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REVIEW ARTICLE

Investigation and Application of Nanomaterials in Sustainable Architecture

*Mohammadreza Hajian *,1, Hossein Hajian [2], Sahar Nouri [3], Afsaneh Barzin[4]*

1 *M.A. in Architectural Technology, College of Architecture, Faculty of Fine Arts, University of Tehran, Tehran, Iran*

2 *M.A. in Architectural Technology, College of Architecture, Faculty of Fine Arts, University of Tehran, Tehran, Iran*

3 *M.A. Student in Architecture and Energy, Faculty of Architecture and Urbanism, University of Art, Tehran, Iran*

4 *Department M.A. Student in Architecture and Energy, School of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran*

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ABSTRACT

The review article seeks to highlight current developments in the investigation of nanotechnology in sustainable architecture. Nanotechnologies play an important role in architectural design. In fact, building materials combined with nanotechnology developed smaller, with work better than current materials. Some developments in the application of nanotechnology in sustainable architecture include improving the durability and strength of concrete, and producing self-cleaning surfaces, glass, and thermal and moisture nano-insulation materials. Any alteration at the nanoscopic level of concrete, ceramic, glass and surfaces and its constituent influences its behavior, including its strength, durability and self-cleaning characteristics. In fact, nanotechnology further influences architecture and design and even design ideas in the world by introducing new materials and how to use energy. Using nanotechnology-produced materials correctly achieves sustainable architecture. We should also consider the unforeseen consequences of developing this technology.

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*Corresponding Author Email: *hajian.mr@ut.ac.ir*

1. Introduction

In recent years, various technologies have been applied to generate more comfort, security and cost savings, particularly in the consumption of energy resources. Nanotechnology is one of the emerging technologies with a very bright future, and its scope of impact is so broad that it is believed this technology could influence most aspects of future human life [1]. It is very important to be suitable for this phenomenon and to have sufficient knowledge of different fields of its applications. In this technology, by synthesizing materials at the nanometer scale, it is possible to control the intrinsic properties of materials, including chemical composition and melting temperature. Significant advances in various fields from engineering to medicine as well as the provision of suitable materials and heating and cooling equipment have become possible through this science [2].

Today, sustainable architecture in all relevant fields is one of the current issues in the field of architecture worldwide, in which nanotechnology can play a significant role, especially through building materials and consumables [3]. In fact, the role of this technology lies in producing materials that are stronger, lighter, and cheaper than current ones, as well as making materials more resistant to climate change effects such as acid rain, corrosion from chemical reactions, cold, and heat.

Antibacterial and self-cleaning nanoceramics and coatings used as glazes are very effective in reinforcing surfaces. Thin, insulated glass with very high resistance and weather adaptability; highly flexible, lightweight, and strong concrete that also insulates against moisture while allowing natural light transmission; and corrosion-resistant steels are just a few examples of how nanotechnology is reshaping materials in architecture.

The application of nanoparticles, especially titanium dioxide (TiO_2) and carbon nanotubes (CNTs), increases the mechanical properties of structural components. They repel water and minimize dirt absorption, making the facade resistant to UV damage. These coatings cover surfaces such as cement, brick, pottery, ordinary stone, tile, marble, wood, ceramic, glass, steel and concrete. Construction of reinforced concrete, self-repairing, self-cleaning, self-cleaning glass, fire-resistant and energy-controlling materials result in energy savings. Hospitals, among others, benefit from nanotechnology in the construction industry by achieving long-lasting structures, bacterial-free environments, and surfaces that are clean and resistant to degradation.

In this review article, we define the recent applications of different nanomaterials that impact aspects of aspects of sustainable architecture. Sections 2, 3 and 4 discuss the definition of nanomaterials, their types, and the role of nanotechnology in architecture. Then the review focuses on the applications of applications of nanomaterials in sustainable architecture (Section 5 and its subsections). Finally, Section 6 draws conclusions on the current state-of-the-art in the field, and future direction.

2. What are nanomaterials?

Nanotechnology implied as the technology that deals with the synthesis of materials measured from 1 to 100 nanometers. Nano is neither a substance nor an object, but simply a scale. Nanomaterials are materials that have at least one of their dimensions within the 1 to 100 nm range. Reducing particle size to the nanoscale leads to significant changes in their physical and chemical properties [4].

The history of nanoparticles dates back to many years ago. Their first use was in Chinese glazes. In a Roman cup called the Licergus Cup, gold nanoparticles were used to create different colors of the cup according to the way the light radiated. The concept of nanotechnology was first introduced in 1959 by Richard Feynman, while experts such as Peter Edon later explored its application in architecture [5].

3. Application of Nanotechnology

Nanotechnology has changed the lives of human society. Many fields of knowledge and achievement now incorporate this emerging technology, and researchers have produced significant results. This technology, along with two other major developments in genetics and information technology will mark the fourth wave of the industrial revolution. Over the next decade, the superiority of processes will depend on the continued evolution of nanotechnology, a phenomenon now integral to all scientific trends. Nanotechnology is another step towards developing powerful tools for building metropolises and anti-gravity halls. Nanotechnology has additional applications in the pharmaceutical and medicinal industries alike delivery systems. After particle sizes are wont to nanometer, the possessions affected through this decrease are their response to light. This outcome managed the creation of nanoclass with significant applications in optoelecteric manufacturing [6, 7]. Table 1 lists various uses of nanotechnology in different fields.

