A Proposed Strategy to Evaluate Nanomaterials in Construction to Boost Sustainable Architecture

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A Proposed Strategy to Evaluate Nanomaterials in Construction to Boost Sustainable Architecture

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Abstract Nanotechnology has gradually emerged in various sectors, including architecture. Nanotechnology developed nanomaterials as environmentally friendly and highly efficient construction materials. It behaves differently with enhanced functional properties such as durability, strength, flexibility, lighter weight, self-cleaning capacity, etc. This study investigated the impact of integrating nanotechnology into the construction field from two perspectives: to minimize the environmental impact of buildings based on sustainability principles and to improve the functional efficiency of construction materials. The study aims mainly to propose a strategy for evaluating nanomaterials in construction as sustainable materials through four aspects related to sustainability principles. This was achieved progressively through a methodology that commenced with a theoretical study of the basics of nanotechnology and how it relates to the field of sustainable architecture. Moreover, it described and summarized some prevailing nanomaterials used in construction, such as concrete, glass, coatings, and thermal insulation materials. It also reviewed their functional efficiency in line with sustainability. Furthermore, this study examined some case studies based on the proposed strategy to evaluate the utilized nanomaterials in the case studies. On average, this study's results found that the used nanomaterials in the three case studies achieved 54.3% for sustainable design principles, 83% for Sustainable materials criteria, 60.3% for energy efficiency aspects, and 71.7% for ambient environment efficiency factors. On the other hand, it indicates that using nanomaterials in construction reduces harmful carbon emissions and improves the functionality of building materials to boost sustainable architecture.

Keywords Sustainable Architecture, Nanotechnology, Nanomaterials, Nanoarchitecture

1. Introduction

1.1. Background

Nanoscience is the science of studying the properties of materials at the atomic level. Atoms can be controlled and manipulated on a scale not exceeding 100 nanometers, called the nanoscale. At this scale, materials gain a wide range of improved properties, including shape, color, strength, weight, conductivity, and elasticity. [1,2]. In Greek, Nanos means dwarf, minimal size, so the prefix Nano is derived from it [3]. Microscopic studies show that when the gold particles are nanosized, they could give different color reflections, such as red, depending on the size and shape of the particles and the distance between them [4]. Several applications of nanotechnology have gained momentum recently. The following are a few keys Nanotechnology definitions:

(a) A nanometer is a metric unit of measure equal to a billionth of a meter, or 10^{-9} meters (1/1000000000) [5].
(b) Nanoscale "The size ranges from roughly 1 to 100 nanometers, where many of the fundamental structures of biology are formed, composite materials

may take on their distinctive characteristics, and many important physical phenomena are found" [1].

(c) Nanoscience is the study of unique properties of matter at the nanoscale, which encompasses physics, materials science, chemistry, and molecular biology [1].

(d) Nano object "Material with one, two, or three external dimensions in the nanoscale".

(e) Nanoparticle, "Nano-object with all three external dimensions on the nanoscale" [6].

1.2. Topic's Importance

The sophisticated properties of nanomaterials have significantly contributed to construction development as one of the nanotechnology applications. Therefore, the construction sector is continuing to emphasize nanotechnology innovations. Thus, the research points out the importance of harnessing nanomaterials in the construction field, as well as it proposes an evaluation strategy for nanomaterials in construction to indicate the effectiveness of using these materials at the environmental level, particularly in regions with high population density and a high level of pollution, as will be clarified in the applied part. To boost sustainable architecture's goals and principles, nanomaterials improve the efficiency of buildings' material functionality and minimize the buildings' environmental impact, such as harmful carbon emissions. Moreover, it purifies the air by reducing the effects of car exhaust and other airborne pollutants. Recently, nanomaterials have become a new trend in construction materials, revolutionizing architectural society [7,8].

1.3. Study Hypotheses

The study hypothesizes that utilizing nanomaterials in construction with their potential at various levels will contribute effectively to enhancing sustainability based on the following four proposed aspects: sustainable design principles, sustainable materials criteria, energy efficiency aspects, and ambient environment efficiency factors.

1.4. Study Questions

This study raises the following critical questions:

- Do nanomaterials contribute to enhancing the functionality of construction materials?
- Does using nanomaterials in the construction sector boost sustainable architecture?

1.5. Study Problem

Many challenges face the construction industry, particularly inefficiency in building materials and harmful environmental implications. Accordingly, it was necessary to adopt and highlight new green materials indicated by nanomaterials that reduce the potential negative impacts on the environment during their entire life cycle, including manufacturing, construction, reuse, and disposal, enhancing sustainability goals.

1.6. Study Objectives

This study aims to:

(a) Propose a strategy to evaluate the impact of nanomaterials in buildings to determine how it boosts meeting sustainability goals.

(b) Review concepts of nanotechnology, its origins, and its importance in architecture, particularly in the construction sector.

(c) Indicate the potential of nanomaterials in sustainable architecture and how they are used to boost environmentally friendly constructions.

(d) Review, then present some nanomaterials and address their significance in construction to boost sustainable architecture.

(e) Selecting and analyzing some applied nanomaterials through the conducted case studies.

The research skeleton, as shown in Figure 1, illustrates the conceptual framework for this study.

2. Literature Review

2.1. Topic Trends

Nanotechnology has emerged in the scientific community for six decades [9]. Richard Feynman was the early nanotechnology pioneer, emerging its basis in 1959. In the "There is a Plenty of Room at the Bottom" lecture, he explained the importance of manipulating and controlling things on a small scale. [10]. The term Nanotechnology was firstly introduced by the Japanese scientist Norio Taniguchi in 1974 [11]. In 1981, scientists could see materials at an unparalleled atomic level by scanning the tunneling microscope (STM) by Gerd Binnig and Heinrich Rohrer at IBM Zurich Research Laboratory [9]. The Atomic Force Microscope (AFM) was invented in 1986 by physicists Gerd Binnig, Calvin Quate, and Christoph Gerber. It allows viewing surfaces at the atomic level, controlling and manipulating atoms [12].

Hence, the actual beginning of the practice of nanoscience and technology was by the American engineer K. Eric Drexler who developed the central concept of Nanotechnology. He drew on Feynman's ideas as a basis, but he outlined his vision. He presented the concept of molecular manufacturing extensively by using designed protein molecules for manufacturing objects and devices at a complex atomic level in his book "Engines of Creation" published in 1986 [13]. In 1989, Feynman and Drexler's basis and visions were realized by Dr. Don Eigler, who could control 35 individual xenon atoms and place them on a nickel surface, shaping IBM logo letters [13,14]. At the beginning of the 21st century, nanotechnology had gained global momentum, with government-funded institutes established in several countries, such as the Nanotechnology National Initiative (NNI) in the USA in 2000 [15].

Nanotechnology is widely applied in producing nanomaterials (NMs), leading to a promising future in the construction sector. The ISO defined nanomaterials as "Material with any external dimension in the nanoscale or having an internal structure or surface structure on the nanoscale" [6]. Nanomaterials are classified according to dimensions, mainly into four types [16-18]:

(a) Zero-dimensional (0D): The three dimensions are in the nanoscale, such as nanoparticles of gold or titanium dioxide.

(b) One-dimensional (1D): It has two dimensions in the nanoscale range, having a form resembling a wire, such as Carbon Nano Tubes (CNTs), one of the most prevailing and promising nanomaterials in the construction sector.

(c) Two-dimensional (2D): It has one dimension in the nanoscale range, as in thin coatings or films, such as self-cleaning nanocoating, used widely on building facades.

(d) Three-dimensional (3D): The three dimensions are more significant than the nanoscale range, such as aerogels widely used as insulation material.

Nanomaterials contributed to the construction industry by manufacturing new materials with unique properties. These enhanced materials can function better than conventional ones, such as self-cleaning glass, high-strength concrete, fire resistance coating, and highly efficient thermal insulating materials. In addition, the steps of manufacturing nanomaterials and the chemical processes associated with them are almost green processes with lower emissions of greenhouse gases. [19]. Thus, nanotechnology can be termed Green Nanotechnology (GN) due to its clean process in all manufacturing stages with lower greenhouse gas emissions and without harmful toxic chemicals. Besides, it minimizes energy consumption with the ability to be recycled [20,21]. The need for nanotechnology applications in construction and architecture has been highlighted regarding its ability to enhance sustainability goals significantly [22,23].

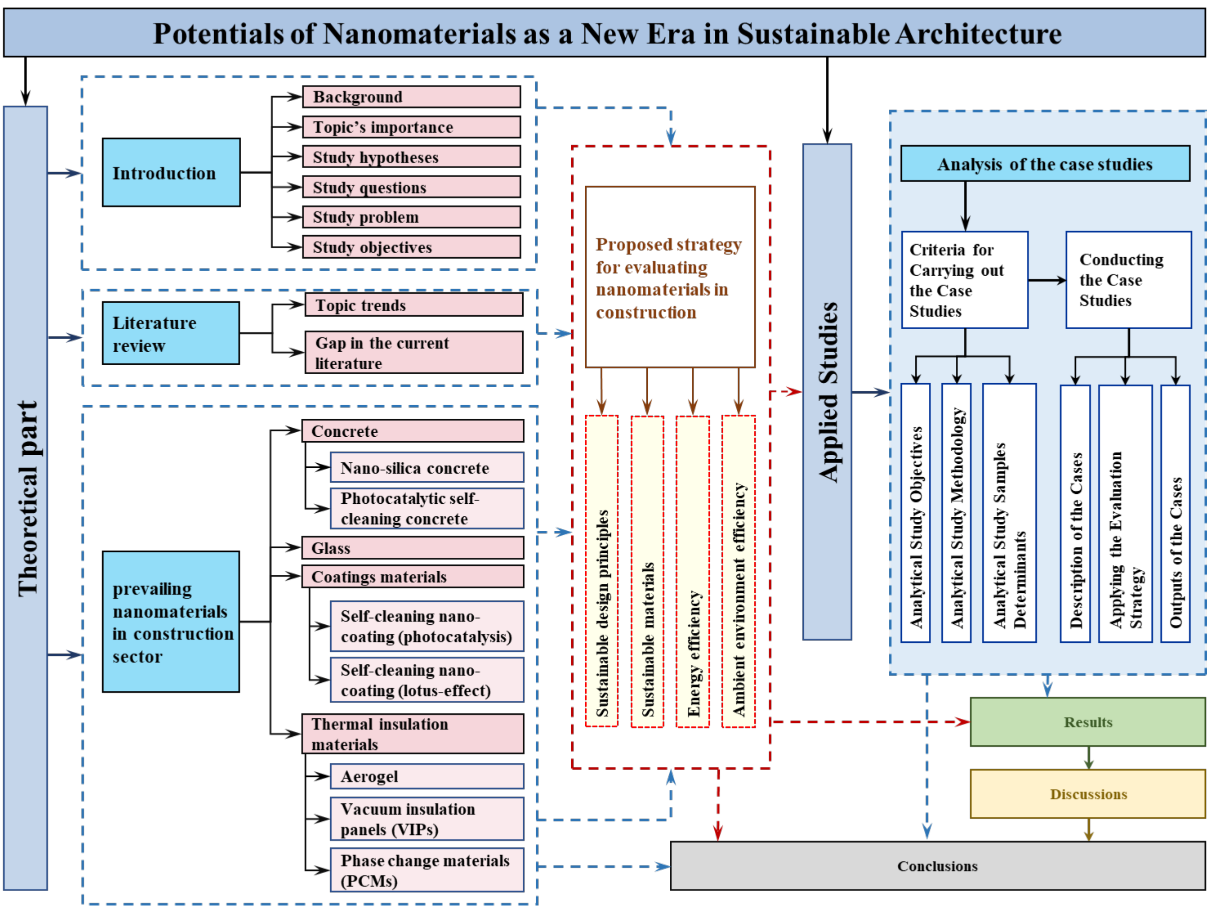


Figure 1. The research skeleton (the authors)

