Review Article

Nanomaterials' Application in Architectural Façades in Italy

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Abstract
Nanotechnology and nanomaterials are revolutionizing the construction industry by improving material's durability, strength, and performance. Nanomaterials have a direct impact on building's energy efficiency, façade aesthetics, urban attractiveness, urban pollution, and built heritage preservation. In this paper, it will be confirmed that nanomaterials are providing cutting-edge technical solutions for the European building stock by addressing current biodeterioration and weathering of buildings, reducing CO_2 emissions, and having a positive impact on the building sector as a whole, including structure, surface coatings, energy consumption, and COVID-19 outbreak. The methodology used is exploratory and descriptive, with two Italian case studies analysis thrown in for good mixed-methods analysis. The empirical analysis investigates the environmental health and economic benefits of deploying nanotechnology systems in Italian building facades. The objective of the research is to analyze the characteristics and functions of nanoparticles; demonstrating how nano-features can lower energy use, improve contextual urban quality, preserve architectural historical identity, mitigate coronavirus outbreaks, and eventually change the future design thinking process of architects. The paper's originality stems from its synoptic approach and holistic analysis of nanomaterials utilized in Italian façade structures.

Keywords: Post-COVID architecture, Urban quality, Urban attractiveness, Buildings restoration, Cultural heritage, Smart façade

1 Introduction

1.1 *Nanotechnology in Europe: An overview*

The concept of green nanotechnology in architecture emerged out of an imperative need for minimal resources and lower environmental impacts. Nanotechnology proved to be beneficial in terms of thermal properties [1], mechanical properties [2], [3], moisture behavior and self-cleaning effect [4], energy efficiency [5], improved air quality [6], and antiviral i.e. COVID-19, antibacterial, and antifungal activities [7].

The whole practice of architects is being transformed to achieve the goal of a Zero Carbon, stable, and healthy built environment. Given its steady widespread adoption in the construction sector, nanotechnology has rapidly gained popularity and raised several concerns regarding its urban quality, sustainability and energy-efficiency aspects. Nanocoating materials have a significant impact on the ultimate sustainability aspect of buildings. They have additional properties and advantages that allow them to outperform conventional coating materials.

The principles, characteristics, and applications of nanomaterials in the conservation and restoration of cultural heritage have been researched by a number of scholars [8], [9]. Nanomaterials have an important place in the building industry, according to Lee *et al.* [10], Mohajerani *et al.* [11], Olafusi *et al.* [12], Pacheco-Torgal and Jalali [13], and others. Authors like Rossetti [14], Losasso [15], and Mirabile [16] introduced advanced nanomaterials that can be used in Italy.

The United Nations' 2030 Agenda for Sustainable Development, which was adopted in 2015 by all

UN Member States, supports the 17th Sustainable Development Goals (SDGs), which aim to lead the world toward a more sustainable and resilient future [17]. These goals are embedded into the three pillars of sustainable development: Environmental, social, and economic. Additionally, UNESCO and ICOMOS have long considered biodeterioration and weathering of buildings and heritage monuments to be major concerns [18], [19]. In this regard, nanomaterials have unique physicochemical characteristics that make them appealing as sustainable and eco-friendly innovative technological solutions.

Major rules for energy performance in buildings entered into force on July 9, 2018, as part of the Clean Energy for All Europeans Package (CEP) Directive 2018/844/EU [20]. The proposed provisions aim to make future buildings more environmentally friendly and convenient while lowering energy usage. In Europe, the building industry accounts for roughly 40% of energy consumption and 36% of CO_2 emissions. Furthermore, nearly 35% of EU buildings are over 50 years old, and nearly 75% of EU homes have inefficient energy use [20]. Within this context, this paper will confirm how nanotechnology and nanomaterials will provide cutting-edge technical solutions in Italy by addressing the current biodeterioration problem and weathering of buildings, reducing CO_2 emissions, and having a positive impact on the building sector as a whole: from structure, surface coatings, to energy consumption. Future considerations and suggestions are also provided at the end.

1.2 *Urban environment and visual quality*

Cities have recently become aware of the concepts of “smart” and “sustainable” architecture, by developing smart strategies for more effectively using the city's resources and reducing the costs, energy consumption, and construction waste. The transformation into a sustainable city entails the development of technological components and their applications in building.

The identity of the city is a determinant of its attractiveness and a key criterion in the marketing process of tourist destinations [21]. Urbanism is the result of a socio-cultural reflection to enhance the livability of the space inside the city. If the architecture represents the positive space, then the collective space is nothing more than the negative space [21]–[23]; thus, the exterior buildings’ appearance and attractiveness considerably affect cities' urban visual quality [24]. Buildings are an integral part of European cultural heritage. Out of the 376 EU listed on the UNESCO database, Italy (including the Holy See) has 52 (14%) of the world's cultural built heritage and built sites [25], which is the highest percentage among other EU member states.