The applications of nanotechnology in civil engineering include the use of nanoscale additives in drilling fluids to increase extraction from reservoirs; the development of catalysts for the gas and petrochemical industries; the production of nanocoatings that are resistant to corrosion, abrasion, and heat to enhance energy efficiency; the fabrication of nanosensors; and the reduction of pollutants, along with advancements in related technologies [8].

4. Types of nanomaterials

Materials with at least one dimension below one micron but larger than one nanometer qualify as nanomaterials [4]. The most classification of nanomaterial is made according to their dimension, as zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D), as shown in Figure 1. We can divide different materials based on their structure, properties, applications, and dimensions. Nanomaterial classification based on their dimensions is one of the most interesting divisions. These four types of nanostructures have significant differences both in terms of synthesis and production methods, as well as in terms of properties and applications [13]. Electrical, optical, and magnetic properties of these nanomaterials are very different and, as a result, each of them will have unique applications [14].

1D and 2D nanostructures show higher electrochemical properties than 0D nanostructures. As shown in Figure 2, 1D and 2D nanostructures have a larger surface area than 0D nanoparticle. Active materials with 1D or 2D nanostructures show various exclusive appeal, and they have been widely studied in order to high-performing electrodes in energy storage and conversion systems. While 2D nanomaterials have great surface areas. 1D nanomaterials, although having relatively smaller surface [15].

Table 1. Application of nanomaterials in different fields

Applications	Description	Ref
medicinal and pharmaceutical	• Production of biosensor systems for the detection of diseases and analytes • Application in drug and gene delivery • Production of artificial tissues compatible with the body • Better health care using nanometer equipment inside the body	[4, 9]
Environment	• Decreased consumption of materials and energy • Production of solar energy	[10]
Agriculture and Food	• Application in fertilizer compounds by nanoscale coatings, or nanomaterials	[8]
Civil engineering and information technology	• Potential for faster and smaller computers with greater memories than current technologies	[11]
Architecture	• A great effect on construction materials and their properties • Reduce the high costs of construction and maintenance of structures	[12]