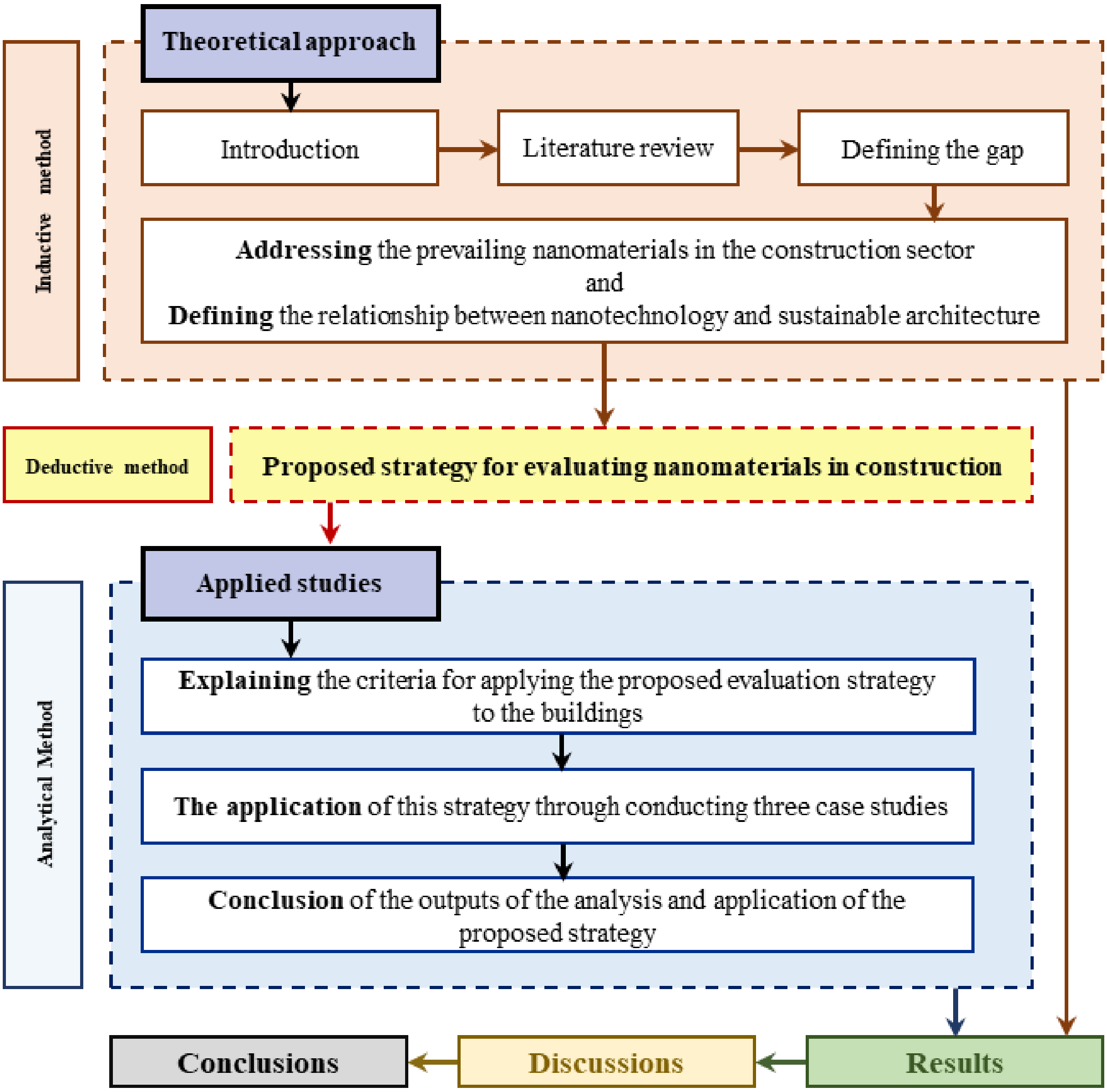


Figure 2. Scheme of the methodologies are used in the study (the authors)

2.2. The gap in the Current Literature

The gap between the research problem and the current condition was extracted by extrapolating the literature mentioned. Therefore, this study seeks to reduce this gap by emphasizing the importance of sustainable nanomaterials and attempts to utilize them in architecture and construction. Moreover, determining the extent to which they can effectively enhance sustainability goals.

3. Methodology

The research adopted various methods, as shown in Figure 2; these are:

(a) Inductive method to review the literature on nanotechnology, its scientific principles, roots, and how it has developed until the current era. Additionally, addressing the prevailing nanomaterials in the construction sector and their impact on sustainable architecture society and determines the relationship between nanotechnology and sustainable architecture through nanotechnology applications represented by nano-construction materials.

(b) Deductive method to formulate the proposed strategy for evaluating nanomaterials in construction as sustainable materials, based on what was extracted from the previous inductive study.

(c) The analytical method to analyze the selected three case studies used construction nanomaterials to demonstrate how it could increase building efficiency and performance within sustainable standards with minimum harmful emissions.

4. Prevailing Nanomaterials Used in Construction Sector

In this section, some of the prevailing nanomaterials in the construction sector, including concrete, glass, coatings materials, and thermal insulation materials, were explained and discussed as follows:

4.1. Concrete

Concrete has been among the most widely used essential building materials; it can last for years. By 2050, cement production will be around 4.38 billion tons worldwide, with a 5% yearly increase [24]. Cement production emits more than 1.6 billion tons of CO_2, accounting for more than 8% of total CO_2 emissions, and occupies the second rank in conditions of greenhouse gas emissions [25,26]. Here, two types of nano-concrete can be reviewed, as follows [27]:

4.1.1. Nano-Silica Concrete (SiO2)

In its natural state, silica is one of the standard components in the concrete mix. However, silica particles act differently at the nanoscale. The concrete and cement nanostructure can be more densified, compact, and robust through Nano-Silica Particles (NSPs) or Silicon dioxide SiO2. When NSPs are mixed into the cement with about 1.5% weight, it acts as a nanofiller enhancing the cement's cohesiveness with the aggregate [28,29]. Consequently, water and other elements cannot penetrate the concrete due to a lower pore volume and lower possibility for concrete degradation, as shown in Figure 3. Thus, concrete is used in bridges and skyscrapers due to its strength and lightweight. Enhancing the properties of concrete and cement and increasing their compressive strength (about 3-6 times higher) minimizes the quantity of material needed for construction and enables lightweight constructions, boosting the principles of long-term sustainability and resulting in a more efficient structure [27,29].

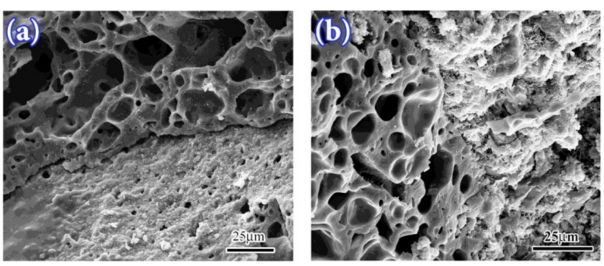


Figure 3. A micrograph using SEM showing a standard concrete mixture in the image (a), adding a high amount of NSPs in (b) [30]

4.1.2. Photocatalytic Self-Cleaning Concrete (TiO_2)

Titanium dioxide nanoparticles TiO2 can also be a significant additive to concrete due to their unique photocatalytic, self-cleaning, and environmental pollution cleansing properties. When the TiO2 particles get UV rays from the sun, they break up any dirt and dust accumulated on the concrete surface into CO2 and H2O, as shown in Figure 4. As a result, removing the reaction outcomes with rainwater or simple rinsing is easy, leaving the surface clean without any traces of water deposits [27,31].

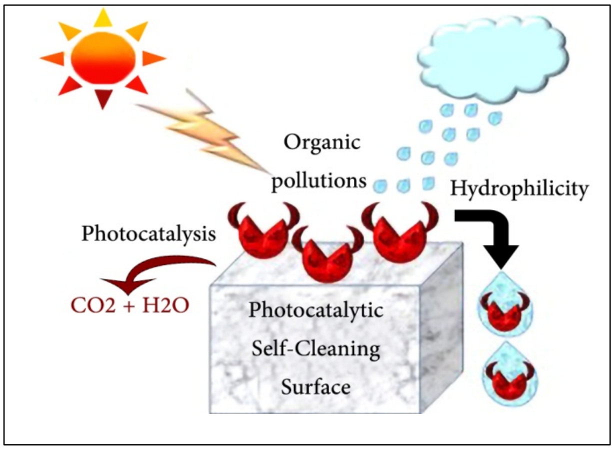


Figure 4. Reactions of Photocatalytic on a Self-Cleaning Surface [32]

This concrete has slowly made its way around the world, particularly in high-density urban regions beset by smog and air pollution. It has a reflective white color that does not fade with time or dust accumulation, enhancing long-term sustainability by saving many maintenance and cleaning costs. The master feature of TiO2 concrete is its ability to purify the air, which can decrease air pollution and smog by 30-40%. The "Jubilee church" in Rome by architect Richard Meier in Figure 5 is an architectural work that presents the beauty of white self-cleaning concrete [32].

Figure 5. The "Jubilee church" in Rome [33]

4.2. Glass

The use of glass in buildings is more common in facade works, whether it is windows, curtain walls, etc. Therefore, treating glass with heat-insulating nanomaterials contributes to reducing heat transfer, thus boosting sustainability by reducing the energy consumed to cool interiors [34]. On the other hand, with nanomaterials, glass gains extra positive properties to be applied on various sides, as follows:

4.2.1. Self-cleaning glass

Titanium dioxide nanoparticles (TiO_2) are integrated into the glass to add photocatalytic features, interacting with UV light to gain its self-cleaning property. Therefore, washing off the glass surface with spilled water or raindrops from broken dirt particles becomes easy without leaving traces or deposits [34-36].