The cultural building asset of Italy is currently being negatively impacted [26], not only by earthquakes [27] but also by the following seven factors [28]–[30]:

1) Efflorescence: The migration of dissolved salts formed in or near the surface of a porous material forming a white chalky powder after water evaporation.

2) Erosive and abrasive effects: Crystallization of soluble salts trapped in pores causing brick/stone/concrete spalling.

3) High humidity concentration: Concrete's compressive strength reduces when the relative humidity level rises, resulting in a decrease in its durability. Mold, mildew, and bacteria thrive in moist settings, which is why moisture is so important.

4) Acid rain attack: Heavily polluted cities, volcanic eruptions, or forest fires can generate compounds like Sulfur Dioxide (SO_2) and Nitrogen Oxides (NO_x) can ascend high into the atmosphere and interact with water, oxygen, and other molecules to generate acid rain (pH scale is below 7), corrodes exposed materials, i.e. limestone, concrete, and metal, and accelerates the deterioration of paint and stone due to the acidic particles. Furthermore, it defaces the exteriors of buildings and monuments, increasing maintenance fees.

5) Mildew and algae: Grow on surfaces with high moisture content, these microorganisms have various negative consequences on one's health.

6) Freeze-thaw effect: Occurs when water seeps into pores or fractures, expands when frozen, and thereby enlarges the gaps by pressure. The cavity may dilate and rupture due to repetitive freeze-thaw cycles.

7) Salt burst and sulfate attack: Crystallization of soluble salts trapped in pores causing brick/stone/concrete spalling.

1.3 *Nearly-zero energy buildings*

Technology is a tool that is being used to address a variety of social-economical, health and environmental problems. The concept of nanotechnology in architecture refers to a technology that can resolve energy use problems and offer both safety and comfort without negatively impacting society or the environment. The drive toward energy-efficient building began in the 1990s, and since then, a slew of legislation, reforms, decrees, and directives have marked the way, culminating in the European directives on energy efficiency known as the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU.

One of the major innovations introduced is the Nearly Zero Energy Buildings (nZEB) standard, intended for all architectural constructions with “super” energy efficiency to nearly zero energy consumption, including green local (or nearby) produced energy. Buildings in which the balance between consumed and produced energy is close to zero are considered as nZEB. CasaClima energy efficiency certification, Passivhaus standard, and LEED (Leadership in Energy and Environmental Design) green building certification are constructions with nearly zero energy requirements for heating, cooling, lighting, and hot water production.

The German Passivhaus, the Italian CasaClima, and the American LEED have oriented themselves towards “near zero”, requiring the building not to exceed certain limits of kWh/m^2/year. For example, Passivhaus requirements/standards for non-residential buildings in cool, temperate climates [31] are shown in Figure 1.

The directive lays out a detailed prescriptive framework that covers everything from defining the minimum requirements for each building component to defining financial instrumentation.

The latest Directive 2018/844/EU amending the Energy Efficiency of Buildings Directive 2010/31/EU and 2012/27/EU requires all real estate assets, from new buildings to existing or renovated public and private buildings, to improve their energy performance [20]. The performance is about the technical systems of the building, i.e., about auto-producing almost all the required energy for heating, cooling, and hot water [20]. Following the trend of the building sector, which has seen the “new” construction significantly reduced in recent years, the revision of the Directive 2018/844/EU focuses on enhancing the energy efficiency of new and old buildings, national strategies for buildings renovation, and development of charging infrastructure for electric vehicles, to be implemented by 2050.

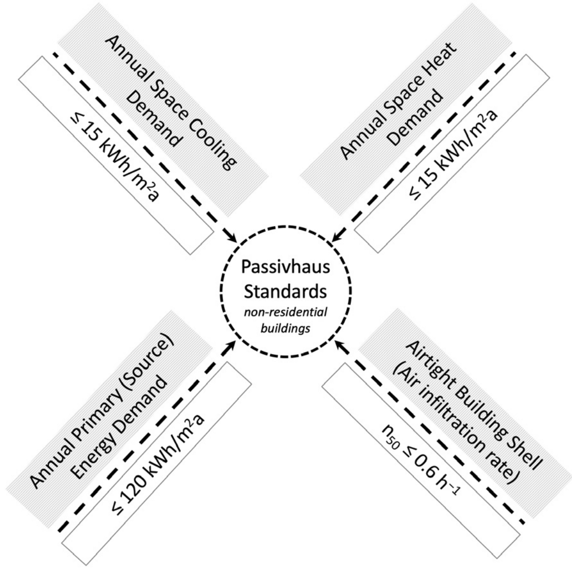

Figure 1: Passivhaus requirements/standard for non-residential buildings.