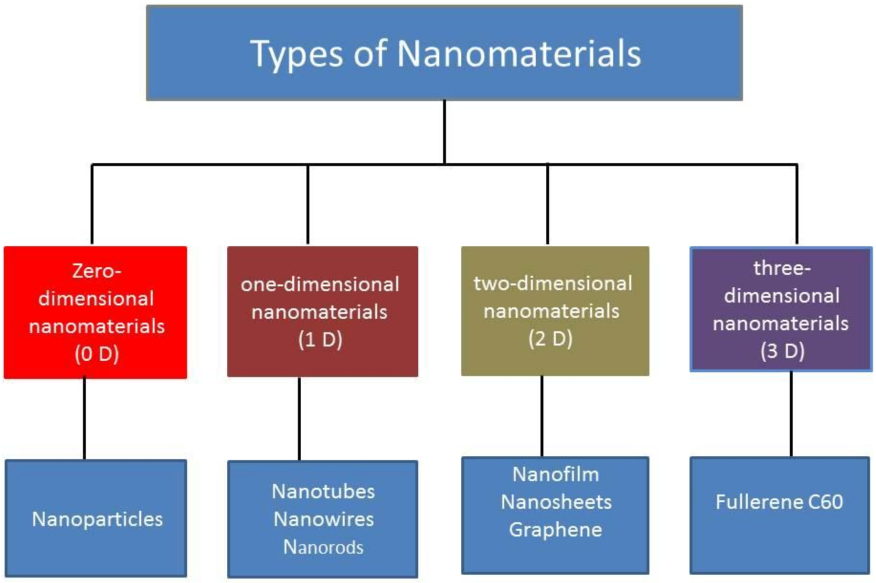

Figure 1. The overview of different nanomaterials in this article

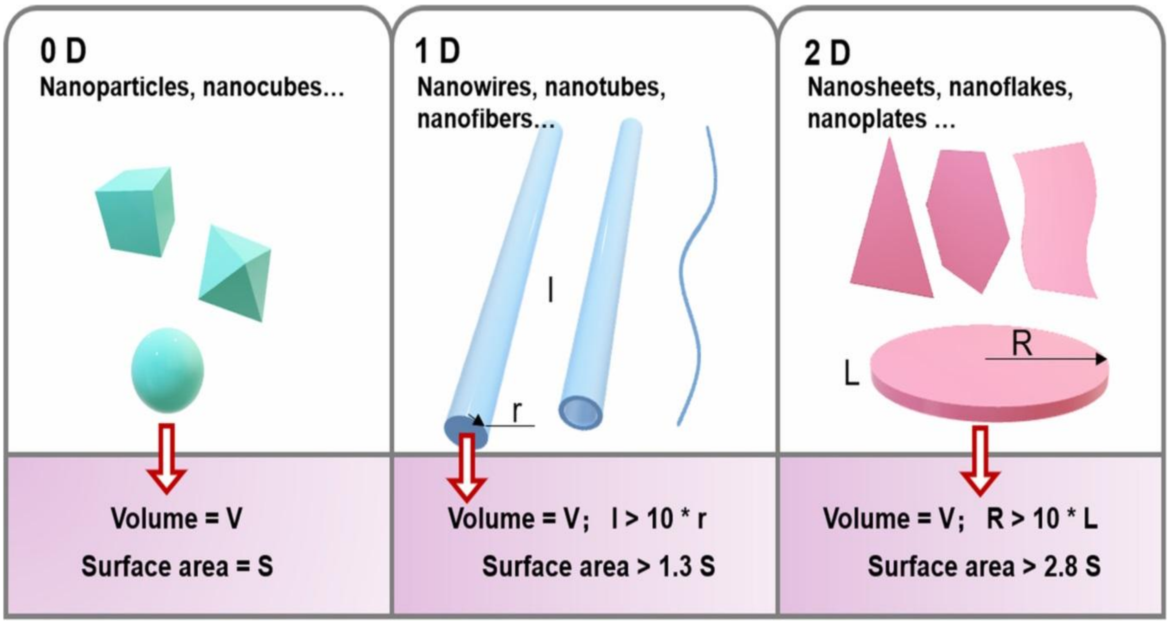

Figure 2. Schematic illustration of the 0D, 1D and 2D nanostructured materials. The surface areas of 1D and 2D nanostructures are greater compared to 0D- dimensional nanoparticles, if the same volume *V* is preserved [15]

4.1. Zero-dimensional nanomaterials (0D)

In this type, all the dimensions of the nanoparticles are in the nano range. Nanoparticles, as 0D-dimensional materials, do not have dimension outside the 1 to100 nm [16]. Nanoparticles can be showed in various shapes, and their small scale tempts an alter in essential properties [17]. These properties can be established in the quantum dots, which are nanocrystalline particles comprising a few hundred atoms. Engineers can use quantum dots (QDs) to design road reflectors that will show incident light [18]. Magnetic nanoparticles can be applied to identify specific biological entities, including diseases and microorganisms [19]. The use of 0D-dimensional nanomaterials in architecture will existent new chances to solve limitation and elevate building design and construction to an optimal level through refining meaningfully the nature of structural efficiency and the way buildings interact with the environment.

4.2. One-dimensional nanomaterials (1D)

1D- nanomaterials are materials in which one or 2D-dimensions are on a nanometer scale and no longer on a nanometer scale; or one dimension is outside the nanoscale. Scientists divide 1D-dimensional nanostructures into several categories based on parameters like dimensional ratio; these categories include nanorods, nanowires, and nanotubes. These nanomaterials can be used as surfaces and thin films in chemistry and electronics [20].

Nanotubes and nanowires have one long axis, and a cross-section that is within the 1-100 nm range. Carbon nanotubes (CNTs) are mechanically powerful materials. Nanotubes are much more powerful than steel and are therefore used to increase strength in many composites [21]. Another application is the production of CNTs fibers, which can be used for a variety of applications. By incorporating these fibers into building materials, their mechanical properties can be significantly improved. CNTs and various composites improve the properties of building materials. A single-walled carbon nanotubes (SWCNTs) has well electrical and mechanical properties. A multi-walled carbon nanotubes (MWCNTs), has semiconductor properties, such as GaN (gallium nitride), Tin oxide (SnO_2) and nanowires of ZnO (Zinc oxide), which are pretty to the microelectronic industry [18, 22].

Metallic nanowires (NWs) as 1D-dimensional nanomaterials have been studied due to good mechanical flexibility and good thermal and electrical conductivity. These nanomaterials can be measured as engineering materials due to their good behavior [23]. In recent years, study into NWs has fortified technological advancements in different areas, such as energy-efficient buildings, electrochromic devices, and flexible transparent conductive films.

4.3. Two-dimensional nanomaterials (2D)

In 2D-dimensional nanomaterials, two dimensions are outside the nanoscale. This type of materials shows nanofilms, nanosheets, nanocoating, graphene, and nanolayers. This type of nanomaterials is deliberated as the thinnest nanomaterials according to their dimensions and thickness on nanoscale. There are layered structure by strong bonds and weak van der waals among layers in 2D nanomaterials. One application of 2D nanomaterials is to enhance the antibacterial effect according to the large surface area and easy surface operation, as well as intimate interactions with the bacterial membrane [24, 25].

4.4. Three-dimensional nanomaterials (3D)

3D-dimensional nanomaterials are materials that are not kept to the nanoscale in any dimension. This type of nanomaterials can comprise nanotubes, powders, nanowires, and nanotubes [2]. 3D nanomaterials can apply in construction applications including structural reinforcements, and high efficient lubricants [26].

