Nanotechnology in the built environment for sustainable development

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Abstract
Nanotechnology as an emerging discipline of the 21st century has immense benefits for mankind due to the exceptional attributes of nanomaterials which can be used to render novel products and services. Amongst several fields of human endeavours, the built environment, largely composed of the disciplines of construction engineering, architecture, fine and applied arts, and urban and regional planning can make use of nanomaterials in creating green facilities with improved properties, aesthetics and innovation. Though there are reports of basic and applied investigations dealing with the production and evaluation of nanomaterials in the built environment, there is still a gap in harnessing the information together for the benefits of the practitioners in the built environment. Therefore, this treatise serves to x-ray the applications of nanotechnology in the built environment with the view of establishing nexus between the two areas. This compendium may stimulate the re-engineering of curricula in the built environment and stimulates new lines of research, product development and evaluation.

Keywords: Nanotechnology, built environment, green facilities, nanomaterials, composites, construction engineering, architecture, fine and applied arts

1 Introduction
The built environment, or the built world, is the human-made environment that grants the scenery for human activities which could range in scale from buildings to cities. It has been described as the human-made space in which humans reside, carry out work and refresh daily [1]. The built environment covers places and spaces formed or adapted by people to serve the
necessities for accommodation, organization as well as recreation. Architecture, building technology, urbanism and planning, civil engineering, fine and applied arts, landscaping and management of infrastructure and operations are areas covered by the sciences of the built environment. In public health, built environment is viewed as an act of building or renovation with the aim of improving the well-being of the community through the construction of improved, aesthetically and environmentally enhanced landscapes and structures for habitation [2].

Sustainability is of fundamental importance to all because it has to do with the continued existence of human species and more or less every living creature on the planet. Green buildings with respect to the environment reduce pollution effects, ensure conservation of natural resources and also prevent environmental degradation. In terms of the economy, they reduce the amount of funds spent by building operators on water and energy and also improve the productivity of the people using the facility. Also, socially, green buildings are beautiful and cause merely negligible strain on the local infrastructure [3]. Buildings which do not adapt with such challenges will become obsolete sooner than later or may require significant refurbishment or end up demolished, where neither option may produce a sustainable built environment [4]. It is estimated that by 2050, about 66% of the total world's population would dwell in urban areas [5] which will give rise to extensive challenges as regards to air pollution, waste management, congestion and human wellbeing [6]. Therefore, it becomes imperative to create smart solutions to surmount the consequences of urbanization. Exploitation of innovative and intelligent technologies is regarded as a major factor in decreasing greenhouse gas emissions and enhancing energy efficiency of cities. These technologies need to be smart, integrated, lean, resource-efficient and cost efficient, and they should have an all encompassing impact on environmental sustainability targets as well as wellbeing of the citizens and financial sustainability [7].

2 Nanotechnology and green synthesis of nanomaterials

Nanotechnology is a unique multidisciplinary idea of the 21st century that involves the study of matter at the nanoscale range. It has connected gaps in natural sciences, materials science, engineering, and medicine, with implausible relevance in diverse sectors [8]. Nanotechnology is concerned with the re-engineering or fabrication of materials and devices by controlling and
manipulating the matter at the atomic level. At the nanoscale, properties of materials are changed from that of the larger scales which represent the “nano-effects” that eventually determine the nature and characteristics that we are familiar with at the “macro-scale” and this is where the influence of nanotechnology comes in; if elements are manipulated at the nanoscale, this can affect their macro-properties and create significantly new materials and processes [9]. Various applications in nanoscience and nanotechnology have continue to increase the possibility of synthesis of nano-sized materials (1-100 nm) in various areas of human activities, thereby bridging the gap across the various frontiers of knowledge [10-15]. This field of technology has attracted and keeps attracting great interests owing to its extensive applications in diverse phases of life endeavors [16-18]. In broad-spectrum, nanotechnology deals basically with the production and stabilization of nanomaterials and nanoparticles of different types [19].

Nanomaterials are fabricated or engineered by different methods which include the physical, chemical, and biological methods. However, the physical and chemical techniques that have been extensively used long-ago result in environmental contaminations, as the processes cause a large volume of toxic by-products, and also use a great deal of energy. Therefore, there arose a claim for green nanotechnology that comprises clean, environmentally friendly, and safe systems of nanoparticles generation [20]. The biological technique, which is a major element of the green nanotechnology has expanded in the last decade to biosynthesize nanoparticles due to wealth of a wide-range of biological resources such as fungi [21], bacteria [22-26] plants [10, 27-35], as well as metabolites of arthropods [13, 15, 36-41] and enzymes [11, 22, 19, 42-48].

Moreover, green synthesis has become a credible alternative which has received unparalleled attention as a function of its reliability, cost effectiveness, less usage of chemicals and eco-friendliness [49], as well simplicity of the procedures and improved biocompatibility of nanoparticles that are biosynthesized [14, 15, 18]. These biosynthesized nanoparticles have found huge applications in various fields of life ranging from health care, biomedicine, drug–gene delivery, cosmetics, environment, food and feed, chemical industries, catalysis, single electron transistors, electronics, light emitters, space industries, energy science, nonlinear optical devices, mechanics, agriculture, remediation, and photo-electrochemical applications [14, 16-18, 50-55].
3 Nanotechnology in building and construction

The applications of nanotechnology in building and construction engineering have been on a steady rise (Table 1). The increasing interest in the relevance of nanomaterials in the building industry is largely due to their perceived positive characteristics which include moisture behavior, thermal properties, improved strength, energy efficiency, self-cleaning, improvement of air quality and antimicrobial effects [56]. At nano-level, gravity becomes unimportant as electrostatic forces take control, and quantum effects pull in. In addition, as particles tend to nano-size, the fraction of atoms on the surface increases compared to those inside, and this results in novel properties. These relatively new properties are what scientists are expansively exploring to take full advantage of the potentials vastly available [9].