1.4 *Research objective*

The empirical analysis described in this research investigates the environmental health and economic benefits of deploying nanotechnology systems in the architectural façades. The analysis delves beyond identifying benefits in terms of monetary gains to consider underlying environmental advantages, such as preserving the Italian cultural built heritage in light of the smart sustainable paradigm. Indeed, the objective of the research is to analyze nanomaterials’ functions, characteristics, and demonstrate how nano-features help in reducing energy consumption, in enhancing urban quality, and in mitigating coronavirus outbreak.

2 Building Envelope and Energy Efficiency

From March to October, sunlight shining through transparent building surfaces creates an uncomfortable indoor microclimate due to the greenhouse effect, even if only for a few hours (depending on geographic location). The electromagnetic wave from sunshine crosses these transparent surfaces through radiation, turning infrared rays (IR) into heat. Consequently, unsustainable and expensive air conditioning (cooling) systems are often indispensable.

Windows and other transparent surface nanocoatings, such as metal oxide engineered nanoparticles (MONPs), block IR rays up to 90%, saving approximately 30% on air conditioning costs (Table 1). The nanocoating can achieve up to 100% of glass transparency and block up to 99.9% of UV radiations (Table 1). As a result, they have become one of the most efficient solar input control technologies [5], [33].

Table 1: Glass solar control

Specification	Percentage	Reference
Costs Reduction	from 20 to 30%	[5], [32], [33]
IR Rays Reduction	from 70 to 90%	[32]
UV Rays Reduction	99.9%	
Glass Transparency	100%	

Heat loss and gain in buildings are mainly due to the weakness of the building envelope. The heated or cooled air leaks are caused by ineffective design/installation of walls, doors, windows, roofs or ceilings, and basements or foundations [34]–[36], air leakage i.e. holes, gaps, temperature differences, and R-value [34], [37], flue [38], air renewal and thermal bridges.

Climate, location, and orientation can also affect considerably the energy efficiency of buildings. In certain climates, energy for lighting and space air conditioning can reach 60% of the total energy consumption [39]. Summer performances and passive cooling in buildings are linked to energy efficiency in hot climates. Italian areas have more varied climates: protection from the summer heat, and energy saving during the winter, both have varying degrees of significance depending on the season. The key factor in southern and central Italy is climate management during the summer months when overheating can be avoided. The energy needed to cool the buildings is likely greater than the energy required to heat them [40].

Nano-insulating layers applied on exterior walls can reduce approximately 45% of energy demand [41]. According to paint producers, Barozzi Group [42] and Syneffex [43], a treated building (roof, walls, and glass windows) with nanotechnology-based coatings can achieve up to 40–45% of less energy consumption. This percentage may increase if indoor and outdoor surfaces are treated at the same time [41]. Barozzi Group [44] reported that heat-reflecting façade paints may decrease the energy demand by 30%. Heat-reflective nanotechnology-based paints and nanocoatings not only reduce the Urban Heat Island (UHI), but also reduce surface cracks and water infiltration.

Engineered nanomaterials, nano-coatings, and nano-paints reduce energy consumption in terms of heating and cooling [1], [45]–[48]. Hincapié *et al.* [46], reported that about 63% of European industrial paint producers had shown improvement or gradual improvement of their ENs paints/coats façade use over the conventional or traditional paints.

2.1 *Nanomaterials for building's façade*

Titanium dioxide (TiO_2) nanoparticles (NPs) and carbon nanotubes (CNTs) are two nano-sized materials that stand out in their applications to building materials. The first NP is used for breaking down pollutants and then wiping them off with rainwater on everything from asphalt to glass, whilst the latter NP is used for stabilizing and controlling concrete due to its exceptional strength features.

In the presence of UV radiation, oxygen or moisture, TiO_2NPs with their photocatalytic property can degrade the organic/inorganic pollutants and microorganisms deposited on the exterior surface or façade [49]. When photocatalytic TiO_2 is used, superhydrophobic surfaces are created. On the other hand, the lotus effect suggests that the dirt on the coated surface will wash away during a rainy day, (Figure 2). The contact surface for dirt particles and water is extremely small due to the micro-structured surface, raindrops immediately bead, dragging dirt particles with them that only slightly adhere to the highly hydrophobic surface. This allows the façade to fulfill a primary water management function. Dew, rain, and fog do not adhere, but bead and flow. Algae and mold have no nutritional basis so the façade remains protected and clean.