5. Application of nanomaterials in sustainable architecture

5.1. Application of nanomaterials in Nanocoatings

In recent years, the addition of nanoparticles to coatings has improved their mechanical and chemical properties [27]. Nanocoatings are types of thin films that are chemically or physically applied to different surfaces and have a thickness of less than 100 nm. Because of their very low thickness, nanocoatings are often very transparent. Nanoscale particles make up their structure, and people use them for various mechanical, chemical, and optical properties [28]. Nanostructured materials in coatings are defined as 1D-dimensional, 2D-dimensional and 3D-dimensional nanometer shapes. Conventional structures, therefore, include coatings containing particles, nanowires, nanorods, nanotubes, and nanofibers [29]. Nanotechnology and nanocoatings find use in building materials, providing corrosion-resistant, anti-scratch, self-cleaning, hydrophobic, and gas-detecting coatings for glass, stone, wood, steel, ceramic, brick, tile, cement, and concrete surfaces. Studies on nanocoatings have shown that their properties in many cases are significantly better than conventional coatings. Nanocoatings have greater coefficient of thermal expansion, hardness and more resistance to abrasion, corrosion, and erosion compared to micrometer coatings.

5.1.1. Self-cleaning surface and glass

The self-cleaning process includes several solutions, such as hydrophobic, and the process of photocatalysis is important. In fact, self-cleaning does not mean that there is no need to clean at all, in fact, in this process, the distance between cleaning becomes longer. Tiles and ceramics are among the most widely used building materials that can be used in different parts of a building. If hydrophilic surfaces are used, these surfaces will remove the chemical structure of the contaminants in the presence of light under the process of photo catalysis. Coatings made of titanium dioxide (TiO_2) nanoparticles are known for their ability to perform light-dependent activities because of their self-cleaning behavior, which increases with increasing size and increasing the ratio of surface area to volume. Different types of oxide semiconductors, including TiO_2 [30], ZnO [31], Cuprous oxide (Cu_2O) [32], etc., have been extensively applied in photocatalysis.

TiO_2 has the potential to become a crucial material for architectural applications worldwide. Japan was the first country to make significant efforts to apply this nanomaterial in architecture [33]. However various other countries such as USA, have also stared applying this field, although, its application in developed country such as India is still restricted. Titanium has become of competitive building material, which can be combined with a plenty of refined ore and raw is needed in order to an enhanced obtainability of the material for large scale apply in building industry. Construction materials incorporating TiO_2 photocatalysts display a range of beneficial properties, including, self- water purification and antibacterial action [34].

Air pollution is one of the most significant factors contributing to the deterioration of building facades. The use of self-cleaning materials in combination with facade paints can be effective in maintaining the appearance of buildings over time [35]. The catalytic procedure as an oxidation procedure can be applied as assay in order to degradation of hazardous materials on building facades. In one study, it was suggested that TiO_2 could be used instead of painting the entire building to help preserve the building appearance. In this study, three types of dyes were mixed with TiO_2, and the resulting coatings were applied to smooth strophomy sheets. These coated sheets were covered with black and white stains. TiO_2 oxidized most of the pollutants that covered the flat sheet after exposing these plates to waterfalls and the UV. Therefore, it can be expected that the mixture of paint components with TiO_2 is strong. Here, electrons can transfer into the paint components and reduce the chance of Electron–hole (e^-/h^+) recombination. O_2 can be adsorbed on the surface of TiO_2-based paint, where it reacts with electrons in order to form the O_2 radicals. This O_2 radical adsorbed the pollutant on the TiO_2 surface. The hydroxyl radicals (•OH) produced via TiO_2 oxidize the adsorbed pollutants on the surface of the sheet. Figure 3A showed the application of the photocatalytic activity of TiO_2 inside the painted surfaces [36].

In addition to TiO_2 nanoparticles, other nanoparticles such as ZnO, SiO_2, and cadmium sulfide (CdS) are also used. Among photocatalytic materials, ZnO has attracted considerable attention due to its photoelectronic and chemical properties. ZnO, like TiO_2, has a wide bandgap, favorable conduction band position, and is cost-effective [37]. ZnO is incorporated into coatings in order to improve hydrophobicity. In a study, researchers showed that a polyvinylidene fluoride (PVDF)-based self-cleaning coating enhanced with ZnO nanoparticles improved hydrophobicity on aluminum panels [38]. Hikku et al. prepared Ag-doped ZnO nanoparticles synthesized through a facile gel-combustion assay with self-cleaning properties. The self-cleaning coating was synthesized with 1% SDZO (silver-doped ZnO), and the photocatalytic degradation of a solution by these nanoparticles was tracked spectroscopically using UV-Vis spectroscopy. As a result, the degradation rate of 1% SDZO nanoparticles under UV light was found to be higher than that of other samples [39].