4.2.2. Fire-protective glass

Fumed silica nanoparticles (SiO2) are used as a clear interlayer between two glass panes to create fire-resistant glass. Then, SiO2 swells, forming an opaque and durable barrier that absorbs the fire's energy. For many years, this function has long been efficient, especially in high-risk conditions, such as fire escape routes or escape ladders for safe user escape [28,31,34,35].

4.2.3. Electrochromic glass

It gains its electrochromic properties by sandwiching an electrically conductive coating of Tungsten Oxide nanoparticles between two panes of glass. Hence, applying an electric current (up to 3 Voltage) turns this nanocoating into blue color and reduces the passage of sunlight through the glass. Although this product is hardly implemented, its future is exceptionally bright [28].

4.3. Self-Cleaning Coating Materials

The term "Nano-coating" is defined as a thin chemical layer in the nanoscale with a thickness range from 10 to 100 nanometers, mainly made of nanoparticles and other beneficial agents and applied on several types of surfaces to boost its functionalities or prevent the negative impact of external factors [37,38]. In this regard, the following two types of self-cleaning nanocoating are reviewed as follows [39]:

4.3.1. Self-Cleaning Nano-Coating (Photocatalysis)

Until now, the most widely used application of Nanotechnology in the building industry is photocatalytic self-cleaning by TiO_2 NPs, where many structures worldwide are already remediated with it. Titanium dioxide nanoparticles are added to the coatings during manufacture to give them self-cleaning properties through photocatalysis. All organic dirt, such as fats, oils, and soot, reacts with titanium dioxide and decomposes in the presence of sunlight and water, resulting in oxygen radicals. Some residues are easily washed off with running water or rainwater [36,40].

4.3.2. Self-Cleaning Nano-Coating (Lotus-Effect)

It is inspired mainly by the lotus plant. Using a waterproof nanomaterial in the form of small heads within the nanoscale range to isolate the surface and reduce its porosity in the so-called hydrophobic surface. Hence, water drops easily roll while maintaining their spherical shape and collecting dirt. The lotus property can be applied in the field of nano-paints by using hydrophobic polymers such as silicon dioxide (Sio_2), either adding it to the paint during the manufacturing stage or placing a powder or spray of these polymers directly on the surface to be applied [40]

4.4. Thermal Insulation Materials

4.4.1. Aerogel

Aerogel is a rigid dry gel, primarily transparent, low-density material with more than 90% porosity (the pore size ranges from 5 to 100 nm). It is characterized by its highly lightweight and is also named air jelly or frozen smoke; it has a foam texture, as shown in Figure 6 [41]. One of its essential characteristics is its exceptional heat insulation of building envelope or glazing [42].

Figure 6. Aerogel (thermal Insulation Materials) [43]

The scientist Steven Kistler first discovered an aerogel version in 1931 [44]. Recently, the silica aerogel became one of the most common species, declared the lightest in the world in 2011, with a 3 kilograms per cubic meter density. Aerogel is commercially available in the form of flexible panels or solid boards that can be used in the building's walls, ceilings, and floors. The panels consist of silica aerogel reinforced with fibers transforming it from a fragile material into a flexible and cohesive one [42,45]. Figure 7 shows a section of a double-glazing pane of argon filled with aerogel [46,47].

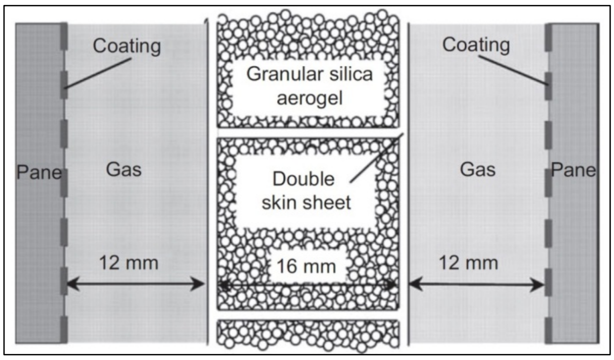


Figure 7. Aerogel glazing section [48]

4.4.2. Vacuum Insulation Panels (VIPs)

A vacuum insulation panel consists of two main components. First, the internal part is termed "the core," material with an open nanopore structure with a maximum diameter of 200 nm. The core provides thermal insulating capability and mechanical strength by impeding the free movement of gas/air particles and thus decreasing heat transmission through air conduction. Various materials can be used to manufacture the core, such as silica aerogel, polyurethane foam, wood, or glass fiber. Secondly, the outer part is termed as "foil"; its function is to encapsulate and protect the core by using impermeable material for water and gases [45,49]. The VIPs are more efficient than the conventional insulation materials by five to ten times the same thickness [49]. In Figure 8, a detailed section shows the VIPs in an insulation wall [50].

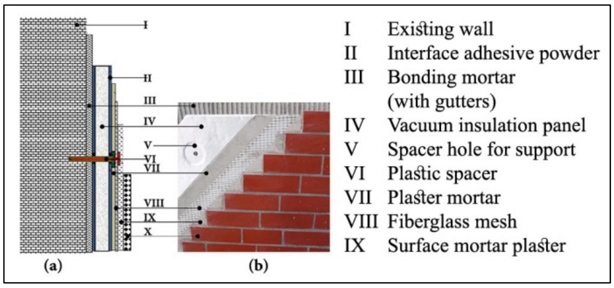


Figure 8. Detailed vacuum insulation system: (a) cross-section and (b) view of an insulated wall [50]

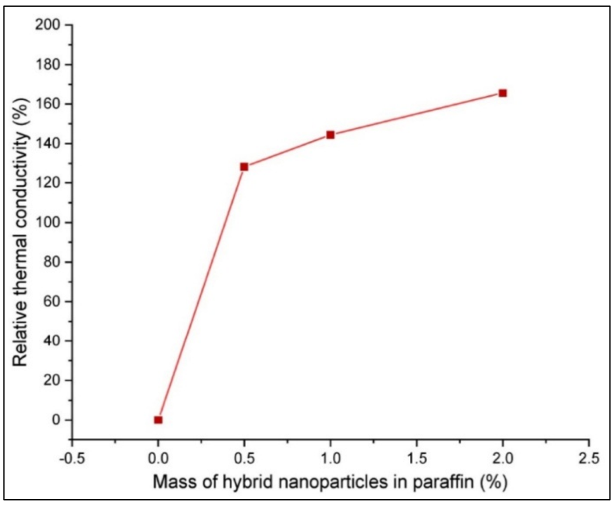


Figure 9. The comparative increase in thermal conductivity when nanoparticles are added [55]

4.4.3. Phase Change Materials (PCMs)

The Nano-Enhanced Phase-Change Material (PCM) has significantly contributed to developing energy-efficient constructions. PCM can absorb heat energy and release a large amount of it, making them suitable for energy-efficient use [51]. PCM can improve users' indoor thermal comfort by reducing indoor temperature variations and potentially reducing global energy consumption through power savings [52]. Nano-PCM can be manufactured with paraffin with nanoparticles added. The addition of nanoparticles to paraffin could increase the latent heat of nano-PCMs such as Fe3O4, CuO, TiO2, and ZnO nanoparticles [53]. It has been found that adding 1% nanoparticles to paraffin is the perfect amount to improve thermal conductivity. Thus, the thermal storage properties are improved, as shown in Figure 9 [54,55].

5. Nanotechnology's Relationship to Sustainable Architecture

Sustainable architecture aims to minimize harmful environmental impacts by integrating modern solutions such as promising technologies, low-impact materials, and unique designs. However, nanoscience and nanotechnology can be classified as science that greatly enhances sustainability goals termed "Green Nanotechnology" (GN). Safely and environmentally friendly manufacturing processes, and a product with low-impact, non-toxic, and recyclable [56,57]. Nanotechnology has slowly made its way into sustainable architecture by presenting different applications, particularly nanomaterials, such as concrete and coatings. Hence, nanoparticles enhance construction materials' properties, such as improving durability, hardness, strength, flexibility, and diversity, reducing weight, boosting insulation efficiency, and reducing materials' toxicity to root the goals of sustainable architecture. The union of nanotechnology and architecture can be termed "Nanoarchitecture". Architects have gradually utilized nanomaterials to solve environmental issues [58,59].

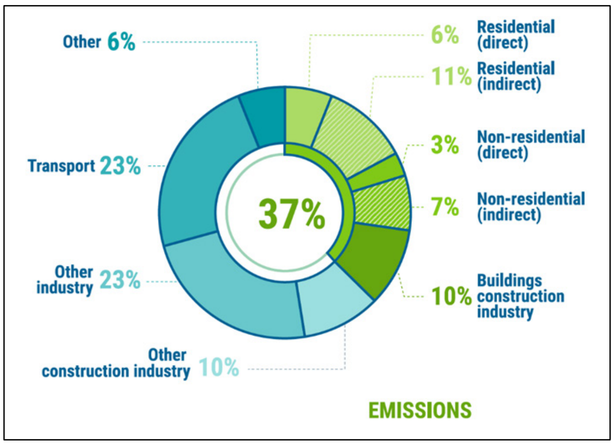


Figure 10. A diagram showing the percentage of globally buildings and construction final emissions in 2021 [60]

6. Impact of Nanotechnology on the Construction Sector

Using nanotechnology as a specialized technique to solve climate change issues and reduce carbon emissions is a promising solution to rescue the planet and achieve sustainable principles. As a result, in the construction field, nanotechnology is significantly connected to sustainability. Thus, numerous governments have pledged to work toward that goal to enhance energy efficiency and lower greenhouse gases. CO2 emissions must be cut in half worldwide by the year 2050, and this is possible only with fast action. The construction industry is one of the top producers of CO2 emissions, reaching 37% globally by 2021, as shown in Figure 10 [60], so energy-efficient construction is essential. Architects can use new nanomaterials to improve energy efficiency and create more sustainable buildings with innovative forms [61-63].

7. Proposed Strategy for Evaluating Nanomaterials in Construction

The research topic is based on what was extrapolated in the previous theoretical sections, including the introduction, the literature review, the prevailing nanomaterials, and their relationship to sustainable architecture, particularly in the construction sector. Hence, a strategy has been extrapolated and proposed in four main aspects to evaluate the efficacy of nanomaterials in the construction sector as follows:

(a) Principles of sustainable design.
(b) Criteria of sustainable materials.
(c) Aspects of energy efficiency.
(d) Factors of ambient environment efficiency.

7.1. Principles of Sustainable Design

The overall purpose of Sustainable design is to minimize human impact on the environment. Here is a list of 6 Principles specific to building, as follows [64]:

(a) Optimize Site Potential: The buildings' location, orientation, landscaping, transportation, and energy usage, affect local ecosystems.
(b) Optimize Energy Use: Global climate change, increased demand for fossil fuels, and decarbonization concerns need to reduce energy loads, enhance efficiency, and integrate renewable energy sources in buildings.
(c) Optimize Building Space and Material Use: Selecting low-impact, minimally energy-intensive, non-toxic, sustainably-made, or recycled materials.
(d) Enhance Indoor Environmental Quality: It affects the productivity, health, and comfort of building users by managing variables such as natural lighting, ventilation and humidity, and insulation.
(e) Optimize Operational and Maintenance Practices: Choosing materials and systems that minimize maintenance, energy, water, and resource costs and use less harmful materials.
(f) Protect and Conserve Water: Efficient water use to reduce freshwater consumption, recycle grey water, and collect rainwater.