In Milan (Italy), a TiO_2 coating of 7,000 m^2 of road resulted in a 60% reduction of nitrous oxides [50]. The use of NPs, such as SiO_2, in concrete results in constructions that are stronger, lighter, and have more flexibility, tensile, and compressive strength than steel. This is an incentive to improve building sustainability while cutting maintenance costs.

The antibacterial/antimicrobial properties of some nanomaterials make it possible to envision buildings with a positive impact on human health, especially during this global pandemic. Antimicrobial-

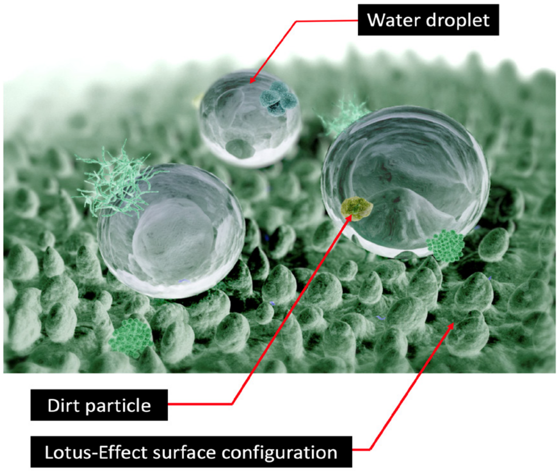

Figure 2: A microscopic view of a Lotus-Effect. Adapted from: William Thielicke, distributed under a CC BY-SA 4.0 license.

coated surfaces protect users by ensuring a healthy and clean atmosphere that prevents the transmission of viruses and bacteria. Bacteria, parasites, fungi, mites, respiratory diseases, allergic rhinitis and asthma, environmental reactions, chemical interactions, and ozone generation are examples of negative health effects [51].

Once the building nanocoating is applied, it may dry within a few minutes and be ready for use in just about 3–6 h and fully cured after a day at the maximum [52], [53]. This coating continues to be effective for approximately five months [52] or up to 10 to 20 years [52]–[54], depending on the applicable surface, coating brand, weather, and the number of recoating. This nanocoating technique has been shown to protect against *Escherichia coli* (*E. coli*) [55], Methicillin-resistant *Staphylococcus aureus* (MRSA) [55], [56], and Coronavirus (COVID-19) SARS-CoV-2 [57], *Escherichia coli* and *Staphylococcus aureus* [58], among other Healthcare-Associated Infections (HCAIs) [59].

For example, the use of AgNPs is useful for combating nosocomial diseases and bacteria in healthcare facilities. Used in the manufacture of switches, floor coatings, or ventilation circuits, makes buildings healthier while reducing maintenance needs. The most important NPs used in constructions and various architectural façades materials (Figure 3) are listed in Table 2, along with their technical benefits. Different NPs are often mixed to reach a combined desired benefit [58], [68], [87].

Table 2: Common engineered nanoparticles used in buildings

Engineered Nanoparticles	Technical Merits	Reference
Zinc oxide *ZnO*	Self-cleaning; Antibacterial; UV-protection	[49], [60]–[63]
Titanium dioxide TiO_2	UV radiation protection; Photocatalytic activity (organic and inorganic pollutants and microorganisms degrading); Abrasion resistance "concrete"; Self-cleaning; Antimicrobial; Water repellent; Flame retardant; IR reflection	[46], [49], [60], [64]–[72]
Silicon dioxide SiO_2	Ultrahigh-performance concrete (UHPC): strength, performance, and durability improvement; Concrete Strength and water permeability enhancement; Concrete workability enhancement; Self-healing "concrete" effect; Water repellent; Dirt repellent (easy to clean); Scratch resistant; Improved colorability; Flame retardant; Nano-filler	[46], [72]–[74]
Aluminium oxide Al_2O_3	Abrasion (scratch) resistance and anticorrosion; Flame retardant	[46], [75]
Silver Ag	Antibacterial, antivirus, and antifungal features	[72], [76]
Cerium(IV) oxide CeO_2	UV-aging resistance; Anticorrosive and self-cleaning effects	[46], [77]
Magnesium oxide *MgO*	Antibacterial agent; Compressive strength improvement and autogenous shrinkage reduction in cement-based materials; Antibiofilm	[46], [78]–[80]
Calcium hydroxide $Ca(OH)_2$	Cement nanofiller	[81], [82]
Iron oxide Fe_2O_3/Fe_3O_4	Compressive and flexural strengths of cementitious composites (microstructural properties improvement: reduced porosity/increased density)	[83], [84]
Nanoclays *NC*	Hydrophilic; Scratch resistant; Flame retardant; Compressive, flexural, and tensile strengths of cement; Corrosion; Gas barrier	[46], [49], [83], [85], [86]