Table 1. Some of the applications of nanotechnology in the built environment

| Nanomaterials               | Characteristics                                      | Applications/Potentials       | References |
|-----------------------------|------------------------------------------------------|--------------------------------|------------|
| Nanosilica                  | Increased compressive strength, workability and setting time | Concrete production           | [57]       |
| Nanosilica/ silica fume     | Compressive strength and long term hardening effect   | Concrete production           | [58]       |
| Nanosilica                  | Increased compressive strength and modification of microstructure | Concrete production           | [59]       |
| TiO$_2$ NPs                 | Photocatalytic properties/ depollution activity       | Concrete production           | [60]       |
| TiO$_2$ NPs                 | Improved water permeability, thermal and mechanical properties | Concrete production           | [61]       |
| Iron (III) oxide nanoparticles | Self detection compressive stress                      | Concrete production           | [62]       |
| Haematite                   | Reduced shrinkage and cracking effect                 | Concrete production           | [63]       |
| Iron (III) oxide nanoparticles | Improved water permeability resistance and reduced setting time | Concrete production           | [64]       |
| Iron (III) oxide nanoparticles | Increased compressive strength                         | Concrete production           | [65]       |
| Multi-walled Carbon nanotubes (MWCNTs) | Increased stiffness and strength                       | Concrete production           | [66]       |
| Silicone nanofilaments       | Oil-repellent properties                              | Textile finishing (polyester fabric) | [67]       |
| SiO$_2$ nanoparticles       | Oleophobic property                                  | Textile finishing (Cotton fibers) | [68]       |
| Carbon nanotubes            | Oleophobic property                                  | Textile finishing (Cotton fibers) | [69]       |
| ZnONPs                      | Antistatic property                                  | Textile finishing             | [70]       |
| AgNPs                       | Antistatic property                                  | Textile finishing (polyester fabric) | [71]       |
| Carbon nanotubes            | Enhanced toughness and strength,                      | Textile finishing             | [72]       |
| Nanomaterials                        | Applications                                                                 | References |
|-------------------------------------|-----------------------------------------------------------------------------|------------|
| ZnONPs                              | Absorb light in UV region and decrease weight                              | [73]       |
| SiO<sub>2</sub> nanoparticles and AgNPs | Antibacterial activities                                                    | [74]       |
| AgNPs                               | Antibacterial activity                                                     | [75]       |
| Multi-walled Carbon nanotubes (MWCNTs) | Electrical conductive property                                             | [76]       |
| AgNPs                               | Antibacterial and antifungal property                                      | [31]       |
| AgNPs                               | Antibacterial and antifungal property                                      | [28]       |
| AgNPs                               | Antibacterial and antifungal property                                      | [29]       |
| AgNPs                               | Antibacterial and antifungal property                                      | [37]       |
| AgNPs                               | Antibacterial and antifungal property                                      | [77]       |
| Silica nanoparticles                | Anti-ageing cycle                                                         | [78]       |
| AgNPs                               | Antibacterial property and Photocatalytic degradation of safranin and methyl orange | [79]       |
| AgNPs                               | Degradation of malachite green                                            | [80]       |
| AgNPs                               | Antifungal property on blotting paper                                      | [81]       |
| CeO<sub>2</sub>NPs, AgNPs, AuNPs, and TiO<sub>2</sub>NPs | Antibacterial activities                                                  | [82]       |
| CuONPs                              | Reduction of COD and microbial populations                                 | [83]       |
| AuNPs and Ag-AuNPs                  | Catalytic degradation of malachite green dye                               | [24]       |
| Ag-AuNPs                            | Catalytic degradation of malachite green and methylene blue dye            | [30]       |
| AgNPs                               | Catalytic degradation of malachite green                                   | [10]       |
| AgNPs                               | Catalytic degradation of malachite green                                   | [13]       |
| AgNPs                               | Catalytic degradation of malachite green and methylene blue dye            | [19]       |
| Ag-AuNPs                            | Catalytic degradation of malachite green and methylene blue dye            | [43]       |
| AgNPs                               | Adsorption of rhodamine B                                                 | [50, 53]   |
| AgNPs                               | Improved performance of DSSC                                               | [84]       |
| AgNPs                               | Improved performance of DSSC                                               | [85]       |
| TiO<sub>2</sub> nanoparticles        | Improved solar conversion efficiency                                       | [86]       |
| AgNPs                               | Improved performance of DSSC                                               | [87]       |
| Nanocrystalline TiO<sub>2</sub>     | Improved DSSC conversion                                                  | [88]       |
Nanofluids consortium of carbon nanotubes, graphite and silver nanoparticles: Improved efficiency for solar thermal collector [89]

TiO₂ nanowires coated with AuNPs or AgNPs: Enhancement of visible light photocurrent for renewable energy [90]

Carbon nanoparticles: Higher sunlight absorption for solar energy [91]

Carbon nanospheres: Improved the photo-thermal properties for solar energy [92]

Al₂O₃ nanofluid: Improved thermal efficiency of solar collector for solar water heating system [93]

MgO nanofluid: Reduced heating loss time for building heating system [94]

Iron oxide nanoparticles and single-walled carbon nanotubes (SWCNTs): Recycling of immobilized enzyme for biofuel production [95]

Ag/TiO₂ nanocomposite: High stability for more than one month for hydrogen production [96]