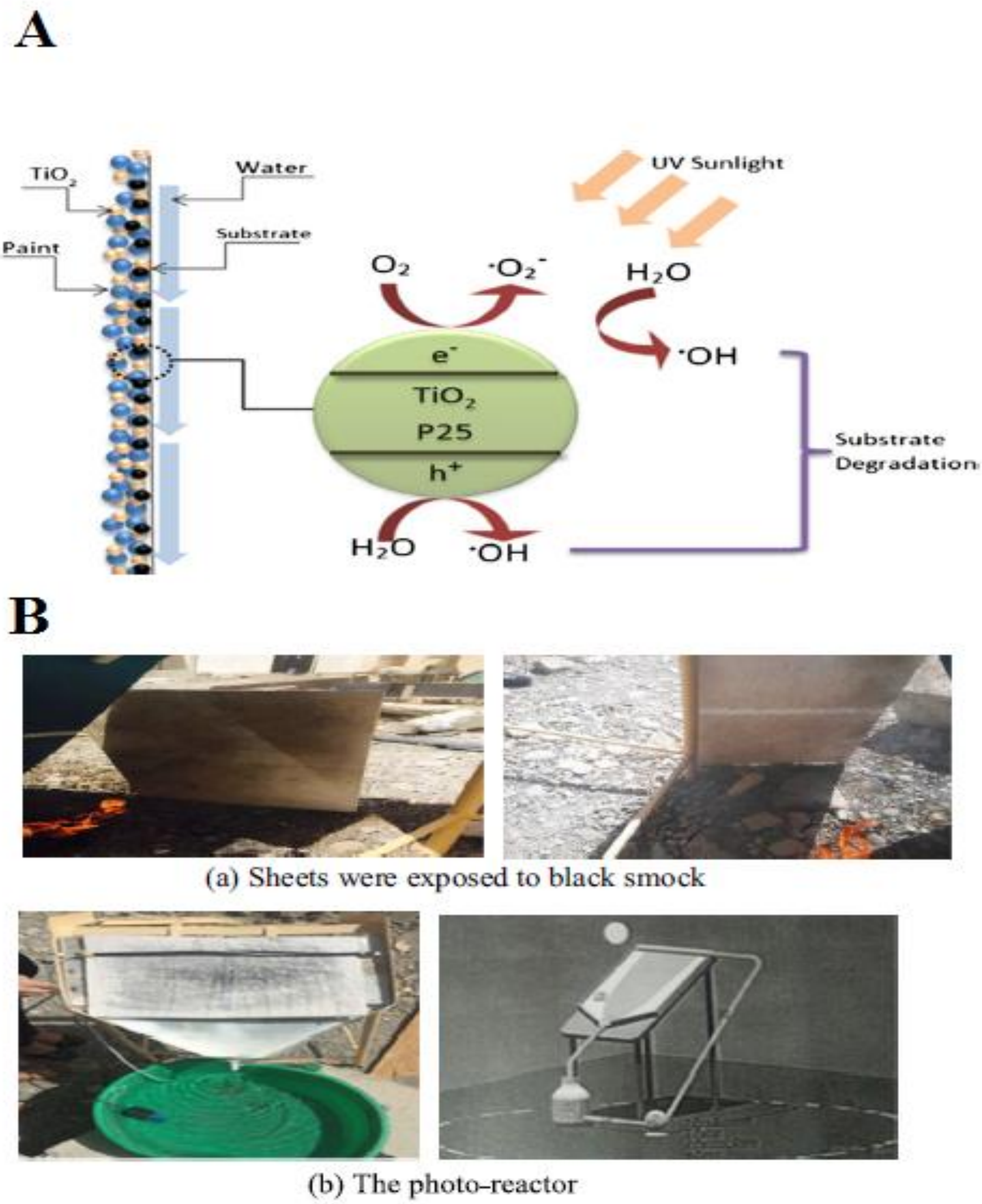

Figure 3. Schematic illustration of the mechanism of photo-catalytic activities of TiO_2 inside the painted surfaces (A);and experimental photos and systematic diagram (B) [36]

5.1.2. Antibacterial and antimicrobial nanocoating

The nano-products used for this purpose are in the form of coatings and paints containing special nanoparticles that adhere to the surface of traditional materials. In some other methods, nanoparticles are used in combination with traditional materials. The use of antibacterial coatings on tiles, ceramics and surfaces and their use in hospitals and clinics can prevent the spread and transmission of pathogenic bacteria and prevent the spread of disease among people [40]. Among the most widely studied antimicrobial agents are silver (Ag) nanoparticles, zinc oxide (ZnO), copper oxide (CuO), titanium dioxide (TiO_2), and nickel oxide (NiO), all of which demonstrate broad-spectrum antimicrobial activity

[41]. This material is capable of eradicating a wide range of microbes and bacteria [41, 42].

Specifically, the antimicrobial effects of ZnO and TiO_2 nanoparticles are largely attributed to their photocatalytic capabilities. TiO_2 has been broadly studied as photo catalyst based on its ability to create surface reactive oxygen species (ROS). ROS produced from photo catalysts can inactivate pathogens through destroying macromolecules [43]. TiO_2 nanoparticles with a size of about 5 nm were applied to functionalize glass slides and glass microfiber filters. The biofilm-forming *Staphylococcus aureus* and *Pseudomonas putida* grew on TiO_2-functionalized surface. UV light irradiation for two hours causes damage to the bacterial cell membrane by production of ROS radicals, and the decrease of cell viability was over 99 % for TiO_2 on glass surfaces. In fact, this study showed the significance of bacterial colonization during dark surface and the problems in eliminating the bacteria biofilms.