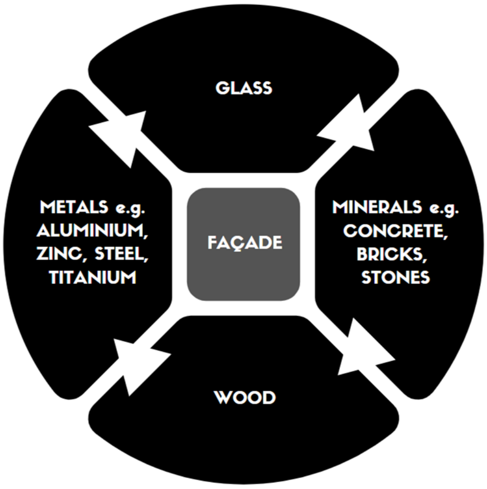

Figure 3: Main construction materials for façades.

The built heritage sites are threatened by both microbiological attacks and unnatural deposition of pollutants carried by rainwater or atmospheric gases. The main components of pollutants are soot, tar, and other impurities generated by transportation, combustion of fossil fuels in heat and power generation, and industrial production in urban agglomerations and traffic-congested areas [88]. Another widespread and expensive maintenance concern in European cities is graffiti sprayers [89]–[92].

3 Case Studies

In the last two decades, the use of NPs in monuments and cultural heritage restoration has been proven. It can promote the cleaning of polluted surfaces, and operate as a shield from the harmful effects of UV radiation. Nanotechnology has become increasingly relevant in the field of cultural heritage restoration.

3.1 *Villa Morosini in Polesella*

The 16th Century Venetian Morosini villa in Polesella, Province of Rovigo, underwent substantial repairs between 2001 and 2004 as a result of years of neglect and deterioration. However, only a few years after the renovation was finished, the plaster and stone on the façades began to show signs of deterioration. This was primarily because of atmospheric conditions, particularly the local humidity and fog, as well as insects, molds, and lichens that thrive in agricultural and tree-lined areas.

The top main floor's exterior surface was covered with SiO_2NPs water-based solution as part of a second exterior façade restoration in 2014. While, the bottom portion of the noble floor, which extended from the ground to the attic, was treated with a conventional siloxane water repellent.

Measurements were made two years following the coating application [93]:

1) Water absorption: Tests using the UNI Normal 44/93 method (TQC Karsten Tube Penetration Test) revealed that the surface treated with SiO_2NPs had not absorbed anything after 30 min, whereas the surface treated with siloxane water repellent had absorbed 3 mL of water.

2) Colorimetric measurement variations: The SiO_2NPs coated surface showed no visible color variations. The part treated with siloxane protection had lower brightness values than the part treated with nanotechnology, according to the *in situ* colorimetric measurements.

3) Scanning electron microscope (SEM): Microscopic images of a plaster sample from Villa Morosini revealed that the plaster surface was primarily made up of carbonate particles. The absence of a film-forming covering proves that the nanomaterial layer had no effect on the plaster's ability to breathe.

3.2 *Pisa Duomo in Pisa*

The European Nano-Cathedral project, from 2015 to 2018, planned to use nanomaterials to regenerate historical artifacts from the Europe's most significant cathedrals. Five representative cathedrals of European cultural heritage were selected for the experiment [94]. The cathedrals selection was based on climatic conditions and lithotypes: marble, sandstones, and limestones. The *in situ* Nano-Cathedral Project was a stone consolidation and protective nanomaterials application on natural stone materials. The project went through a thorough façade humidity content analysis, surface inhomogeneities induced by previous reconstruction measures (investigated using thermographic and multispectral techniques), microclimatic analysis, colorimetric investigations, materials characterization and their decay forms, and biodeteriogens.