Nanotechnology provides a world of practically infinite possibilities in building technology; concrete can be much stronger, long-lasting and more easily set, steel can be tougher, while glass can produce some interesting properties including a self-cleaning effects. Thus, nanotechnology can enhance the performance of conventional construction materials, for instance concrete, glass, steel, paint, insulating materials, and coatings. Also, in recent times, nanotechnology is becoming popular to achieve sustainable built environment. The prospects of nanotechnology in terms of the improvement of building and construction materials are focused on the use of nanoparticles, nano-fibers, and carbon nanotubes to amplify the strength and resilience of cement composites, in addition to pollution reduction. Also, construction of inexpensive corrosion free steel, fabrication of thermal insulators (with performance 10 times of the existing commercial options), and production of thin films and coatings with self-cleansing capability and self-colour transformation to reduce energy consumption are some of the innovative interventions of nanotechnology in the built environment. The influence of nanotechnology on the built environment so far cannot be over emphasized, and this has led to the development of innovative structural materials with unique properties, stronger and lighter composites, sound absorber, fire insulator, low maintenance coating, nano-clay filled polymers, water repellants, self-disinfecting surfaces, UV-light protector, nano-sized sensors, air cleaners, ultra thin-strong-conductive wafers, solar cells amongst others.
It is well known that concrete is the foremost material in structural applications, where strength, firmness, and cost play a key role in the attributes of concrete. Concrete is a compound material at macroscale but its properties can equally be enhanced both at meso- and nanoscale [97], and nanotechnology has a high probability to add to the understanding of concrete’s behaviour, to facilitate improvement of its mechanical properties and reduction of its ecological and construction materials’ production costs [98]. According to Silvestre et al. [97], the most efficient nanoparticles for concrete production are nanosilica (NS) and silica fume (SF), titanium dioxide, Iron (III) oxide, chromium (III) oxide, nanoclay, calcium carbonate, alumina, carbon nanotubes (CNTs), and graphene oxide (GO). Nanosilica or silicon dioxide (SiO₂) nanoparticles and its colloidal form named as silica fume have attracted substantial interest from the scientific and technical communities. The advantages of using silica fume include high speedy compressive force, flexural strength, high tensile, modulus of elasticity, low permeability, enhanced durability amongst other. Behnood and Ziai [99] reported improvements of up to 25 % in compressive strength for heat and unheated samples with 10 wt % cement replacement. Rashad [57] presented a wide-ranging overview on the effects of nanosilica on the major properties of traditional cement materials and alkali-activated fly ash. It was presented that using nanosilica in the production of concrete has a high possibility to improve a variety of basic properties in concrete, such as strength, workability and setting time, fire and abrasion resistance or leaching, heat of hydration, and other behaviours under aggressive environments. Shakhmenko et al. [58] tested the effect of inclusion of nanosilica and silica fume on the mechanical properties of cement. The results obtained showed that mixtures containing silica fume and silica fume compositions with nanosilica particles demonstrated higher values of compressive strength (over 3 times higher at early ages and around 15 % at 28 days) and better long term hardening effect when compared to pure cement paste. Jalal et al. [59] tested mechanical, durability, microstructural, and rheological properties of high-performance self-compacting concrete incorporating microSiO₂ (microsilica) and nanosilica which replaced a portion of Portland cement. It was concluded that the replacement by 2 % nanosilica in the binary mixes elevated the compressive strength for a binder content of 400 kg/m³ for up to 73 % at 90 days. Also, the inclusion of nanosilica particles was found to control hydration behaviour and this led to modifications in the microstructure of the hardened paste. An excellent dispersion
of nanosilica particles in the cement mortar resulted into a denser microstructure and sped up the hydration course of the cement paste. Moreover, it is renowned that the cement industry is accountable for the emission of high levels of pollutants, such as carbon dioxide and nitrogen oxides, which has led to a rising need for environmental policy to stimulate the development of new strategies to minimize the polluting agents [60]. Thus, combining TiO$_2$ nanoparticles with cement-based materials proffers a good solution, owing to its strong photocatalytic activity, which brings about environmental pollution remediation, high stability, self-cleaning, self-disinfection and comparatively low cost of production [100]. Titanium dioxide nanoparticles can attract photon energy resulting in the elevation of an electron from the valence band to the conduction band of titania when exposed to UV-irradiation, and this produce \textquotedblleft holes\textquotedblright\ ($h^+$, electron vacancy) in the valence band. This electron–hole pairs may then re-combine in a short time to begin redox reactions. These reactions are dependent on the ambient conditions, producing several radicals, such as H$_2$O$_2$ or O$_2$ (from reduction), OH (from oxidation) when water vapour and oxygen are present around the activated titanium dioxide. Pollution is remediated when the radicals produced react with harmful substances that are absorbed on the TiO$_2$ surface, thus resulting in the degradation of these substances and release of harmless substances such as CO$_2$ and H$_2$O [101, 102]. The photocatalytic activity of TiO$_2$ is influenced by its crystallinity, crystal size, crystal structure and surface hydroxylation. Therefore, the application of TiO$_2$ nanoparticles may increase this activity compared to bulk TiO$_2$.

Cárdenas et al. [60] studied depollution activity of samples of cement pastes, added with TiO$_2$ nanoparticles by studying nitrogen oxide degradation. TiO$_2$ nanoparticles at different blend ratios were tested and measurements were made at two ageing times of 65 h and 28 days and the results showed that all cement pastes-containing TiO$_2$ nanoparticles had photocatalytic properties, irrespective of the ratio and the percentage of TiO$_2$ used. Also, TiO$_2$ nanoparticles can enhance the resistance to water permeability of concrete when it is added to the cement pastes with improvements up to a maximum replacement level of 2.0 wt \% of TiO$_2$ nanoparticles [61]. A number of \textquotedblleft depolluting\textquotedblright\ and \textquotedblleft self-cleaning\textquotedblright\ concrete products with TiO$_2$ nanoparticles are already being produced and applied in some facades of buildings and in pavement materials for roads especially in Europe and Japan [103].
The opportunity of developing concrete that can sense or perceive its own strain and damage has opened new prospects in the subject of monitoring and controlling materials, and building performance during their life cycle. The merits of producing concrete having self-monitoring characteristics are immense; it provides absence of mechanical property degradation, and greater durability due to the embedment of sensors and fairly low cost [62]. Iron (III) oxide nanoparticles, also known as haematite, play a major role in this aspect. Li et al. [62] tested different samples of cement mortar with additions of iron (III) oxide nanoparticles. The results showed that cement mortar with the nanoparticles is able to detect its own compressive stress in the elastic and inelastic systems, and this is due to their capability to modify the volume electric resistance as the load applied changes.