7.2. Criteria of Sustainable Materials

It can be defined as materials with a limited negative environmental impact. Classification of materials as sustainable must achieve some criteria as follows [65,66]:

(a) Low-impact materials: Reduced environmental impact such as Co_2 and preferably be local materials.
(b) Non-toxic- materials: Reduced toxic emissions.
(c) Energy-efficient material: High efficiency in thermal and energy needed in the construction process.
(d) Function fulfillment: Durability and weather resistance.
(e) Recyclable: Recyclability and renewability of materials and the demolished building.
(f) Reduce maintenance: Low cost of transport and maintenance.

7.3. Aspects of Energy Efficiency

It is a vital aspect of sustainability; the correct use of Nanomaterials in buildings plays a crucial role in achieving energy efficiency. Nanomaterials such as glass, insulation materials, and coatings reduce energy consumption in buildings. Energy efficiency can be achieved in buildings through some aspects as follows [3,67,68]:

(a) Improve thermal insulation.
(b) Reducing energy consumption in manufacturing.
(c) Reducing energy consumption in implementation.
(d) Reducing energy consumption in operation.

7.4. Factors of Ambient Environment Efficiency

Integrating Nanomaterials in building design and harnessing it to achieve sustainability goals and serve environmental issues lead to enhancing the quality of the ambient environment by reducing pollution in the air. The Titanium Dioxide Nanoparticles (TiO_2) play a crucial role in this goal, purifying the surrounding air through a photocatalytic effect. These are the two main aspects of this nano property [69,70]:

(a) Reduce carbon emissions.
(b) Air purification of pollutants and bacteria.

7.5. Steps to Apply the Proposed evaluation Strategy to the Buildings:

The proposed strategy can be applied through the following steps:

(a) Description and analysis of the building in all its primary aspects, such as its location determinates, construction elements, environmental impact, and the used nanomaterials.

(b) Explanation of the used nanomaterials, how they were applied, and how they contribute to achieving the strategic aspects.
(c) Based on the gathered and analyzed data, the proposed evaluation strategy of the nanomaterials used in the building can be applied, which consists of four main aspects, indicating the extent to which the used nanomaterials achieve these aspects. This is detailed in a branched table, each aspect has several elements, and each element is evaluated separately in detail; hence an evaluation is given to the extent to which the nanomaterial used has achieved this factor, ranging from excellent effect, good effect, medium effect, weak effect.

8. Criteria for Carrying Out the Case Studies

Following are the three main points that the case studies are structured around:

8.1. Analytical Study Objectives

It can be outlined in four objectives, as follows:
(a) Apply the proposed evaluation strategy to the three buildings of the case studies to clarify the evaluation methodology and its outputs.
(b) Explanation of the performance of nanomaterials used in the building and their functional efficiency.
(c) Elucidation of the extent to which nanomaterials achieve sustainable design principles.
(d) Clarification of the impact of harnessing nanomaterials in construction on the ambient environment.

8.2. Analytical Study Methodology

As shown in Figure 11, the three case studies were conducted through several stages to achieve the primary objective, as follows:
(a) A comprehensive description to enumerate the used nanomaterials and their different applications.
(b) Applying the evaluation strategy out of four main aspects, as follows:
- Achieving sustainable design principles.
- Achieving sustainable materials criteria.
- Achieving energy efficiency aspects.
- Achieving ambient environment efficiency aspects.

(c) Discuss the outputs of the evaluation.

8.3. Analytical Study Samples Determinants and Selection

The study samples were selected based on the following determinants:
(a) Diversity in the type of building, its function, location, and the surrounding environmental conditions.
(b) Diversity in nanomaterials used.
(c) The date of completion of the building does not exceed fifteen years from the present time.

Accordingly, three case studies were selected based on the mentioned determinants, and they are as follows:
- Manuel de Gonzalez Hospital façade in Mexico.
- Italy Pavilion (Milan Expo) in Italy.
- Yale University Sculpture Building and Gallery in the USA.

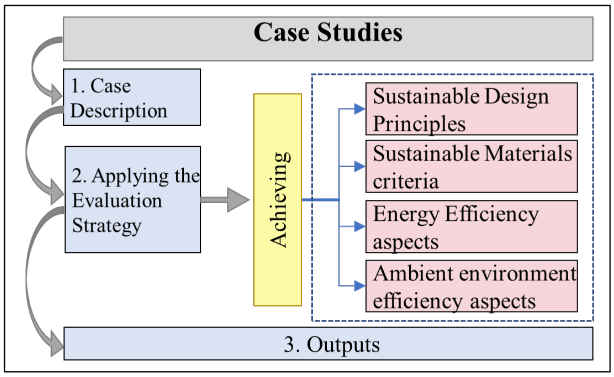


Figure 11. Analytical Study Methodology (the authors)

9. Conducting the Case Studies

Three case studies were selected based on the mentioned determinants, as follows:
- Manuel de Gonzalez Hospital façade in Mexico.
- Italy Pavilion (Milan Expo) in Italy.
- Yale University Sculpture Building and Gallery in the USA.

9.1. Case 1: Manuel de Gonzalez Hospital façade

9.1.1. Description of Case 1

It comes in seven items, as shown in Table 1.

Table 1. Manuel de Gonzalez Hospital façade description [71]

#	The item	Description
	Project Name	Manuel de Gonzalez Hospital facade
	Location	Mexico City, Mexico
	Architect	Allison Dring & Daniel Schwaag
	Year completed	2013
	Type	Medical
	Area	2500 m2
	Nanomaterials used	Titanium dioxide coating (Photocatalysis-Effect)

In 1992, Mexico City was the most polluted city globally, with about 35,000 deaths reported yearly [72,73]. The Manuel de Gonzalez hospital is located on the main street. It is impacted by heavy traffic, which contradicts the environment required for medical buildings. Consequently, the architect used nanoscale (TiO2) to reduce the negative impact by purifying the air from damage equivalent to 1,000 cars per day [71,74]. This unique quasicrystal facade of the hospital took around four years to complete. It consists of "prosolve370" modules covering an area of 2500 m2 made with a lightweight thermoformed plastic sheet coated with superfine nano TiO2, as shown in Figure 12.

This elegant pattern was fixed on the southern facade of the building 100 meters long, which faced the sun rays strongly and directly for the most extended period. Thus, the primary function of this aesthetic form is to treat the building and its surroundings environmental with photocatalytic capabilities. The nano TiO2 coating interacts with the sun's rays continuously on the southern facade; it breaks down the harmful pollutants in the surrounding air into oxygen and other harmless substances, which works to purify the air of exhaust and pollutants and resist bacteria, dirt, and fungi, as illustrated in Figure 13 and Figure 14 [71,75]. Furthermore, the sculptural facade creates shade areas on the building, helping to keep the interior spaces at a cool temperature. As a result, this raises energy efficiency and reduces the consumption needed to cool the building to a minimum [71].

Figure 12. A view of Manuel de Gonzalez Hospital elevation [71]

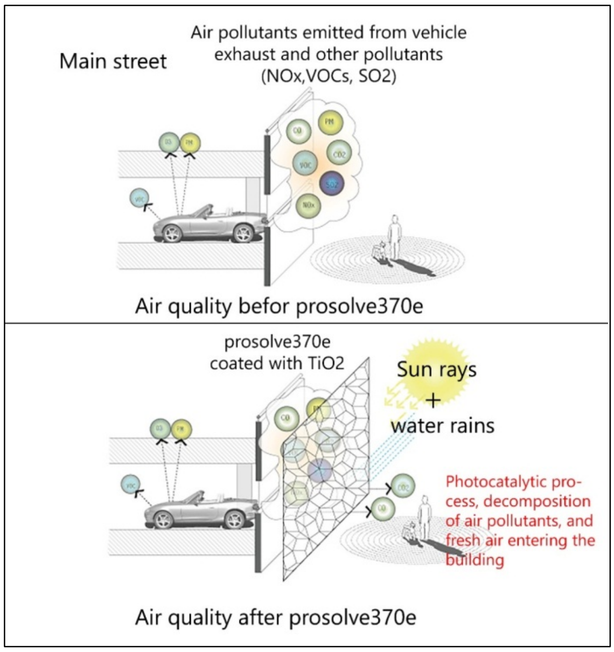


Figure 13. The functioning of the TiO_2-coated façade (Prosolve 370e) and the difference between it and the conventional façade [71]

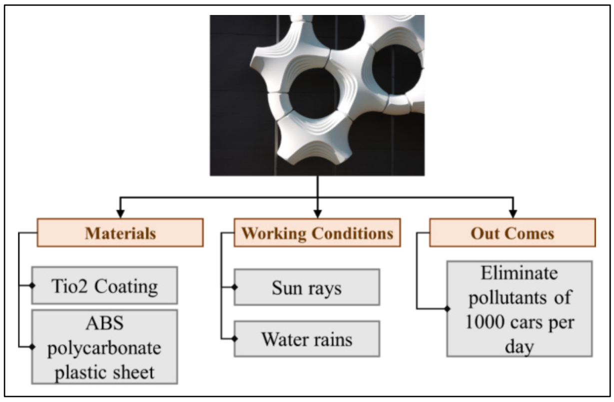


Figure 14. Prosolve 370e Analysis [71] (edited by the authors)

9.1.2. Applying the Evaluation Strategy

The evaluation explained in Table 2 was based on the four main aspects previously explained:

Table 2. Evaluation strategy for applying nanomaterials for Manuel de Gonzalez Hospital

√ Used - Non used ◙ Excellent effect

● Good effect ○ Medium effect ○ Weak effect

Nanomaterials used in buildings (Nano-construction-materials)							
Nano-thermal insulation materials			Nano-coatings		Nano-concrete		Nano glass
Vacuum insulation panel (VIP)	Phase change material (PCM)	Aerogel	Self-cleaning lotus effect coating	Self-cleaning Photocatalytic coating	Nano-silica concrete	Photocatalytic self-cleaning concrete	
-	-	-	-	√	-	-	-

Evaluation strategy for applying nanomaterials to the building according to the following four aspects					
(a) Sustainable design principles					
Optimize site potential	Optimize energy use	Optimize building space and material use	Enhance indoor environmental quality	Optimize operational and maintenance practices	Protect and conserve water
●	●	◙	◙	●	○

(b) Sustainable materials						(c) Energy efficiency				(d) Ambient environment efficiency	
Low-impact materials	Non-toxic materials	Function fulfillment	Recyclable	Reduce maintenance	Aesthetic standards	Improve thermal insulation	Reducing energy consumption in manufacturing	Reducing energy consumption in implementation	Reduce energy consumption in operation	Reduce carbon emissions	Air purification of pollutants and bacteria
◙	◙	◙	◙	◙	◙	○	●	●	●	◙	◙

9.1.3. Outputs of Case 1

A self-cleaning photocatalytic coating material was applied to the building facade, which led to many promising outcomes that were used to evaluate the elements of the strategy aspects; they can be summarized as follows:

(a) Fighting environmental pollution and eliminating pollutants of 1000 cars a day.