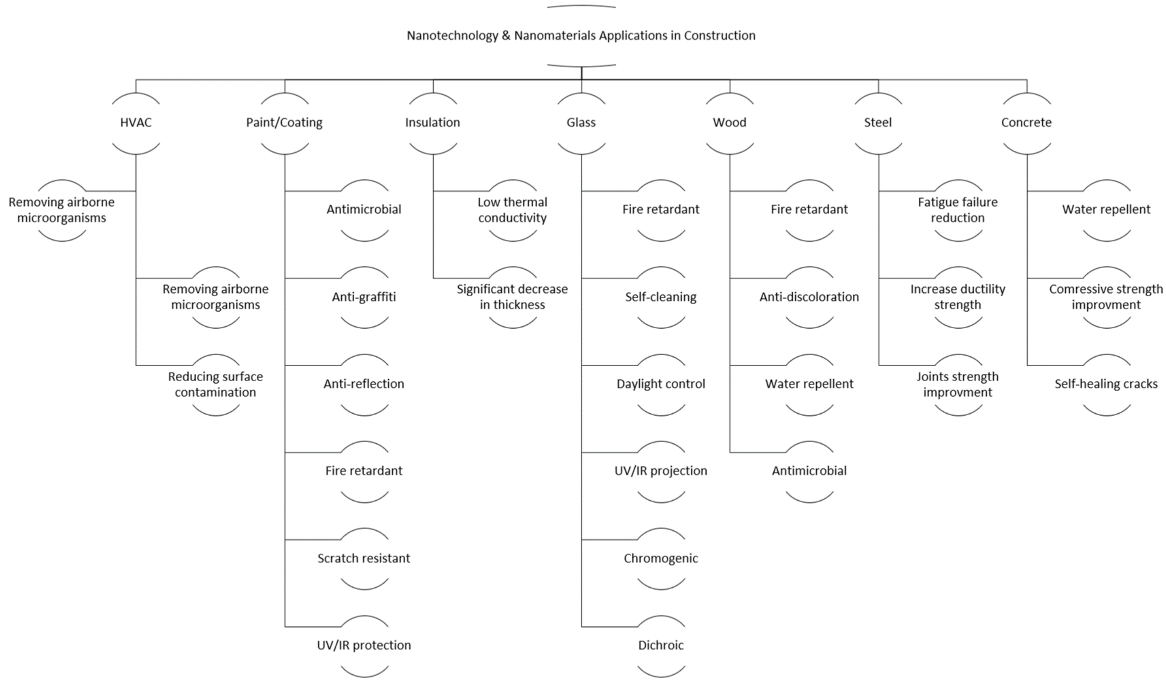

Figure 4: The multiplicity of the nano-structured products used and applied in the construction sector.

Nanomaterials are able to achieve high penetration depth into the microstructure of stones while preserving them. The efficacy is largely determined by the material's pore system and moisture content. $CaCO_3$NPs were used as an innovative solution for the 11th Century Pisa Cathedral restoration instead of the conventional restoration techniques like lasers. The porosity allows NPs to infiltrate the stone and to bridge the cracks, whilst still ensuring perspiration of the treated stone to maintain its efficiency [81].

After treating the stone with the consolidating substance $Ca(OH)_2$NPs (with an alcohol solvent e.g. propanol), $CaCO_3$ crystalline network is formed within inner cracks and fissures as alcohol evaporates. The new $CaCO_3$ crystals act as “micro-grouting” consolidating damaged parts and improving their cohesion and mechanical properties [81]. $CaCO_3$ crystals must have the same chemical nature and morphology as the treated stone so the physical-mechanical processes that occur over time within the treated stone do not damage the stone substrate layers. By selecting unique preparation conditions from the matrix, a) alcohols, b) time, and c) shaking speed and the binary ratio of water-alcohol mixture, the precipitated $CaCO_3$ crystalline polymorph, and morphology, can be controlled [95]. The nano-cathedral project provided the external marble surface aging of Pisa Duomo a better material stability, water repellency, and biofilm growth prevention. Flaking plaster grains and pigments on surfaces due to salt efflorescences can be fixed by $CaCO_3$ crystalline [96].

4 Advantages and Drawbacks of Nanomaterials

4.1 *Multi-functionality of the nano-structured products*

Culture as an architectural design generator is based on the idea that cultural heritage protection is essential for the continued transmission of a built and personal identity, even if through a mediator, such as nanocoating because it provides the visual transformations as required.

Nanotechnology provides long-lasting, multifunctional façade protection for the existing building stock and cultural built heritage (Figure 4). With the use of nano-coatings, which are normally compatible with standard building materials like concrete, red bricks, and others, this cutting-edge technology can quickly develop vapor-permeable protective coatings on the outer surfaces of structures. Street graffiti sprayers will be unable to make permanent scribbles if a nano-coating is applied to the building envelope so their designs will be quickly dissolved with only water, causing no damage to the surface. According to references in Table 2, applying a thin layer of nano-coating to wood, stone, rock, glass, or any other type of surface ensures that this protective and antibacterial coating will give additional benefits to vertical surfaces. This includes among others in Figure 4:

- Building and urban attractiveness.
- Building envelope durability and strength.
- High performance of building materials: concrete, steel, and glass.
- Long-term protection against organic pollutants and degrading effects from UV radiation.
- Self-cleaning cleaning surface/façade with sunlight-activated TiO_2 and hydrophilicity properties,
- Anti-graffiti/sticker.
- Removability and recoverability: surface damage-free.
- Costs reduction in vertical surface maintenance.
- Life-span from 10 to 20 years depending on coating/paint brand and quality.
- Air purification.