There are also reports on radiation-shielding properties of concrete-containing haematite. Gencel et al. [63] investigated the physical and mechanical characteristics of concrete with haematite, with specific focus on workability and durability. It was found that haematite only had a minor effect on the compressive strength which was the same with that of plain concrete. However, haematite had high impact on other properties, such as shrinkage, and due to the reduction of stresses as a result of drying shrinkage, the cracking effect also diminished. Nazari and Riahi [64] examined the rate and percentage of water absorption, workability and setting time of binary blended concrete with fractional replacement of cement by iron (III) oxide nanoparticles at various concentrations. The results obtained showed that water permeability resistance increased as the concentration of the nanoparticles increased. However, the setting time and workability of fresh concrete decreased as concentration of the nanoparticles increased. Also, Nazari and Riahi [65] investigated the workability and compressive strength of concrete with addition of iron (III) oxide nanoparticles (average size of 15 nm) of various concentrations and results indicated an increase of 15 % in the ultimate concrete strength at maximum replacement level of 1.0 %.

Carbon nanotubes (CNTs) are almost certainly one of the most promising nanomaterials ever, owing to their superior mechanical properties compared to other forms of nanomaterials. CNTs have produced an enhancement of the mechanical properties of structural materials [104]. CNTs are tubular nanostructures having diameter of a few nanometers, a huge length/diameter aspect ratio and its atomic structure comprise of a single or several concentric hexagonal lattices of carbon atoms linked by sp2 bonds. An imperative area in the study of application of CNTs for
mechanical enhancement of materials is their dispersion in the reinforced matrix. The effective application of CNTs in nanocomposites is dependent on the ability to disperse CNTs within the matrix with no reduction their aspect ratio. Generally, two types of CNTs have been mostly reported, which are single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT), and the differences between them is mainly in their overall thickness (Figure 1). Theoretical calculations and experimental results reported on SWCNT showed that it has more desirable thermal, mechanical, photochemical, and electrical properties [105]. However, MWCNTs are less susceptible to buckling phenomena as a result of van der Waals forces in between different tube walls. Also, they are less expensive and can be effortlessly produced with its multiple walls, which undoubtedly justifies their more extensive applications [106] in strengthening other materials.

Studies on the reinforcing effect of MWCNTs in a cement matrix proposed that the cement paste matrix strengthened with CNTs can boost its flexural strength and Young’s modulus by 25 and 50 % respectively. It was also specifically reported that little quantities of well-dispersed MWCNTs can significantly increase the stiffness and strength of the cementitious matrix [66]. CNTs can also enhance the conductivity of cementitious materials, besides the fact that cement-based materials have piezoresistive properties which indicates that excellent sensors can be generated for cement structures monitoring and the sensors can sense or detect microcracking and failure easily [107]. Additionally, as a result of bonding capacity of carbon atoms with other matter, materials modified with CNTs can be used as insulator, semi-conductor or conductor of electricity. Consequently, carbon nanotubes will have noteworthy influence on the building and architecture industry as such materials can variously act as source of light, generation of energy, switchable conduit, and conveyor system [108].
4 Nanoarchitecture

For the urban and regional planning, architecture and construction engineering profession, nanotechnology will influence the nature and properties of construction materials. As materials are manipulated at the nanoscale, so also they will behave in different ways that will impact their applications. Carbon nanotubes that are about one hundred times stronger than steel are a great example of how novel materials can be engineered through nanotechnology. Nanoarchitecture is the meeting point of nanotechnology and architecture, and it is predicted to totally revolutionize the architecture world in virtually every way; either the way architects think or how their ideas are inspired, the materials employed in building and finishing, or the way we express to the world and building users [108]. In essence, nanotechnology is bid to have profound effects on the ways humans live. Teaching of nanotechnology as a course of study would be required very soon in most architecture and engineering curricula because of the impact of nano-engineered materials in the construction industry. Therefore the need to widen an understanding of this broad-spectrum subject matter for architectures of the future cannot be underestimated. The possibility of manipulating matter at the scale of less than one billionth of a meter is a great
benefit presented by nanotechnology, and this presents the potential to transform the built environment in ways almost unimaginable today in return because as materials attain such transient features, new architectural design and construction will evolve. Nanotechnology is already utilized in the production of everyday items from various clothing materials to sunscreen among others, and sooner than later, it will take over the production of building enclosure materials (such as panels, insulation, and coatings) to striking new levels of performance in terms of light, energy efficiency, security, smartness and intelligence. Many nano-engineered materials are already made accessible to builders and architects, and they have begun to transform our buildings, including what we can perform in them, and what they can do for us. Projecting into the nearest future, nanotechnology in research and development will likely have a massive impact on building designs over the next twenty to fifty years. Carbon nanotubes, for instance, could impact extraordinary strength and flexibility on buildings, which will lead to new forms, new functions, as well as new relationship between people, building and environment at large [108].