The antimicrobial potential of ZnO can according to creation of ROS, release of zinc ions and cell membrane destruction. The mechanisms depend on the properties of ZnO nanoparticles. Valenzuela et al. developed a sol-gel method for synthesis ZnO suspensions with size of 100–300 nm for producing electrosprayed coatings. A low-cost scalable Electrospray technique can convert droplets into solid particles to produce a thin coating. These electrosprayed coatings showed antibacterial activity in contrast to *Staphylococcus aureus*, with >99% decrease in the number of cultural cells. Antibacterial activity is because of the production ROS on the surface of ZnO coatings and Zinc ions. These photoactive coatings reserved various surfaces free from microbial colonization [37]. One of the most significant properties of ZnO nanoparticles is their capacity to escape biofilm formation of pathogens in historical buildings [44]. Some microorganisms are involved in the process of biodeterioration and changes in the properties of materials, which is one of the important factors, in the destruction of cultural heritage along with other factors for instance climate. In 2020, Schifano et al. assessed the antimicrobial activities of ZnO-nanorods (Zn-NRs) and graphene nanoplatelets decorated with Zn-NRs (ZNGs) against *Achromobacter spanius* and *Arthrobacter aurescens* on stones and surfaces [45].

Silver nanoparticles have important properties, especially according to their antimicrobial activity against wide ranges of bacteria [46]. Ag-incorporated titania coatings can prevent biofilm formation of *S. epidermidis* by regulating the expression levels of related genes (icaR and icaA for *S. epidermidis*). Ag-nanoparticles were arranged onto Ti surfaces to progress a delivery platform enabling the controlled release of silver ions. release of Ag ions. These levels have the ability to regulate the expression of genes associated with biofilm creation, thereby reducing bacterial adhesion and growth [46, 47] (Figure 4). Table 2 showed the examples of various nanomaterials with anti-microbial properties.

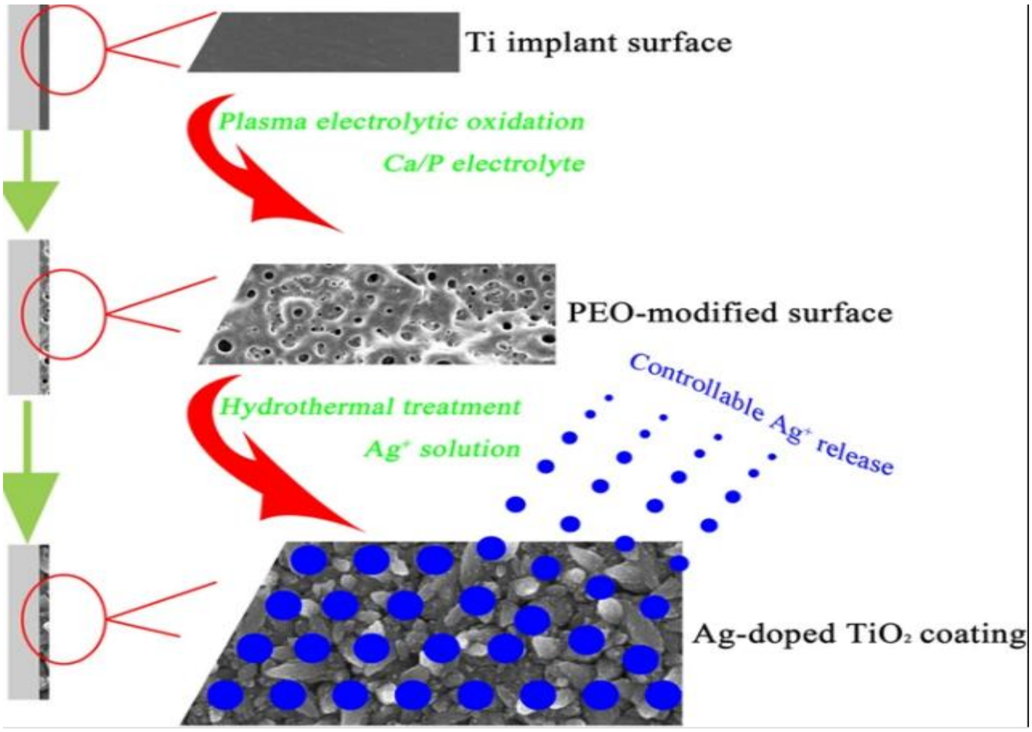

Figure 4. Schematic illustration of the fabrication procedure for the Ag-doped TiO_2 coating [47]

Table 2. Examples of nanomaterials with anti-microbial properties

Types of nanomaterials	Types of pathogens	Ref
TiO_2	*P. putida*, *S. aureus*	[43]
Silver	*S. aureus*, *Shigella flexneri*, *S. pneumonia*	[48]
ZnO	*L. monocytogenes*, *E. coli* O157:H7, *Bacillus subtilis*	[49]
Graphene oxide	*S. aureus*, *E. coli*	[50]
Selenium dioxide	*S. aureus*, *Proteus mirabilis*, *P. aeruginosa*	[51]
Gold nanoparticles	*Corynebacterium pseudotuberculosis*, S. *pneumoniae*	[52, 53]