(b) The integrations of the nanomaterial were used to the site's limitations and conditions, as the city was famous for its high pollution rates.

(c) Integrating the nanomaterial to the type of building (medical) requires pure air.

(d) Improving indoor and outdoor environment quality.

(e) Reducing maintenance costs due to the self-cleaning property.

(f) Increasing energy efficiency by keeping the interior environment cool thanks to the shadows created on the building by the installed module façade.
(g) Reducing environmental impacts such as CO2 emissions.
(h) Achieving aesthetic standards, as the building façade represents a distinctive white sculptural module.
(i) Modular units are lightweight, so they do not need cranes to install them, but relatively well-trained workers, which saves on the energy consumed in installation.

A self-cleaning photocatalytic coating material had a medium to weak effect in the following:
(a) Improving thermal insulation.
(b) Protecting and conserving water.

9.2. Case 2: Italy Pavilion (Milan Expo)

9.2.1. Description of Case 2

It comes in seven items, as shown in Table 3.

Table 3. Italy Pavilion (Milan Expo) description [76]

#	The item	Description
	Project Name	Italy Pavilion (Milan Expo)
	Location	Milano, Italy
	Architect	Nemesi & Partners Srl
	Year completed	2015
	Type	Culture/ Entertainment
	Area	27000 m²
	Nanomaterials used	Photocatalytic self-cleaning concrete (Photocatalysis-Effect)

The designer of the Italy pavilion at expo 2015 has combined architectural technology and primitive images of the forest concept to produce this architectural sculpture with its branched outer envelope. The pavilion features a unique facade represented in a geometric pattern of entwined random branches, as shown in Figure 15. These exterior biodynamic panels are made of self-cleaning concrete with a photocatalytic feature that absorbs air pollutants and converts them to inert salts, lowering smog levels, which contributes enormously to the purification of the internal and external environment of the building. Also, The facade is self-cleaned by rainwater and does not need to be maintained periodically like traditional concrete, which reduces maintenance costs [76,77].

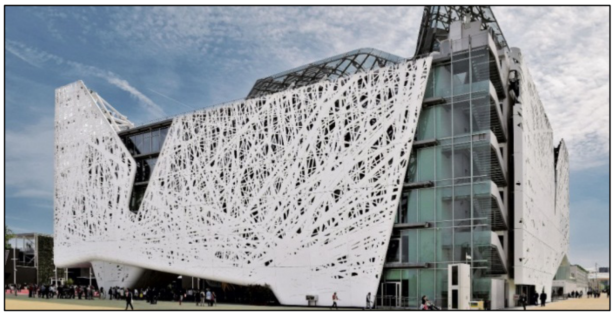


Figure 15. Italian Pavilion Expo exterior showing the branched TiO_2 concrete [76]

Over 700 branched TiO2 panels (about 2,000 tons of TiO2 concrete) have been installed on the pavilion façade by cranes covering an area of 9,000 m2. Thus, this active concrete interacts with ultraviolet rays and eliminates air pollution and dirt presented in Figure 16. Hence, the mortar is made of 80 percent recycled aggregates, including leftover material from Carrara marble quarries, adding more luster than traditional white cement. In addition, the designer integrated photovoltaic glass in the roof on flat, curved geometric shapes, which increased the building's energy efficiency and lowered carbon emissions, as illustrated in Figure 17 [77].

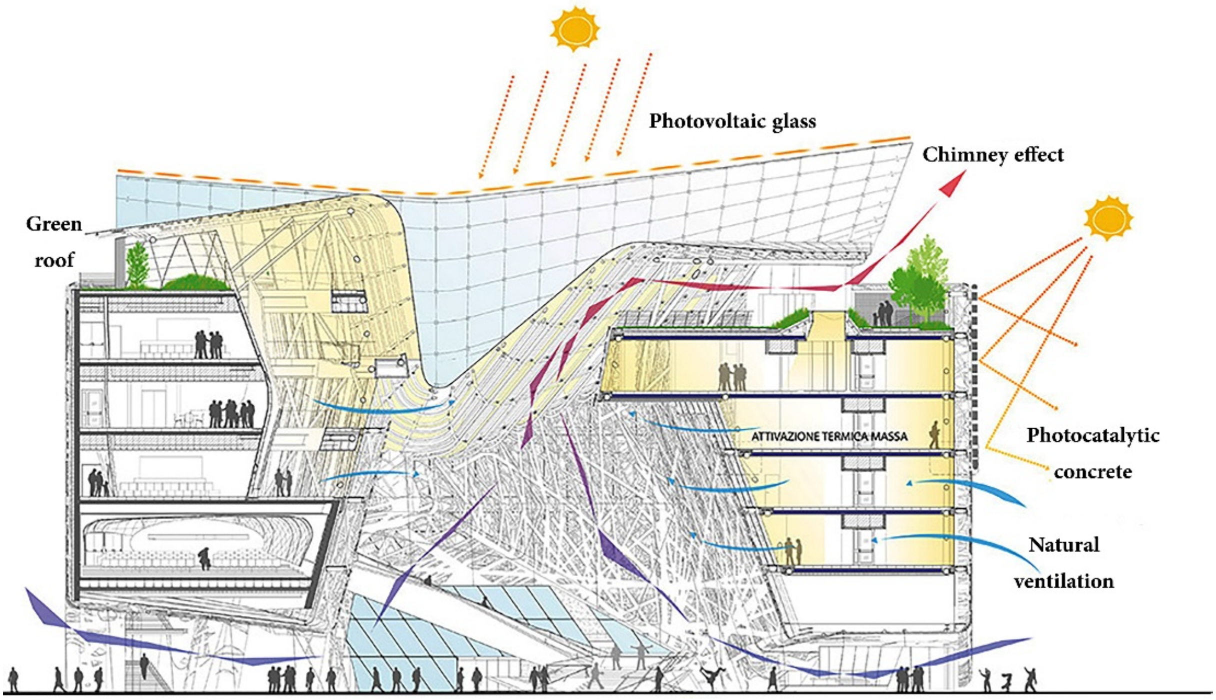


Figure 16. Section diagram showing the used techniques in Italy pavilion [78]

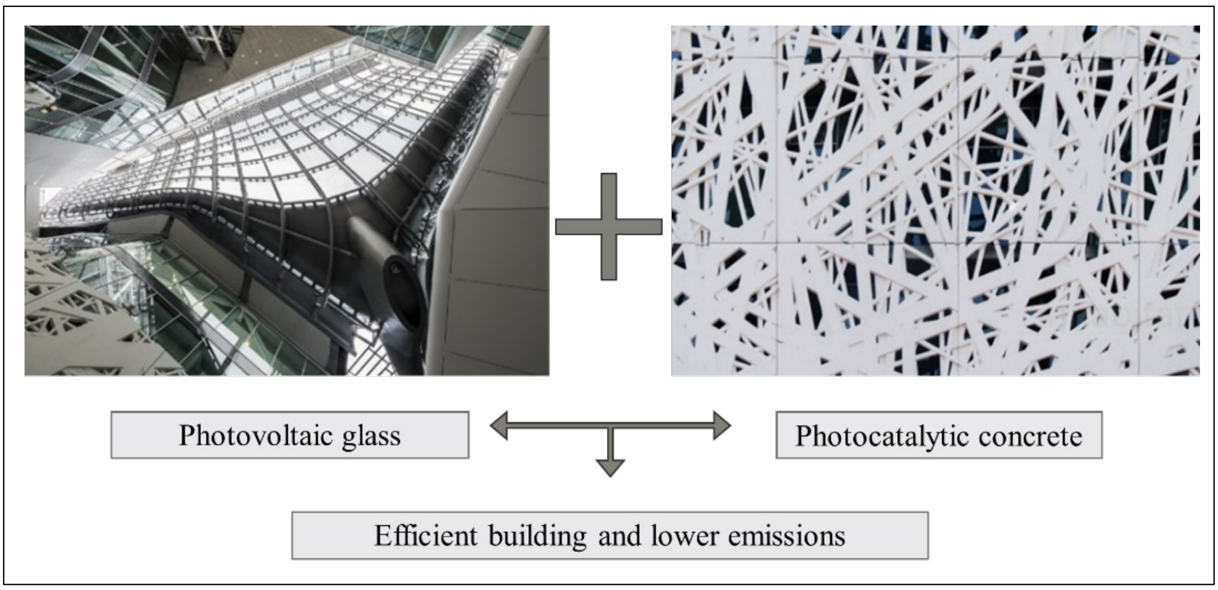


Figure 17. A photovoltaic glass roof and photocatalytic TiO_2 self-cleaning concrete cladding of the Italian pavilion [77,79], edited by the authors

9.2.2. Applying the Evaluation Strategy

The evaluation explained in Table 4 was based on the four main aspects previously explained:

Table 4. Evaluation strategy for applying nanomaterials for Italy Pavilion (Milan Expo)

√ Used - Non used ◙ Excellent effect

● Good effect ○ Medium effect ◌ Weak effect

Nanomaterials used in buildings (Nano-construction-materials)							
Nano-thermal insulation materials			Nano-coatings		Nano-concrete		Nano glass
Vacuum insulation panel (VIP)	Phase change material (PCM)	Aerogel	Self-cleaning lotus effect coating	Self-cleaning Photocatalytic coating	Nano-silica concrete	Photocatalytic self-cleaning concrete	
-	-	-	-	-	-	√	-

Evaluation strategy for applying nanomaterials to the building according to the following four aspects					
(a) Sustainable design principles					
Optimize site potential	Optimize energy use	Optimize building space and material use	Enhance indoor environmental quality	Optimize operational and maintenance practices	Protect and conserve water
●	○	◙	◙	●	◌

(b) Sustainable materials						(c) Energy efficiency				(d) Ambient environment efficiency	
Low-impact materials	Non-toxic materials	Function fulfillment	Recyclable	Reduce maintenance	Aesthetic standards	Improve thermal insulation	Reducing energy consumption in manufacturing	Reducing energy consumption in implementation	Reduce energy consumption in operation	Reduce carbon emissions	Air purification of pollutants and bacteria
◙	◙	◙	◙	◙	◙	◌	●	○	●	◙	◙

9.2.3. Outputs of Case 2

A Photocatalytic self-cleaning nano concrete was applied to the building facade, which led to many promising outcomes that were used to evaluate the elements of the strategy aspects; they can be summarized as follows:

(a) Fighting environmental pollution and eliminating car exhaust.
(b) Improving indoor and outdoor environment quality and purifying air from pollutants.
(c) Reducing environmental impacts such as CO_2 emissions.
(d) Reducing maintenance costs due to the self-cleaning property.