5 Applications of Nanotechnology in Fine and Applied Arts: Textiles, Coatings and Paints

5.1 Textiles

There has been a general increase in demands by customers for textiles with improved appearance, colour, texture, shape and functionality [110]. Functionalized textiles can be applied in various areas including medical monitoring of body function and metabolism, and rehabilitation [111, 112]. It is possible to integrate flexible electronics, optical devices and sensors into textiles [113]. Nanoengineered functional textile is new frontier in clothing technology [114]. The benefit of nanomaterials has to do with creating functions without changing the soothing properties of the substrate. The engineered materials are expected to be seamlessly incorporated into garments and be comfortable and flexible without allergic effect to the body. Also, the nano-engineered materials need to satisfy weight, appearance, colour and performance properties [110]. Textiles through nano-engineering can be made to have some specific functions including antibacterial properties, hydrophobicity, conductivity, anti-wrinkle properties, light guidance and scattering, and antistatic behavior.
Textiles with oil-repellent properties have also been produced. Artus et al. [67] reported that polyester fabric could be coated with silicone nanofilaments and then treated with plasma fluorination to convey super oleophobic properties onto the textiles, and the fabric samples thus produced had an oil repellency grade and repelled alkanes. It has been revealed that hydrophobic and oleophobic properties could be concurrently imparted to textiles. Hoefnagels et al. [68] reported that cotton fibers were impregnated with SiO\textsubscript{2} nanoparticles to create a dual-size surface roughness, this was followed by hydrophobization with poly dimethylsiloxane (PDMS) which resulted in a static water contact angle of 155° for a droplet. To stimulate oleophobic property, the SiO\textsubscript{2} nanoparticles on the fibers were treated with a perfluoroalkyl chain producing static contact angle of 140° and a roll-off angle of 24° for oil droplets. Liu et al. [69] reported that lotus leaf nanostructures also inspired biomimetic studies for potential application in textiles. Cotton fibers were coated with pristine and surface modified carbon nanotubes to imitate lotus leaves nanostructure, yielding fabrics with contact angle of more than 150°. In a similar study using lotus leaves, nanocoats with average size of 20 nm impacted hydrophobicity on textiles [115]. ZnO whiskers, TiO\textsubscript{2}NPs, and antimony (Sb)-doped tin oxide (SnO\textsubscript{2}) nanoparticles have been utilized to convey antistatic properties on synthetic fibers. These nanomaterials are electrically conductive and the static charges accumulated are dispersed on the textile. Silane nanosol have also been said to enhance antistatic properties, because it absorbs moisture in the air via hydroxyl groups [110]. Zhang and Yang [70] reported that ZnONPs have been utilized to induce antistatic properties on fabrics and Qiaozhen [71] also reported that the addition of AgNPs reduced static voltage of polyester fabric by 60.4%.

Nanocoatings that prevent wrinkle while conserving comfort are sought-after in textile products. Conventionally, fabrics are impregnated with resin to impart antiwrinkle properties to textiles. However, this method reduces the tensile strength of the fiber, dyeability, and abrasion resistance, while stimulating hydrophobicity. To pass on wrinkle resistance properties on fabrics, nanoparticles have been successfully used on cotton and silk. TiO\textsubscript{2}NPs with carboxylic acid as a catalyst have been used to form cross-links in between cellulose molecules and the acidic groups. Therefore, carboxylic-acid treated fabrics with TiO\textsubscript{2}NPs were reported to be softer compared to untreated fabrics [110]. Generally, TiO\textsubscript{2} through its inherent catalytic property can be utilized as a cocatalyst with sodium hypophosphite (NaPO\textsubscript{2}H\textsubscript{2}) to treat cotton with 1, 2, 3, 4-butane
tetracarboxylic acid [116]. Carbon nanotube (CNT) reinforced polymer composite fibers have been developed to enhance toughness and strength, and decrease weight [72]. Nanoscale semiconductor oxides such as TiO₂ and ZnO can proficiently absorb and scatter UV radiation. Inorganic UV blockers are chemically stable and nontoxic, and can operate at high temperatures. ZnONPs synthesized were immobilized on dyed polyester/cotton fabrics and the resulting fabric absorbed light in the UV region [73].

The demand for functional textiles with antimicrobial properties is expanding with increasing attention to health and hygiene of consumers. AgNPs, TiO₂NPs, and ZnONPs can be applied to induce fungicidal and antibacterial properties to textiles. AgNPs have large surface areas thus this leads to an increased contact with bacteria and fungi. The antiseptic system of AgNPs is based on interaction with proteins present in these microorganisms and adversely affecting their cellular function thus inhibiting cell growth. They also cut down microbial respiration, restraining the activities of the basal metabolism of the electron transfer system, and transportation of substrate into the cell membrane. When AgNPs make contact with moisture or bacteria, they stick on to the cell wall and membrane [110]. The antimicrobial efficacy of AgNPs additives depends on their concentration, surface area, as well as the rate of release of the Ag⁺ ions [117]. In our laboratory, we have demonstrated the antibacterial properties of textile functionalized with biosynthesized AgNPs (Figure 2). TiO₂NPs can also be employed to induce textiles with antibacterial properties. The catalytic activity of TiO₂NPs is its inherent strength which is usually leveraged on to provide antibacterial properties in textiles. The photocatalytic activity can be enhanced by creating nanocomposites of TiO₂/SiO₂ or Au-doped TiO₂ nanocomposites in cotton fabrics with self-cleaning properties [118, 119].
Figure 2. Antibacterial activity of textile functionalized with AgNPs against *Escherichia coli* (a, control; b, functionalized textile)

ZnONPs coated onto textiles was reported to show self-cleaning properties in the presence of Gram-negative *Escherichia coli* and aerobic Gram positive *Staphylococcus aureus*. Additionally, SiO$_2$ nanoparticles and AgNPs having a core-corona structure were electrostatically coated on cotton surfaces with high packing density to induce antibacterial properties to fabrics [120]. The nanoparticles were loaded with antibacterial moieties such as quaternary ammonia salts as well as metal coatings on the cotton fabrics [120]. SiO$_2$NPs can also be incorporated in polyimidoamide fibers through spinning and the incorporated of nanoparticles in fibers can create electrically conductive channels with enhanced antistatic and mechanical properties [110]. Yue *et al.* [75] reported the synthesis of silver nanoparticles-sericin (AgNPs-sericin) hybrid colloid which showed high bacterial reduction rates of 96.25 and 96.46 % for *S. aureus* and *E. coli* after 20 washing cycles. All these have shown that fabrics with special attributes can be created for applications in the built environment such as curtains and manufacture of upholstery and rugs.

5.2 Paints

Paints are widely used because their processes of application are relatively simple, inexpensive and robust compared with other coating techniques. At present, this area is focused on
finding innovative formulations with enhanced properties over microbial and environmental degradation, hydrophobicity, mechanical strength, adhesion and opacity, with consideration for the use of nanostructured materials as additives [121]. Yedra et al. [76] developed a new paint with electrical conductive characteristics from a polymer matrix in which are dispersed multi-walled carbon nanotubes (MWCNTs). Carbon nanotubes (CNT) have excellent and unique properties, such as electrical, optical, thermal and mechanical properties. The paints incorporated with dispersed MWCNTs displayed better resistance to degradation than the conventional pristine paint. Properties such as hardness and adhesion were not affected by the incorporation of nanofillers in the new paint. The potential application of nanoparticles as additives in paints have been widely reported and this indicates that the paint industry may benefit from the applications of these novel nanomaterials to improve the quality of the paint against biodegradation, microbial attack, and chemical deterioration [121, 122] which is an additional efforts towards achieving sustainable built environments.