Nanotechnology will potentially favor the construction industry, as it has already done in the areas of concrete, steel, and glass. Concrete is heavier, more robust, and simpler to install than steel, which is harder. Increased strength and durability are also part of the effort to reduce the environmental footprint of the built environment through resource efficiency.

Furthermore, there is not much evidence on the usage of anti-viral NPs and self-disinfection surfaces in Italian public places or structures. Although its scientific advantage in preventing the spread of coronaviruses has been proved [97]–[102].

As indicated in Figure 5, antibacterial nanocoated surfaces may be divided into three categories: a) surfaces that prevent bacteria adhesion, b) surfaces that kill bacteria on its contact, and c) surfaces that leach antibacterial agents. antibacterial nanocoated surfaces are in use for verified benefits in concrete, glass/wall coating, paint, and other applications. Nonetheless, only a few public buildings in Northern Italy have gone above and beyond: Teuliè Military School (Milan), Istituto Schiaparelli-Gramsci (Milan),

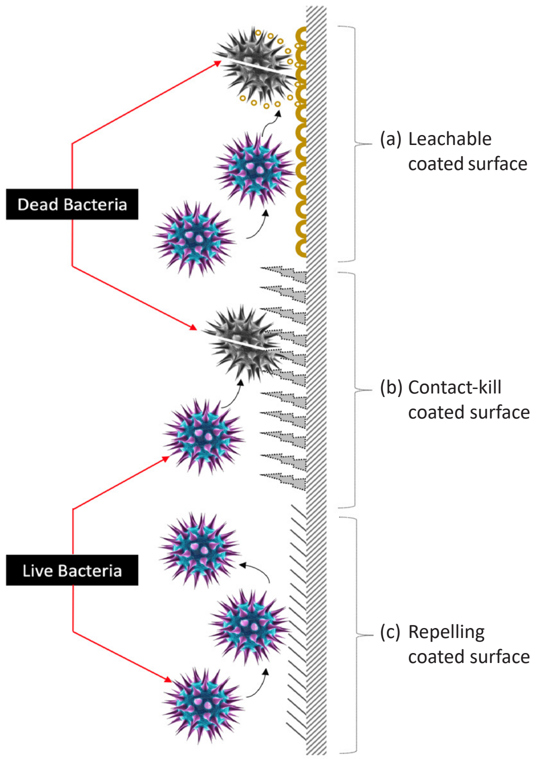

Figure 5: Antibacterial surfaces are classified as (a) Leaching antibacterial agents, (b) Contact-kill bacteria, and (c) Prevent bacteria adhesion.

Istituto San Carlo (Milan), Istituto Primo Levi School (Montebelluna - TV), Primary school "Virtus et labor" and kindergarten "Bambi" (Martellago-VE), Desio Bank (Milan) and numerous supermarkets, shops, restaurants and cafeterias across North Italy [103].

In all mentioned initiative, ready-to-use high-tech nano-air-filter devices were installed to improve air quality, and combat COVID-19 spreading. People spend approximately 90% of their time indoors [51], and this figure has increased to 100% last year due to home isolation requirements imposed by governments around the world to reduce the COVID-19 spread [104]. Most respiratory illnesses have been associated with poor air ventilation, as well as indoor relative humidity (RH) [51]. It is important to point out that these nano-air filters are ready-to-use high-tech devices that can be mounted almost anywhere in a building or room without requiring any design or technical work or alteration. Coating surfaces, on the other hand, necessitates further work and effort.

4.2 *Life cycle cost*

Liu and Runion [105] have developed an *in situ* anti-scratch and anti-corrosion spray system using NPs to be applied to steel structures. This nanocoating protected infrastructures from natural weathering and enhanced their structural capacity [105], [106]. The nanocoating system developed by FHWA researchers is durable and cost-effective and has a significant reduction in the annual infrastructure management costs (labor, maintenance, and rehabilitation) and time [106], [107]. As shown in Table 1, nanocoatings can achieve about 30% of energy consumption reduction, the initial investment can be amortized after a few years. Improvements in life-cycle performance and maintenance costs can have a significant financial impact on the construction industry.

4.3 *Nanomaterials drawbacks*

4.3.1 Nanotoxicity

NPs have already sparked concerns about their possible toxicity [108]. Based on various studies, NPs can induce symptoms similar to those produced by asbestos fibers. Grassian *et al.* [109] investigated the effects of inhaling TiO_2 particles, with main particles' sizes of 5 and 21 nm, detecting lung inflammation at different concentrations 5 nm (5, 20, 30 μg/50 μL) and 21 nm (25, 100, and 150 μg/50 μL). If NPs are discharged into the environment, they are said to have a possible harmful impact on soil and water [110].