(e) Increasing energy efficiency by keeping the interior environment cool thanks to the shadows created on the building by the installed branched façade.
(f) Integrating sustainable architecture and nanotechnology results in nanoarchitecture (photovoltaic glass + TiO_2 concrete) to cover the building's energy needs efficiently and autonomously.
(g) Achieving aesthetic standards, as the building façade represents a landmark of the expo.

A Photocatalytic self-cleaning nano concrete had a medium to weak effect in the following:
(a) Improving thermal insulation.
(b) Reducing energy consumption in implementation due to using cranes to install the façade.
(c) Optimizing energy use.
(d) Protecting and conserving water.

9.3. Case 3: Yale University Sculpture Building and Gallery

9.3.1. Description of Case 3

It comes in seven items, as shown in Table 5.

Table 5. Yale University Sculpture Building and Gallery description [80]

#	The item	Description
	Project Name	Yale University Sculpture Building
	Location	Connecticut, USA
	Architect	Kieran Timberlake Associates
	Year completed	2007
	Type	Mixed Use (Education/ Entertainment/Culture).
	Area	5760 m^2
	Nanomaterials used	Aerogel (Thermal insulation)

The mixed-use Yale building features a highly efficient façade that integrates solar shading and triple-glazed curtain walls. It extends over a wide area of the building facade with low-emissivity panels and is filled with translucent nano-aerogel in its cavity, 2.4-meter-high operable windows, as presented in Figure 18. As a result, the structure has a high level of energy efficiency while staying almost entirely transparent. According to testing, the spandrel assembly's overall R-value (thermal resistance) exceeds R 20 while keeping a 20 percent visible light transmittance [80].

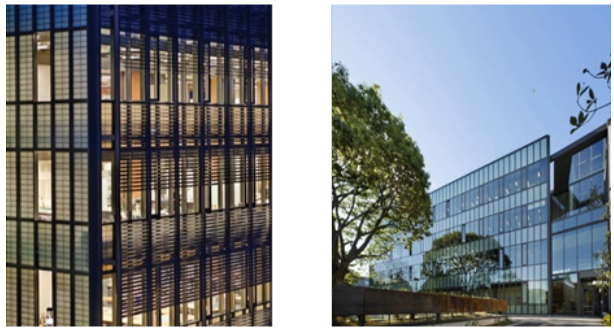


Figure 18. The high-performance façade of Yale University Sculpture Building and Gallery [81]

The need for cooling and heating systems is reduced by exposed concrete slabs and high-performance curtainwall isolated by translucent aerogel. Consequently, while delivering natural light to indoor areas, it limits solar heat gain in the summer, saves a significant amount of energy consumed by artificial lighting, raises the quality of the indoor environment, and reduces CO2 emissions, as shown in Figure 19. Based on these efforts, the building has been certified by LEED with the Platinum Certificate [81,82].

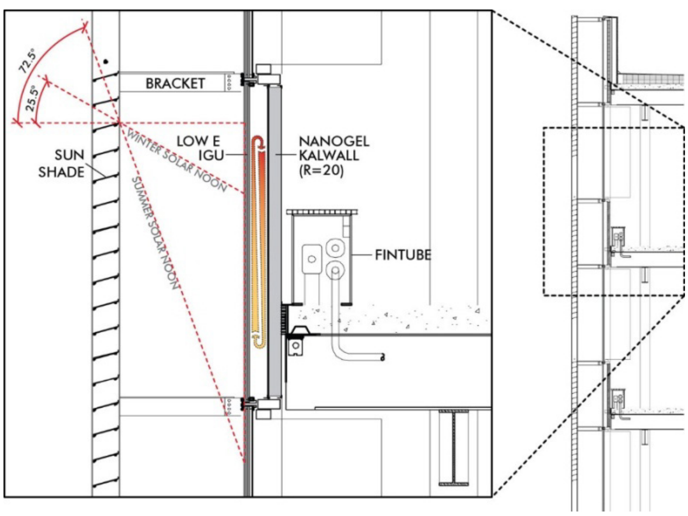


Figure 19. Section diagram of Yale University Sculpture Building [83]

9.3.2. Applying the Evaluation Strategy

The evaluation explained in Table 6 was based on the four main aspects previously explained:

Table 6. Evaluation strategy for applying nanomaterials for Yale University Sculpture Building and Gallery

√ Used - Non used ◙ Excellent effect

● Good effect ○ Medium effect ◯ Weak effect

Nanomaterials used in buildings (Nano-construction-materials)							
Nano-thermal insulation materials			Nano-coatings		Nano-concrete		
Vacuum insulation panel (VIP)	Phase change material (PCM)	Aerogel	Self-cleaning lotus effect coating	Self-cleaning Photocatalytic coating	Nano-silica concrete	Photocatalytic self-cleaning concrete	Nano glass
-	-	√	-	-	-	-	-

Evaluation strategy for applying nanomaterials to the building according to the following four aspects					
(a) Sustainable design principles					
Optimize site potential	Optimize energy use	Optimize building space and material use	Enhance indoor environmental quality	Optimize operational and maintenance practices	Protect and conserve water
○	◙	◙	●	○	◯

(b) Sustainable materials						(c) Energy efficiency				(d) Ambient environment efficiency	
Low-impact materials	Non-toxic materials	Function fulfillment	Recyclable	Reduce maintenance	Aesthetic standards	Improve thermal insulation	Reducing energy consumption in manufacturing	Reducing energy consumption in implementation	Reduce energy consumption in operation	Reduce carbon emissions	Air purification of pollutants and bacteria
◙	◙	◙	◙	○	◙	◙	◙	◙	◙	◙	◯

9.3.3. Outputs of Case 3

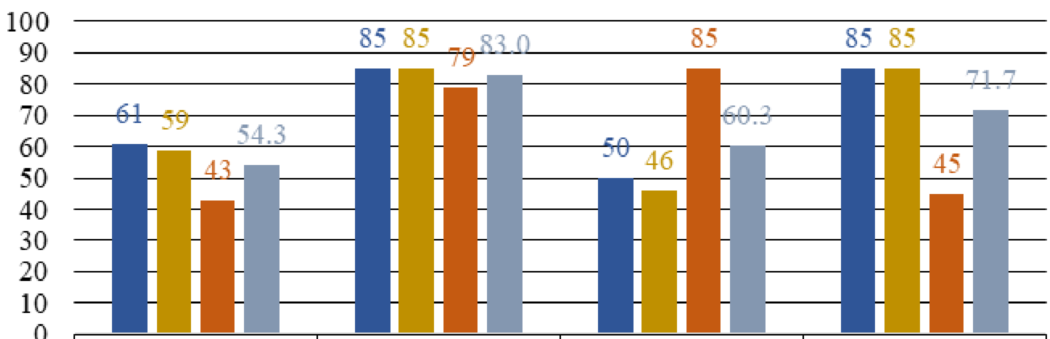
An Aerogel nano-thermal insulation material was applied to the building, which led to many promising outcomes that were used to evaluate the elements of the strategy aspects; they can be summarized as follows:

(a) Achieving superior thermal insulation compared to traditional insulation material with R-value exceeding 20, optimizing energy use.
(b) Utilizing natural light instead of artificial light with a 20% visible light transmittance increases energy efficiency.
(c) Enhancing user interaction with the external environment through translucent isolated glazing by aerogel.
(d) Improving indoor and outdoor environment quality
(e) Reducing environmental impacts such as CO_2 emissions.
(f) Achieving aesthetic standards, as the distinctive glazing represents the building façade.

An Aerogel nano-thermal insulation material had a medium to weak effect in the following:
(a) Purification of the air out of pollutants.
(b) Reducing maintenance costs.
(c) Protecting and conserving water.
(d) Optimizing site potential

10. Results

Clarifying the efficiency of the used nanomaterials by reviewing the theoretical studies and analyzing the previous cases, an evaluation was done based on the four main aspects previously explained. Through the previous Tables 2,4,6 and Figure 20, this study shows:



	(a) Sustainable design principles	(b) Sustainable materials criteria	(c) Energy efficiency aspects	(d) Ambient environment efficiency factors
Case 1	61	85	50	85
Case 2	59	85	46	85
Case 3	43	79	85	45
Average	54.3	83.0	60.3	71.7

Figure 20. Histogram relationship of cases to the four main evaluation aspects (the authors)

- For case 1, the percentage of achieving aspect (a) is 61%, 85% for aspects (b) and (d), whereas the lowest percentage is 50% for aspect (c).
- For case 2, the percentage of achieving aspect (a) is 59%, 85% for aspects (b) and (d), whereas the lowest percentage is 46% for aspect (c).
- For case 3, the percentage of achieving aspect (b) is 79%, 85% for aspect (c), and 45% for aspect (d), whereas the lowest percentage is 43% for aspect (a).
- For aspect (a), the nanomaterials used in the three cases achieved a percentage ranging from 43-61%, averaging 54.3%.
- For aspect (b), it achieved a percentage ranging from 79-85%, with an average of 83%.
- For aspect (c), it achieved a 50-85% percentage, averaging 60.3%.
- For aspect (d), it achieved a percentage ranging from 45-85%, averaging 71.7%.

11. Discussion

The study confirmed the research's objectives by enumerating and analyzing the nanomaterials in the previous case studies based on the proposed strategy. A set of aspects were proposed to evaluate these nanomaterials, which demonstrate the impact of using them in the construction sector, leading to:

(a) Among all aspects, aspect (b) averaged the highest percentage, 83%, indicating that the nanomaterials utilized in the selected case studies considerably meet the criteria of sustainable materials. As a result, nanomaterials can be used to boost sustainability from this point of view.

(b) The aspect (d) comes in second place on average 71%, indicating that the used materials meet the factor of ambient environment efficiency. As a result, titanium dioxide nanoparticles proved their efficiency in these cases by integrating photocatalytic properties with traditional materials such as concrete in case 2 and coatings in case 1, leading to a practical solution to fight air pollution and reduce carbon emissions and the need for maintenance.

(c) Aspect (c) achieved an average of 60.3%, indicating that the used materials meet the energy efficiency factor. Aerogel thermal insulation nanomaterial used in case 3 reached 85% in this aspect, showing unique properties in thermal insulation, enhancing energy efficiency, reducing consumption, and thus leading to lower carbon emissions.

(d) Aspect (a) achieved the lowest percentage, averaging 54.3%, indicating that the nanomaterials utilized in the selected case studies considerably meet the criteria of sustainable design principles in varying proportions. As a result, harnessing nanomaterials in the construction sector boost buildings to be greener and reduce negative environmental impacts with better functional performance, meeting the sustainability goals.

(e) Location diversity of the addressed buildings in these case studies, with their different climatic regions and the various surrounding conditions, indicate the possibility of using nanomaterials in various regions, except for some cold regions due to photocatalytic properties requiring much sunlight.