In a study reported in our laboratory [31], impregnation of emulsion paints with AgNPs synthesized using cocoa bean extract effectively inhibited the growth of both bacterial and fungal isolates like; *E. coli*, *Klebsiella pneumoniae*, *Streptococcus pyogenes*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Aspergillus flavus*, *A. fumigatus* and *A. niger*. We also reported that incorporation of AgNPs synthesized using cocoa pod husk extract into emulsion paint led to effective inhibition of the growth of *E. coli*, *K. pneumoniae*, *S. pyogenes*, *S. aureus*, *P. aeruginosa*, *A. flavus*, *A. fumigatus* and *A. niger* compared to abundant growth on the control plates [29]. Lateef et al. [28] in a related research reported a total eradication of bacterial strains of *E. coli* and *P. aeruginosa* as well as fungal strains of *A. niger*, *A. fumigatus* and *A. flavus* in paint treated with AgNPs synthesized using pod extract of *Cola nitida*. AgNps synthesized using cobweb extract was shown to present total growth inhibition against *E. coli*, *P. aeruginosa*, *A. niger* and *A. flavus* when employed as paint additive [37] (Figure 3). Also, a complete suppression of the growth population of *S. aureus*, *P. aeruginosa*, *A. fumigatus* and *A. flavus* was reported when AgNPs synthesized using cell-free extract of *B. safensis* was incorporated as additive into emulsion paint [77].
Figure 3. The antibacterial and antifungal activities of emulsion paint impregnated with AgNPs [37]

5.3 Nanocoatings

Nanocoatings are progressively used by the construction industries on building surfaces, such as walls, windows and doors, as they unlock new horizons for environment-friendly and sustainable buildings. Nanocoatings create a surface of the preferred protective or functional properties while providing a protective layer bound to the base material. The major mechanism of nanocoatings is their ability to produce self-healing properties through a process of self-assembly [123]. A self-cleaning glass mechanism based on a thin film titanium oxide (TiO₂) coating can be actualized [124] where the glass cleans itself in major two stages. The first stage is a photocatalytic process that breaks down the organic dirt on the glass using UV light and confers superhydrophilicity on the glass. At some point in the following superhydrophilic stage, rain water washes away the dirt, leaving more or less no streaks, because water spreads uniformly on superhydrophilic surfaces [125]. The films also have high-quality photo-induced antibacterial and antireflective properties. Both hydrophobic and hydrophilic coating systems are applicable for flat building surfaces and base materials such as tiles, woods, and stones.
Wang et al. [126] suggested that flame-retardant nanocoatings via the addition of nano-size magnesium-aluminium-layered double hydroxides (LDHs), titanium oxide (TiO$_2$) and silicon oxide (SiO$_2$). Quagliarini et al. [127, 128] and Munafo [129] reported that nanostructured titanium oxide (TiO$_2$) based coatings have promising properties on historical and stone surfaces respectively, while silica nanoparticles have been reportedly used on a permanent anti-graffiti polyurethane coating, which positively affected the anti-graffiti performance against ageing cycles [78].

6 Water pollution management

Human activities including industrialization and extreme use of pesticides for improving agricultural yield and production have negatively affected the ecosystem, causing pollutions in the available natural water reserves. Majority of the natural sources of drinking water such as surface water, lakes and reservoirs, groundwater, rivers and canals, including rainwater have been found to be polluted with ample variety of toxic materials as well as pathogenic microorganisms [130-135]. Remediation of contaminated and polluted water has been an area of interest with many techniques being applied for the improvement of quality of available natural water to the level that will be appropriate for human consumption. Conventional water disinfection procedures have some restrictions resulting in apprehensiveness about their applications at a large scale.

However, nanotechnology is a disruptive technology that is a capable of making an impact in the area of water purification as nanostructures offer large surface to volume ratios which is ideal for surface reactions. The prospect of creating photocatalytic membranes by impregnating semiconducting nanostructures on conventional membranes makes this idea even more striking [136]. Point-of-use water purification systems can be devised using antimicrobial nanomaterials such as silver (Ag) and zinc oxide (ZnO) [137]. Active functional membranes incorporated with photocatalytic or antimicrobial nanomaterials will be proficient in accomplishing multiple treatment targets in a singular course of action, and at the same time reducing fouling [137].

Nanostructures originating from metal oxide semiconductors such as zinc oxide (ZnO), titania (TiO$_2$), tungsten oxide (WO$_3$) and zinc stannate (Zn$_2$SnO$_4$) can be appealing means of water purification as it is capable of eliminating chemical and biological contaminants [138]. Higher
adsorption of the target molecules is possible because nanostructured photocatalysts will offer large surface to volume ratios. Concerted research over the past decade for implementation of nanotechnology in the purification of drinking water can be found in the literature [139-142]. Moreover, nanofiltration is a kind of membrane filtration used mostly with fresh groundwater and surface water having lesser amounts of dissolved solids. The major objectives of nanofiltration are elimination of DOB precursors such as natural and synthetic organic matter, and softening of water. Nanofiltration is a cross-flow filtration technology, that can be placed in between ultrafiltration and reverse osmosis, and the types of materials that can be filtered out depends upon the pore sizes of the filtration membranes. The pore size of the nanofiltration membrane can be as low as about 1 nm [142] which is adequate enough to screen out microorganisms.

