an integrated framework that combines materials science, building design, lifecycle assessment, and regulatory oversight, it can support transitions toward lower-carbon, more durable, and adaptable building systems, while maintaining environmental responsibility and societal accountability.

Author Contributions

D.B.: conceptualization, investigation, writing, reviewing and editing; S.B.: writing an original draft; D.B.: research design, data analysis; S.B.: data curation, writing-reviewing and editing; R.B.: writing, reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

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