12. Conclusions

The study highlights the importance of developing and utilizing nanomaterials to achieve the goals of sustainable architecture. Nanomaterials did not yet reach most worldwide due to their high cost. This study reviewed the theoretical background of nanotechnology and covered its use in architecture by addressing the prevailing nanomaterials in the construction sector as a major application. It detailed concrete, glass, coating, and thermal insulation materials. Additionally, it defined its relationship to sustainable architecture and its potential to boost sustainability. Furthermore, it explained how these materials reduce the carbon footprint and enhance the material properties. By the end of the theoretical section, the study proposed a strategy to evaluate nano-construction materials based on the four main aspects: sustainable design principles, sustainable materials criteria, energy efficiency aspects, and ambient environment efficiency factors.

Therefore, the applied section contained an analytical study for three case studies through two subsections; the first defined the criteria for carrying out the case studies; the second conducted the case studies. Results of the study, the discussion, and the analysis showed that harnessing nano-construction materials boost sustainable architecture. Moreover, it improves the functions and performance of construction materials to boost sustainability in the four mentioned aspects. This study addressed nanomaterials only from the environmental point of view. Hence, it is recommended to cover the social and economic sides for future studies. On the other hand, it is recommended to direct research generally to nano-applications in all architectural aspects.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

REFERENCES

[1] Initiative, N.N. Glossary. https://www.nano.gov/about-nni/glossary, accessed on 16 January 2022.

[2] Rockwood, T. Studying bionanoengineering | Ask a biologist, building at a Nanoscale. https://askabiologist.asu.edu/explore/building-nanoscale accessed on 5 December 2021.

[3] Leydecker, S., "Nano materials: in architecture, interior architecture and design," Springer Science & Business Media: Berlin, Germany. ISBN:978-3-7643-7995-7, 2008. https://link.springer.com/book/10.1007/978-3-7643-8321-3, https://doi.org/10.1007/978-3-7643-8321-3.

[4] Freitas, L.F.d.; Varca, G.H.C.; Batista, J.G.D.S.; Lugão, A.B. "An overview of the synthesis of gold nanoparticles using radiation technologies," Nanomaterials, vol. 8, no.11, pp. 939, 2018, doi: https://doi.org/10.3390/nano8110939.

[5] Karkare, M., "Nanotechnology - Fundamentals and Applications," First ed.; Wiley: India.

ISBN:9789389583724, 2020.https://www.flipkart.com/nanotechnology-fundamentals-applications-first/p/itm6e4d582cd27fb,

[6] Iso.org. ISO/TS 80004-1:2015(en), Nanotechnologies–Vocabulary–Part 1: Core Terms. https://www.iso.org/obp/ui/#iso:std:iso:ts:80004:-1:ed-2:v1:en, accessed on 11 April 2021.

[7] Dhir, R.; Ghataora, G.; Lynn, C., "Sustainable Construction Materials: Sewage Sludge Ash," Woodhead Publishing: ISBN:9780081009871, 2017. https://doi.org/10.1016/B978-0-08-100987-1.01001-5.

[8] Alia, R.A.; Kharofab, O.H. "The impact of nanomaterials on sustainable architectural applications smart concrete as a model," Materials Today: Proceedings, vol. 42, pp. 3010-3017, 2021, doi: https://doi.org/10.1016/j.matpr.2020.12.814.

[9] Bayda, S.; Adeel, M.; Tuccinardi, T.; Cordani, M.; Rizzolio, F. "The History of Nanoscience and Nanotechnology: From Chemical–Physical Applications to Nanomedicine," Molecules vol. 25, no.1, pp. 112, 2020, doi: https://doi.org/10.3390/molecules25010112.

[10] L. Love; B. Post; M. Noakes; A. Nycz; Kunc, V. "There's plenty of room at the top," Additive Manufacturing, vol. 39, no.-, pp. 101727, 2021, doi: https://doi.org/10.1016/j.addma.2020.101727.

[11] Mulvaney, P. "Nanoscience vs. Nanotechnology—Defining the Field," ACS Nano, vol. 9, no.3, pp. 2215-2217, 2015, doi: https://doi.org/10.1021/acsnano.5b01418.

[12] Krieg, M.; Fläschner, G.; Alsteens, D.; Gaub, B.M. "Atomic force microscopy-based mechanobiology," Nature Reviews Physics, vol. 1, no.1, pp. 41-57, 2019, doi: https://doi.org/10.1038/s42254-018-0001-7.

[13] Sanders, W.C., "Basic Principles of Nanotechnology," 1st ed.; CRC Press: Boca Raton. ISBN:9781351054423, 2018. https://www.taylorfrancis.com/books/mono/10.1201/9781351054423/basic-principles-nanotechnology-wesley-sanders, https://doi.org/10.1201/9781351054423.

[14] IBM. Scanning Tunneling Microscope. https://www.ibm.com/ibm/history/ibm100/us/en/icons/microscope/breakthroughs/ accessed on 23 July 2021.

[15] Initiative, N.N. Nanotechnology Timeline. https://www.nano.gov/timeline, accessed on 12 March 2022.

[16] Betancourt, M.L.G.; Ramirez-Jimenez, S., "Low Dimensional Nanostructures: Measurement and Remediation Technologies Applied to Trace Heavy Metals in Water," in: Trace Metals in the Environment-New Approaches and Recent Advances. Intech Open.https://ideas.repec.org/h/ito/pchaps/200463.html, https://doi.org/10.5772/intechopen.93263.

[17] Giovaabbatichio. Categorization of Nanomaterials: 0D - 1D - 2D. https://steemit.com/steemstem/@giovaabbatichio/categorization-of-nanomaterials-0d-1d-2d, accessed on 6-Jan-2021.

[18] Khan, F.A., "Nanomaterials: types, classifications, and sources," in: Applications of Nanomaterials in Human Health. Springer Singapore: Singapore, pp. 1-13. https://doi.org/10.1007/978-981-15-4802-4_1.

[19] Wong, S.; Karn, B. "Ensuring sustainability with green nanotechnology," Nanotechnology, vol. 23, no.29, pp. 290201, 2012, doi: https://doi.org/10.1088/0957-4484/23/29/290201.

[20] Khan, S.H., "Green Nanotechnology for the Environment and Sustainable Development," in: Green Materials for Wastewater Treatment. Springer International Publishing: Cham, Vol. 38, pp. 13-46. https://link.springer.com/chapter/10.1007/978-3-030-17724-9_2, https://doi.org/10.1007/978-3-030-17724-9_2.

[21] Konbr, U.; Lebda, A. "Criteria of Sustainable Interior Design based on the Green Pyramid Rating System," Journal of Engineering Research, vol. 3, no.December, pp. 48-60, 2019, doi: https://doi.org/10.21608/erjeng.2019.125753.

[22] Elvin, G., "Building Green with Nanotechnology," in: 2007 Cleantech Conference and Trade Show Cleantech 2007.1st Edition ed.; CRC Press: pp. 167-170. https://www.taylorfrancis.com/chapters/edit/10.1201/9780429187469-43/building-green-nanotechnology-elvin, https://doi.org/10.1201/9780429187469-43.

[23] Shiba, A.S.E. "The use of nanomaterial's applications in buildings and their contribution to supporting green technology," Journal of Architecture, Arts and Humanities Science, vol. 9, no.43, pp., 2022, doi: https://doi.org/10.21608/MJAF.2022.107389.2560.

[24] Cheng, T.-W.; Kang-Wei Lo; Lin, K.-L.; Lan, J.-Y. "Study on the effects Nano-SiO2 and spent catalyst ratios on characteristics of metakaolin-based geopolymers," Environmental Progress Sustainable Energy, vol. 38, no.1, pp. 220-227, 2019, doi: https://doi.org/10.1002/ep.12921.

[25] IEA. Tracking Buildings 2021; The International Energy Agency: IEA, Paris, 2021. https://www.iea.org/reports/tracking-buildings-2021.

[26] Shilar, F.A.; Ganachari, S.V.; Patil, V.B.; Khan, T.M.Y.; Almakayeel, N.M.; Alghamdi, S. "Review on the Relationship between Nano Modifications of Geopolymer Concrete and Their Structural Characteristics," Polymers, vol. 14, no.7, pp. 1421, 2022, doi: https://doi.org/10.3390/polym14071421.

[27] Mohajerani, A.; Burnett, L.; Smith, J.V.; Kurmus, H.; Milas, J.; Arulrajah, A.; Horpibulsuk, S.; Kadir, A.A. "Nanoparticles in Construction Materials and Other Applications, and Implications of Nanoparticle Use," Materials (Basel), vol. 12, no.19, pp. 3052, 2019, doi: https://doi.org/10.3390/ma12193052.

[28] Nanowerk. Nanotechnology in Construction. https://www.nanowerk.com/spotlight/spotid=26700.php, accessed on 31 August 2021.

[29] Leone, M.F. "Nanotechnology for Architecture. Innovation and Eco-Efficiency of Nanostructured Cement-Based Materials," Journal of Architectural Engineering Technology, vol. 1, pp. 1-9, 2012, doi: https://doi.org/10.4172/2168-9717.1000102.

[30] Zhang, P.; Xie, N.; Cheng, X.; Feng, L.; Hou, P.; Wu, Y. "Low dosage nano-silica modification on lightweight aggregate concrete," vol. 8, pp. 1847980418761283, 2018, doi: https://doi.org/10.1177/1847980418761283.

[31] Health, I.o.O.S.a. Nanotechnology in Construction and

Demolition Guidance for industry; Loughborough University, 2017. www.iosh.co.uk/nanotechnology.

[32] TOPÇU, İ.B.; AKKAN, E.; UYGUNOĞLU, T.; ÇALIŞKAN, K. "Self-Cleaning Concretes: An Overview," Journal of Cement Based Composites vol. 1, no.2, pp. 6-11, 2020, doi: https://doi.org/10.36937/cebacom.2020.002.002.

[33] LLP, R.M.a.P.A. Jubilee Church. https://archello.com/project/jubilee-church, accessed on 26-March-2022.

[34] Mann, S. Nanotechnology and Construction, 2006; Nanoforum-European Nanotechnology Gateway: Institute of Nanotechnology, 2006. www.nanoforum.org.

[35] Khandve, P. "Nanotechnology for building material," International Journal of Basic Applied Research, vol. 4, pp. 146-151, 2014.

[36] Tradekorea. TiO2 Photocatalyst. https://www.tradekorea.com/product/detail/P291864/TiO2-Photocatalyst.html, accessed on 10 September 2021.

[37] Nanowerk. Nanocoatings. https://www.nanowerk.com/nanocoatings.php, accessed on 20-September-2021.

[38] Nasiol. What is Nano Coating? Is It Really Important? https://www.nasiol.com/nanoblog/why-is-nano-coating-important/, accessed on 23 March 2022.

[39] Engineering, I. Nano-Coatings for Home and Industrial Use. https://interestingengineering.com/nano-coatings-for-home-and-industrial-use, accessed on 20 March 2022.

[40] Nanowerk. Nanotechnology Solutions for Self-Cleaning, Dirt and Water-Repellent Coatings. https://www.nanowerk.com/spotlight/spotid=19644.php, accessed on 21 Feb 2022.