Ramaswamy and Mani [79] reported that industrial waste water treated with AgNPs biosynthesized using Allium fistulosum displayed antibacterial efficiency against pathogenic bacteria Proteus vulgaris, Shigella dysenteriae and Escherichia coli isolated from industrial waste water. Also, the particles degraded safranin and methyl orange by 43.1 and 34.6% respectively. Allam et al. [80] described the biosynthesis of AgNPs by cell-free extracts from some bacterial species. The AgNPs was utilized as nanocatalyst for the elimination of malachite green dye (MG) from waste water with continuous reduction in dye absorbance at 617 nm until it disappeared over a period of 160 min. Dankovich and Gray [81] showed that filtration of contaminated water sample through paper impregnated with AgNPs could be an effective emergency water treatment technique in a study where AgNPs impregnated on blotting paper displayed antibacterial properties toward suspensions of Enterococcus faecalis and Escherichia coli in the effluent. García et al. [82] studied the antimicrobial activities of titanium dioxide, cerium dioxide, gold and silver nanoparticles in wastewater treatment. The activities of thermophilic, mesophilic, anaerobic, hetrotrophic and ammonia oxidizing bacteria in waste water were inhibited by the nanoparticles in this order; CeO$_2$NPs, AgNPs, AuNPs, and TiO$_2$NPs. Also, Kuppusamy et al. [83] reported the biosynthesis of Commelina nudiflora mediated copper nanoparticles as a novel bio-control agent and the CuONPs was employed for the treatment of palm oil mill effluent. It was shown that CuONPs sufficiently reduced COD and microbial populations in the treated effluent.
Ojo et al. [24] have reported that AuNPs and silver-gold alloy nanoparticles (Ag-AuNPs) biosynthesized using supernatant of *B. safensis* LAU 13 displayed excellent catalytic activities in the degradation of malachite green in the range of 86.1-92.7 % after 48 h at concentrations of 20-100 µg/ml. Lateef et al. [30] studied the catalytic degradation activities of leaf, seed, seed shell and pod extracts of *Cola nitida* mediated Ag-AuNPs against malachite green and methylene blue, with activities ranging from 63.2-97.1 %, and 2.1-73.2 % for malachite green and methylene blue respectively within 24 h. Lateef et al. [10] evaluated AgNPs mediated by leaf and seed extracts of *Synsepalum dulcificum* to degrade malachite green with activities of approximately 80 % within 24 h. Furthermore, AgNPs biosynthesized using nest extract of paper wasp (*Polistes* sp) degraded malachite green dye to the tune of 93.1 % [13]. Moreover, fungal xylanases have been used for synthesis of nanoparticles which have been reported to display dye degradation potentials. Fungal xylanases mediated AgNPs reportedly degraded malachite green and methylene blue with highest activities of 78.97 and 25.3 % respectively while both malachite green and methylene blue dye were degraded by fungal xylanases mediated Ag-AuNPs within 24 h at the range of 74.86-91.39 % and 12.1-47.1 % respectively within concentrations of 20-100 µg/ml [19, 43]. Similarly, nanoparticles have also been used for the adsorption of dyes in water [50, 53].

7. Nanotechnology and renewable energy sustainability

Renewable energies are that form of energy sources that can generate electricity and heat, as well as provide light, without polluting or contaminating the environment. Fossil fuels includes crude oil, natural gas and coal, they are not renewable, but are gone forever once burnt and more than 90 % of the world energy demand is supplied from these sources [143]. The sources of fossil fuel are generally believed to be exhaustible and they are also regarded as the major cause of emissions of greenhouse gas. Thus, there is a critical need to increase the portion of renewable energy sources in supplying the primary energy need of the world at large [144]. Moreover, consumption of petroleum was reportedly as $10^5$ times faster than the capacity that nature can create and with this elevated consumption rate, the world’s reserve for fossil fuel was predicted to have diminished by the year 2050 [145]. Also, the global demand for energy is projected to be more or less 30 and 46 TW by the year 2050 and 2100 respectively [143].
The expansion of renewable energy resources has attracted global attention in recent years. Energy sources which include wind, solar, tidal wave, hydropower, geothermal and ocean thermal are regarded as the renewable energy resources. The sporadic fluctuations in the available energy from these sources make the advances of reliable and efficient storage systems crucial. These storage systems should have the capacity to collect and retain energy supplied during peak hours and supply the energy stored at periods when supply is low for necessary use [146]. According to Elegbede and Lateef [8], the roles of nanotechnology in improving the dependability of energy system covers every aspects of energy infrastructure, which includes production, storage, distribution, as well as the utilization. Creation of more resourceful products that can be utilized at the various levels of the energy architecture for more capable and optimal energy systems can be achieved via nanotechnology advances. In realizing an energy secured society, a more reliable energy system infrastructure will be required since traditional energy systems have fallen short in a lot of ways [147].

The prospect of applications of nanotechnology in provision of sustainable renewable energy cannot be underestimated. Devices that can store energy such as batteries and super-capacitors can be appreciably altered by the various applications of nanotechnology. Nanotechnology can be applied to re-engineer to ensure that certain relevant elements of lithium-ion batteries flexible, heat resistant and high-performance electrodes. Nanoporous materials like zeolites can be used to better improve the storage systems for thermal energy, which eventually could be employed as heat storages in for industrial and residential uses [143].

Solar energy is generally said to be one of most excellent supply of renewable energy but the major drawback in using most solar devices is that the apparent weakness in the absorption properties of the conventional fluids which ultimately leads to reduction in efficiency. However, with advances in nanotechnology, this can be easily solved. The amplified surface area to volume ratio of nanoparticles should practically increase the potentials of solar energy collection and efficiency by subjecting more conducting surfaces to sunlight. Nanotechnology will also boost solar cell efficiency when materials such as lead-selenide is used because they have capacity to cause more electrons to be released when hit by a photon of light. Dye-sensitized solar cell (DSSC) are solar cells that supports optical absorption and charge separation/injection
by connecting a dye sensitizer (light-absorbing material) to semiconductor (having a wide-band gap) of nanocrystalline morphology as the photoanode [143].