Even though nanotechnology is used in a variety of applications, including dentistry, medical treatments, cosmetics, paints, toothpaste, sunscreens, and confectionery, the effects of nanotechnology on human health are related to the potential side effects of its use [111]. Since nanotechnology is such a new field, there is a lot of debate about whether it would be beneficial or harmful to human health.

Nanotechnology's health effects can be broken down into two categories [112]: side effects for medical applications in the treatment of diseases, and possible health hazards associated with nanomaterial exposure. Scientists' opinions are divergent and contradictory [113]; obviously, more research is required to discover the nanomaterial impact on health [114]. However, the results presented by Wu *et al.* [115] are the most conclusive at present. In their research, they investigated the health hazards of 14 nanotechnology work plants for a period of four years among workers handling nanomaterials. Because of the utilization of wet procedures and liquid suspensions in production plants, nanoparticle exposure levels were drastically lowered. With the exception of an increase in antioxidant enzymes, Wu *et al.* research found no evidence of potential harmful health effects among nanomaterials handling staff at current working exposure levels. Obviously, manipulating and handling of NPs powders requires safety, precautions, and industrial hygiene for human exposure and environmental emissions control.

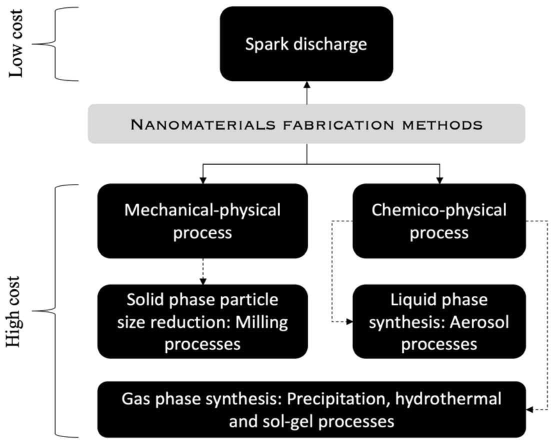

Figure 6: Nanomaterials manufacture methods.

4.3.2 High processing costs

Pacheco-Torgal and Jalali [13] documented that NPs are not cost-effective, which prevents their commercial expansion and use in architecture. NPs are available in different sizes, shapes and material content purity for diverse applications, such as research, medicine, engineering, and industry. NPs are produced according to three different and non-cost-effective methods [116], [117] (Figure 6).

For example, currently, 100 grams of solid raw silver with 99.99% purity costs about $100 while 100 grams of colorless and transparent AgNPs powder (2.200 ppm with 2 nm size) price is about $130. The processing and manufacturing of raw silver metal into nanoscale could raise its price to almost 7 times; gold NPs could reach 1,600 times more than the original raw material.

According to Rane *et al.* [118] "Spark Discharge" is a promising low-cost nanofabrication method (Figure 6). Consequently, cost-efficient and sustainable large-scale nanofabrication methods could produce low-cost NPs, thus, facilitating their commercialization and encouraging their use by architects and engineers.

5 Conclusions

Nanomaterials are revolutionizing construction materials by enhancing their performance and functions, and architectural design by affecting energy efficiency, façade aesthetics, urban quality, economy, and built heritage preservation. With the use of nanotechnology, architects can find other solutions to existing technical and/or architectural systems, such as solar panels or shading devices. After determining the most difficult components of each case study and developing a cost-effective coating for each façade structure, architects can create interventions to raise the caliber of nanomaterials. The epidemic has forced many building businesses in Italy and around the world to incorporate more nano-solutions, and architects are realizing the value of TiO_2NPs and AgNPs. Coronavirus erased all questions about NPs' ability to reduce energy consumption and heat loss. Fighting the infection requires immediate nanotechnology solutions. COVID-19 is encouraging construction sectors to use nanotechnology, which clarifies the future of smart buildings.

6 Recommendations

Future research is advised to analyze more the structure and morphology of nanomaterials used in Italy facade buildings, which can be significantly influenced by several reaction parameters, including humidity, wind, temperature and therefore, these should be optimized to produce a particular desired result. Similarly, more evidence is needed on the use of the anti-viral NPs and self-disinfection surfaces in Italian public places or structures. Aside from this, specialized characterization approaches should be applied for good implications and properties analysis. Before employing these materials for any applications, it is more vital than ever to consider nanomaterials effectiveness, particularly in the case of materials that can be used to consolidate, sandstones, limestones, marble, tuff, plasters, stuccos, and murals.

Conflicts of Interest

The author declares no conflict of interest.

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