[41] Buratti, C.; Moretti, E.; Belloni, E., "Nanogel Windows for Energy Building Efficiency," in: Nano and Biotech Based Materials for Energy Building Efficiency. Springer International Publishing: Switzerland, pp. 41-69. https://link.springer.com/chapter/10.1007/978-3-319-27505-5_3, https://doi.org/10.1007/978-3-319-27505-5_3.

[42] Riffat, S.B.; Qiu, G. "A review of state-of-the-art aerogel applications in buildings," International Journal of Low-Carbon Technologies, vol. 8, no.1, pp. 1-6, 2012, doi: https://doi.org/10.1093/ijlct/cts001.

[43] Aerogel. Welcome to Open Source Aerogel. http://www.aerogel.org/, accessed on 11 April 2022.

[44] Kistler, S.S. "Coherent Expanded-Aerogels," The Journal of Physical Chemistry, vol. 36, no.1, pp. 52-64, 1932, doi: https://doi.org/10.1021/j150331a003.

[45] Moga, L.; Bucur, A. "Nano Insulation Materials for Application in nZEB," Procedia Manufacturing, vol. 22, no.-, pp. 309-316, 2018, doi: https://doi.org/10.1016/j.promfg.2018.03.047.

[46] Reim, M.; Beck, A.; Körner, W.; Petricevic, R.; Glora, M.; Weth, M.; Schliermann, T.; Fricke, J.; Schmidt, C.; Pötter, F.J. "Highly insulating aerogel glazing for solar energy usage," Solar Energy, vol. 72, no.1, pp. 21-29, 2002, doi: https://doi.org/10.1016/S0038-092X(01)00086-X.

[47] M. Reim; Körner, W.; Manara, J.; Korder, S.; Arduini-Schuster, M.; Ebert, H.-P.; Fricke, J. "Silica aerogel granulate material for thermal insulation and daylighting," Solar Energy, vol. 79, no.2, pp. 131-139, 2005, doi: https://doi.org/10.1016/j.solener.2004.08.032.

[48] Buratti, C.; Belloni, E.; Merli, F.; Zinzi, M. "Aerogel glazing systems for building applications: A review," Energy and Buildings, vol. 231, pp. 110587, 2021, doi: https://doi.org/10.1016/j.enbuild.2020.110587.

[49] El-Hafez, M.A.; Elmokademorcid, A.A.E.; Abu-Samra, N. "Improve Energy Efficiency through Nano Pore Vacuum Insulation Panels "Vips"," Port-Said Engineering Research Journal, vol. 18, no.1, pp. 171-179, 2014, doi: https://doi.org/10.21608/PSERJ.2014.46825.

[50] Boafo, F.E.; Kim, J.-T.; Chen, Z. "Configured cavity-core matrix for vacuum insulation panel: Concept, preparation and thermophysical properties," Energy and Buildings, vol. 97, pp. 98-106, 2015, doi: https://doi.org/10.1016/j.enbuild.2015.03.056.

[51] Teggar, M.; Arıcı, M.; Mert, M.S.; Ajarostaghi, S.S.M. "A comprehensive review of micro/nano enhanced phase change materials," Journal of Thermal Analysis and Calorimetry, vol. 147, no.6, pp. 3989-4016, 2022, doi: https://doi.org/10.1007/s10973-021-10808-0.

[52] Zhu, N.; Ma, Z.; Wang, S. "Dynamic characteristics and energy performance of buildings using phase change materials: A review," Energy Conversion and Management vol. 50, no.12, pp. 3169-3181, 2009, doi: https://doi.org/10.1016/j.enconman.2009.08.019.

[53] Amin, M.; Afriyanti, F.; Putra, N. "Thermal properties of paraffin based nano-phase change material as thermal energy storage," IOP Conference Series: Earth and Environmental Science, vol. 105, no.1, pp. 012028, 2018, doi: https://doi.org/10.1088/1755-1315/105/1/012028.

[54] Tofani, K.; Tiari, S. "Nano-Enhanced Phase Change Materials in Latent Heat Thermal Energy Storage Systems: A Review," Energies, vol. 14, no.13, pp. 3821, 2021, doi: https://doi.org/10.3390/en14133821.

[55] Pasupathi, M.K.; Alagar, K.; Stalin, M.J.; M.M, M.; Aritra, G. "Characterization of Hybrid-nano/Paraffin Organic Phase Change Material for Thermal Energy Storage Applications in Solar Thermal Systems," Energies, vol. 13, no.19, pp., 2020, doi: https://doi.org/10.3390/en13195079.

[56] Larramendy, M.; Soloneski, S., "Green Nanotechnology: Overview and Further Prospects," ISBN:9535124099, 2016. https://www.intechopen.com/books/5170 https://doi.org/10.5772/61432.

[57] Elghonaimy, I.; Gharbal, S. "Creating a Healthy Sustainable Environment to Creating a Healthy Sustainable Environment to Maintain Bahraini Women' Rights Maintain Bahraini Women' Rights," BAU Journal - Creative Sustainable Development, vol. 2, no.2, pp. -, 2021.

[58] Saha, D. Nanotechnology in architecture. Manipal, 2015.

[59] Konbr, U. "Smart Buildings and Sustainability in Egypt-Formularization of a Concept and a Methodology Establishing," JES. Journal of Engineering Sciences, vol. 44, no.4, pp. 472-501, 2016, doi: https://doi.org/10.21608/jesaun.2016.117613.

[60] UNEP. 2021 Global Status Report for Buildings and

Construction: Towards a zero-emissions, efficient and resilient buildings and construction sector; United Nations Environment Programme Nairobi, 2021. https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction.

[61] Leydecker, S., "Nano Materials in Architecture, Interior Architecture and Design," Birkhäuser: ISBN: 978-3-7643-8321-3, 2008. https://doi.org/10.1515/9783764383213, doi:10.1515/9783764383213.

[62] Wei, Z.; Zandi, Y.; Gholizadeh, M.; Selmi, A.; Roco-Videla, A.; Konbr, U. "On the Optimization of Building Energy, Material, and Economic Management using Soft Computing," Advances in Concrete Construction, vol. 11, no.6, pp. 455-468, 2021, doi: https://doi.org/10.12989/acc.2021.11.6.455.

[63] Konbr, U.; Freewan, W.; Alshuk, R., The Use of Mud Material in Desert Cities' Construction as an Approach to Sustainability: Ghadames as a case study," in: Tanta University, the third international environmental forum, 2016; pp. 1-13. https://www.researchgate.net/publication/311570795_The_use_of_Mud_Material_in_Desert_Cities'_Construction_as_an_approach_to_Sustainability-_Ghadames_as_a_Case_Study.

[64] Committee, T.W.S. Sustainable https://www.wbdg.org/design-objectives/sustainable, accessed on 6 October 2021.

[65] Patil, K.M.; Patil, M.S. "Sustainable Construction Materials & Technology in Context with Sustainable Development," International Journal of Engineering Research and Technology, vol. 10, no.1, pp. 112-117, 2017.

[66] Konbr, U. "Building Materials: An Approach to Sustainable Construction System in Tanta City," Journal of Al-Azhar University Engineering Sector, vol. 7, no.21, pp. 2083-2095, 2012.

[67] Abdin, A.R.; Bakery, A.R.E.; Mohamed, M.A. "The role of nanotechnology in improving the efficiency of energy use with a special reference to glass treated with nanotechnology in office buildings," Ain Shams Engineering Journal, vol. 9, no.4, pp. 2671-2682, 2018, doi: https://doi.org/10.1016/j.asej.2017.07.001.

[68] Konbr, U.; Maher, E. "Boosting Sustainability in Egypt by Developing Initiatives to Promote Smart Energy Systems," WSEAS Transactions on Environment and Development, vol. 17, pp. 89-109, 2021, doi: https://dx.doi.org/10.37394/232015.2021.17.10.

[69] Salam, W.M.Z.A.E. A Methodology of Utilizing Nanotechnology within Building Envelope for Achieving Life Quality. Helwan University, Doctor of Philosophy, Unpublished, 2021.

[70] Konbr, U. "Studying the Indoor Air Pollution within the Residential Buildings in Egypt as a Factor of Sustainability," JES. Journal of Engineering Sciences, vol. 45, no.5, pp. 722-741, 2017, doi: https://doi.org/10.21608/jesaun.2017.116874.

[71] Prosolve370e. Torre de Especialidades, Hospital Manuel Gea Gonzales. http://www.prosolve370e.com/home, accessed on 11 February 2022.

[72] Numbeo. Quality of Life Index by City. https://www.numbeo.com/quality-of-life/rankings.jsp?title=2013-Q1, accessed on 11 Feb 2022.

[73] Numbeo. Pollution in Mexico City, Mexico. https://www.numbeo.com/pollution/in/Mexico-City, accessed on 11 Feb 2022.

[74] Wolfson, E. Mexico City Hospital 'Eats' Pollution: Torre de Especialidades Features Innovate Facade Tiling That Neutralizes Smog. https://www.medicaldaily.com/mexico-city-hospital-eats-pollution-torre-de-especialidades-features-innovate-facade-tiling-265942, accessed on 11 Feb 2022.

[75] Embellishments, E. Facade on the Torre de Especialidades. https://archello.com/project/torre-de-especialidades, accessed on 10 May 2022.

[76] Viva, A. Italian Pavilion, Expo Milano 2015. https://arquitecturaviva.com/works/italian-pavilion-expo-milano-2015, accessed on 12 Feb 2022.

[77] ARQA. Italy Pavilion Milan Expo 2015. https://arqa.com/en/_arqanews-archivo-en/italy-pavilion-milan-expo-2015.html, accessed on 12 Feb 2022.

[78] Proger. Italy Pavilion at EXPO 2015. https://www.proger.it/en/progetto/padiglione-italia-allexpo-2015/, accessed on 13 Feb 2022.

[79] Novozhilova, M. The spectacular Palazzo Italia building in Milan is a smog-eating machine. https://inhabitat.com/striking-palazzo-italia-at-the-milan-expo-is-a-smog-eating-machine/, accessed on 30 July 2022.

[80] KieranTimberlake. Yale Achieves First LEED Platinum in Connecticut. https://kierantimberlake.com/updates/yale-achieves-first-leed-platinum-in-connecticut/, accessed on 26 March 2022.

[81] Architects, T.A.I.o. Yale Sculpture Building and Gallery. https://www.aiatopten.org/node/126, accessed on 22 March 2022.

[82] Maged, J.; Moussa, R.R.; Konbr, U. "An Investigation into the Causes of Pedestrians' Walking Difficulties in Cairo Streets," Civil Engineering and Architecture, vol. 10, no.1, pp. 12-26, 2022, doi: https://dx.doi.org/10.13189/cea.2022.100102.

[83] Timberlake, K. Creating a Curtainwall of Optimal Performance.https://kierantimberlake.com/updates/creating-a-curtainwall-of-optimal-performance/, accessed on 14 April 2022.