Improved performance of a DSSC using AgNPs-modified fluorine tin oxide (FTO) electrode via successive ion layer adsorption and reaction (SILAR) was reported by Eli et al. [84] and it was shown that the modification of fluorine tin oxide (FTO) electrode led to approximately 22% improvement in photocurrent over that of bare FTO without AgNPs. Also, Eli et al. [86] presented the enhanced performance of DSSC modified with AgNPs through SILAR implementation. It was reported that AgNPs-modified DSSC produced 63% improvement in efficiency, 48.4% augmentation in short circuit current density and 8.5% improvement in open circuit voltage which was predictably influenced by the absorption strength of AgNPs due to its surface plasmon resonance. Moreover, Eli et al. [85] noted the improved solar conversion efficiency (η) of 0.0067% which was an influence of of TiO$_2$ nanoparticles in DSSC of H. sabdariffa. Similarly, Onimisi et al. [87] investigated the impacts of AgNPs on DSSC performance via SILAR. The results obtained indicated that 36% improvement in efficiency was attained in the AgNPs modified DSSC. Bazargan [88] reported that dye sensitized solar cell (DSSC) was synthesized using natural pomegranate juice for sensitization of nanocrystalline TiO$_2$. Pulse current electron deposition method was used to prepare platinum and graphite coated electrodes while soot staining method for use as counter electrodes. The overall conversion efficiencies of fabricated (DSSC) were found to be 1.5 and 0.9% for cell operated with platinum electrode and carbon coated counter electrodes respectively.

Moreover, Otanicar et al. [89] reported efficiency improvements of up to 5% in solar thermal collectors by using nanofluids (from a variety of nanoparticles such as carbon nanotubes, graphite and silver) as an absorption mechanism. Liu et al. [90] reported the enhancement of visible light photocurrent by coating TiO$_2$ nanowires with gold or silver nanoparticles. The improvement was realized due to optical scattering from the plasmonic nanoparticles, which amplified the effective optical path of the thin film. The scattering and absorption characteristics of nanofluids composed of aqueous suspensions of single wall carbon nanohorns was in investigated by Mercatelli et al. [91] in order to use them as direct sunlight absorber fluids in solar devices. Considerably higher sunlight absorption was achieved induced by the carbon nanoparticles when compared to those of pure water. As a result, it was assumed that the carbon
nanohorns could be efficiently applied for overall efficiency improvement of sunlight exploiting devices. Also, Poinern et al. [92] studied the potentials of nanoparticles of functionalized carbon nanospheres (CNS) to improve the photo-thermal properties of the working fluid. The photo-thermal response of both films composed of (CNS) and nanofluids were examined under 1000 W/m² solar irradiation and the results obtained showed that the functionalized (CNS) nanofluids had the prospect to efficiently enhance the solar absorption capabilities of direct-absorption solar collectors.

Tiwari et al. [93], in a theoretically based study investigated the effect of applying Al₂O₃/water nanofluid in a flat-plate solar collector as an absorbing medium and the results revealed that applying 1.5 % particle volume fraction of Al₂O₃ nanofluid improved the thermal efficiency of solar collector by about 31.64 % when compared with the conventional solar water heating system. Obaid et al. [94] investigated of the thermal energy storage efficiency by using nanofluid (adding magnesium oxide, MgO to distilled water). The system was intended to heat a building that has a reflector that concentrated solar energy to heat the fluid passing through it, then the fluid storage tank store the fluid and this was circulated by using a pump and solar radiator which transfer the heat into the air in the room. The results showed that addition small quantities of nanoparticles (MgO) (0.1 and 0.2 wt %) in the building heating system driven by solar energy reduced the heating loss time while the capability to heat gain was lower than pure water.

Zhang et al. [148] utilized carbon-based nanostructured catalyst with medium acid density for the production of biodiesel via catalytic distillation, and it was reported that the produced biodiesel was easy to amplify and promising, which was possible because some drawbacks of previous available methods were adequately avoided. Goh et al. [95] reported the incorporation of iron oxide nanoparticles into single-walled carbon nanotubes (SWCNTs) to create magnetic single-walled carbon nanotubes (mSWCNTs) which was used to recycle the immobilized enzyme, en route valuable use in biofuel production processes. This could lead to greater efficiency in carbon nanotube-enzyme bioreactors coupled with the intrinsic properties of the nanotubes, and reduction in capital costs in industrial enzyme systems can also be attained. The prospect of photoelectrochemical hydrogen production from water/methanol decomposition with Ag/TiO₂ nanocomposite thin films was demonstrated by Alenzi et al. [96]. The results obtained
revealed the nanocomposite films had high stability for hydrogen production for more than one month, also the films can be more suitably used than powders and they could be recycled easily.

8 Prospects of Nanotechnology in building and architecture

Nanotechnology has the possibility to drastically alter the built environment and how humans live generally. It is possibly the most transformative technology man has ever had which has generated more debate and research than space travel, computers, nuclear weapons, or any of the other technologies that have shaped our lives so far. Accompanied with it are enormous questions, concerns and consequences. Yet, its prospect to transform the built environment still remains largely unexplored. By transforming the critical features of matter, nanotechnology has capacity to change the way we build. Structures could be possibly constructed from the bottom-up because materials such as carbon nanotubes can self-assemble. In profoundly affecting the architectural industry, the designers’ creative mind will be unleashed and more innovative ideas can spring up. Generally, all areas of architectural designs, building construction, as well as providing a safe environment at all levels, interior designs, and city design will all profit from advances in nanotechnology. Nanotechnology could give superior interactive functions to architectural designs as occupants may be able to select and communicate what transient states they would like to experience, this may include windows and walls with variable transparency, and mood/context sensitive clothing [108].

9 Conclusion

Nanotechnology gives unparalleled influence to architects and construction engineers in shaping and manipulating our world, and this could result in having buildings that shape us, as well as our relationships with one another and the environment at large. The actualization of sustainable built environment is achievable via the vast applications of nanotechnology in building constructions, as well as provision of enhanced finishes both in interior designs and city design itself. With advances in nanotechnology, architecture will have the aptitude to function at more optimal levels in revolutionizing the way inhabitants live. Therefore, ignorance about the vast potentials of nanotechnology in relations to the built environment can only predispose to being
suddenly left behind of technological advances as billions of dollars are poured into new research and development every year and innovative advances pour out.

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