5.2. Application of nanomaterials in nano-insulations

In the context of sustainable architecture, one of the important solutions is decreasing fossil fuel consumption. Studies have shown that, as of 2012, buildings worldwide accounted for approximately 32% of total final energy consumption and one-third of direct CO_2 emissions and particulate matter. This high level of energy use is often attributed to insufficient insulation, poor thermal and humidity regulation, and inefficient air conditioning systems. As a result, the commitment of countries to reducing energy consumption and greenhouse gas emissions to increase the energy efficiency of buildings. Notably, more than 50% of the current global building stock is expected to remain in use by 2050 [54].

There are different common thermal insulation materials, such as rock wool, polystyrene and fiber glass. However, these materials have various disadvantages, including poor structural strength, low deformation resistance, and non-biodegradable in the environment. In contrast, nanomaterials with low thermal conductivity offer promising alternatives. Nano-insulating materials (NIMs) can reduce wall thickness, while maintaining thermal insulation properties, making them a valuable component in sustainable construction strategies [55]. The use of nano-insulating products in building envelopes presents a promising alternative to customary insulation materials. Analyses have shown that incorporating these materials into building structures can increase the thermal performance of the envelope, thereby contributing to reduced energy consumption and achieving energy efficiency targets in the built [56].

Aerogel is an ultralight material of superior thermal and acoustic insulation belongings. The base material is silica, which shows low thermal conductivity. Aerogels can be synthesized using other materials such as chromium, aluminum, and carbon. Due to the vacuumed air within its porous structure, aerogel has a thermal conductivity as low as 0.0010 W/mK, and it can withstand temperatures up to 500 °C. Aerogels are also used as a good sound insulating material. As a result, this material can be used as a highly durable, hydrophobic and anti-flammable material in buildings. However, compared to other common materials, it has a higher cost [57]. By incorporating nanogels into other systems, materials with high thermal insulation can be made, depending on the proportion of aerogel used—typically ranging from 80% to 95%. These plasters have water resistance properties, and are also resistant to microbial agents due to their mineral composition. They are also used as sound insulation due to their porous structure [57].

Some of other nanomaterials that can be applied in order to building purposes are CNTs, TiO_2, silicon dioxide, and etc. The applications of these nanomaterials as a composite with other materials, increases their performance, especially in thermal insulation, contributing to more efficient energy use [58-60].

Nanocomposites have been widely reported in thermal insulation and conduction. Polymer-based nanocomposites are attractive according to their low weight, low cost, and good corrosion resistance, making them suitable for thermal insulation uses. In fact, polymer nanocomposite indications improve the properties of polymer itself.

Insulating polymeric nanocomposites with great thermal conductivity have pronounced potential in order to apply as thermal-management materials in optoelectronics. However, current composite materials need a large amount of electrically conducting fillers. Flexible nanocomposite films with linear densely packed BN structures (LDPBNs) have demonstrated a thermal conductivity of 1.5

W/mK [61].

Polyurethane (PU) is one of the most versatile polymers with high compatibility and thermoplastic properties. In one study, a thin thermal building insulation material was developed using a PU–clay nanocomposite via the solution intercalation method. This PU nanocomposite showed the probable to absorb more water, a property that may offer benefits in the development of thermal insulation materials for building [62].

Researcher used an environment-friendly and low-cost material for example date pits (DP), as an effective thermal insulator material for buildings. Date pits are described through water insolubility and stability, and high mechanical strength. In the study, synthesized DP nanoparticles formed a semi-homogeneous mixture known as DP0S50E, with no observable structural changes. The thermal conductivity of the DP0S50E obtained 0.26 W/mK, and it showed the lowest thermal diffusivity. As a result, DP0S50E polymer can be applied as a coating material for buildings at a thickness of 10 mm. This polymer is capable of achieving 6% energy savings and reducing CO_2 emissions by 6%, effectively lowering energy costs in existing buildings [63].

However, there remains a significant need for enhanced thermal and acoustic insulation to reduce energy waste across different industrial applications. Greater effort and investment are still needed to fully leverage nanotechnology for these purposes.

5.3. Application of nanomaterials in concrete and cement

Concrete is used as one of the significant materials in the construction industry. Natural pozzolanic powder is added to concrete to increase durability, reduce the cost of concrete production and reduce environmental pollution caused by cement production. Recently, the applications of nanoparticles for progressing the properties of concrete have attracted the attention of numerous researchers in concrete technology. According to the role of nanomaterials in improving the bulk properties, they can be suggested in producing the concrete [64]. Nanoparticles can act as fillers by refining the interfacial transition zone in cement and forming denser bulk concrete [65]. Nanotechnology also improves different properties of concrete, such as faster setting times and the production of thinner, yet strong, concrete elements [66].

Silica is one of the most important materials that can be applied in the manufacture of concrete [67]. Other nanoparticles such as titanium oxide, carbon tube and nano-alumina can be used in nanoconcrete [68, 69]. In a study, Qing et al. [70] showed that adding nano-silica to concrete compounds can increase the performance of concrete. Due to their suitable size, these nanoparticles can act as good filler in concrete. The micro-cavities in the concrete can be compacted and provided a neat concrete microstructure. Another advantage is their ability to influence compressive strength via helping to control the water-to-cement ratio.

Some studies have shown that the addition of nano-silica in a specific dose can increase the resistance of HSC and even act as a partial substitute for cement. Considering the reduction of 20 to 30% of cement content by nano-silica, it can be concluded that this material can act as a suitable alternative to cement. In some countries, silica is also used in the concrete industry [71].

CNTs are 1D nanomaterial with a hollow structure which can be categorized as SWCNTs and MWCNTs. The length and diameter of these nanoparticles are about 50 μm with an aspect ratio larger than 1000 [72]. Various researches have been carried on the role of nanoparticles in concrete applications. For example, cement-based composites incorporating 0.018 wt.% and 0.036 wt.% MWCNTs were formed for cohesion after aging. Results showed that 0.036 wt.% CNT addition increased cohesion by 24% and 19%, respectively, and enhanced shear resistance [73].

In ultra-high-performance concrete (UHPC), CNTs contribute to enhanced flexibility, tensile strength, and compressive capacity. CNTs can replace steel reinforcement, allowing for lighter structural elements capable of bearing additional loads. In fact, it is believed that by replacing steel in UHPC, lighter and lighter sections can be created, reducing construction time and cost. However, due to the high cost and scarcity of CNT resources, interest in using CNT in UHPC has decreased [74, 75].

In one study, the compressive and tensile strength of CNTs in concrete were investigated. In this study, CNTs with a size of 2 nm were used, and several mixes were prepared containing 0.01%, 0.02%, and 0.03% CNTs by weight of cement, along with a control mix without CNTs. The outcomes showed that the addition of CNT can increase the compressive, tensile and bond strength of specimens compared to control. Moreover, SEM analysis of the control and CNT-containing samples showed that the CNT-enhanced samples had a more refined structure [76].

TiO_2, the natural oxide of titanium, can also be added to cement for various functional benefits. [77]. Addition of TiO_2 to concrete, in addition to its effect on self-cleaning properties, can also increase the strength of concrete. Mainly, in UHPC, TiO_2 can produce a glass-like layer on the surface, enhancing overall performance. Its function is that in order to improve the performance, TiO_2 in concrete can form a fiber-reinforced system. TiO_2 can contribute to the development of a fiber-reinforced system, refining the hydration gel and improving durability [78].

Other researchers described the improvement of concrete microstructure by using TiO_2, which improved its mechanical strength. In this study, concrete samples with different weight ratios of TiO_2 were examined and compressive strength was also investigated. According to Table 3, the strength of cement is inversely proportional to the weight ratio of TiO_2 at different *temperature*s. Here, strength of concrete first increases and then decreases with the increases weight ratio of TiO_2. In this assay, when the weight ratio of TiO_2 nanoparticles reached 2%, the compressive strength of the concrete peaked. Furthermore, the concrete with TiO_2 nanoparticles reached an extreme compressive strength that was 7% greater compared to the non-added nanoparticle concrete [79].

6. Conclusion and future direction

In recent years, different developments have had negative effects on the environment. Therefore, the issue of sustainability—especially in architecture, known as sustainable architecture—has proposed, which this assay helps to minimize the environmental footprint of buildings by enhancing efficient use of materials and energy. Therefore, nanotechnology is one of the newest technologies in the world, which is actually the science of controlling matter at the molecular scale. Nanomaterials have showed the potential to improve the mechanical properties of Portland cement. Nanomaterials including TiO_2, silica, CNTs, zinc oxide, and graphene give good results in order to Portland-based concrete. Nanotechnology-based systems are not only stronger than other systems, but are also more environmentally friendly. In the future, nanomaterials can replace traditional construction materials such as bricks, eliminating the require for temporary materials. Novel carbon-based nanomaterials can be applied to make most buildings safer. There is also a need for smart appliances in order to the design and construction of buildings with self-cleaning surface, colored coatings, and light-sensitive appearance. For thermal insulation, polymer nanocomposites are outstanding nanocomposites to these ends.

These components have the ability to interact with users and adapt to changing conditions. In general, the pervasive impact of nanotechnology on human life and how it relates to the environment and buildings is inevitable and unimaginable. Therefore, nano-based materials should replace conventional materials to bring about an important transformation in the construction industry. On the other hand, providing architectural designs based on the morphological structure and nano-cells will be an antidote for today's form-driven architecture.

Table 3. Strengths of concrete at various temperatures [79]

Entry	Weight ratio of TiO_2	20 °C	155 °C	-20 °C	-40 °C
1	0%	36	31	49	49
2	2%	39	34	60	64
3	4%	34	31	56	65
4	6%	37	33	51	65

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