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Review

Present scenario and futuristic applications of nanomaterial-based products in the industry—A review

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Abstract: The article's proposed engineering uses are based on theories presented in the reviewed research articles and on findings from online investigations into companies that claim to use nanoengineering in their wares. Several pre-existing online consumer inventories and nanotechnology news were examined as part of the internet inquiry. The data about the nanoparticles (NP), or nanostructure, used in commercially available products comes from the remarks made by the manufacturer. Nanoengineered coating agents and textile additives are examples of commercial items developed for industrial clients that fall under the aforementioned uses.

Keywords: automotive; chemical; construction; electronic; engineering; nanomaterial; textiles

1. Introduction

Nanotechnology is the technology domain that concentrates on manipulating and controlling structures, devices, and systems at the nanoscale, including their design, characterization, production, and application. It possesses significant commercial viability across a wide range of businesses. The traditional techniques and the conventional material employed by the industry require attention owing to the strict environmental rules and constraints in energy consumption. This is primarily because traditional procedures used in preparing various items typically do not yield lasting effects and eventually become ineffective. In addition, applying nanoparticles to various materials will not compromise their breathability or tactile sensation. Nanotechnology enhances materials by providing properties such as wrinkle resistance, hydrophobicity, UV protection, flame retardation, antibacterial and antistatic capabilities, soil resistance, and improved dyeability.

The present and potential engineering applications outlined in **Figure 1** are derived from the hypotheses put forth in the analyzed research publications, as well as from internet research on manufacturers who assert the utilization of nanoengineering in their products. The internet investigation was conducted by analyzing several existing online consumer inventories and news articles relevant to nanotechnology. The information concerning the employed nanoparticle or nanostructure in commercially available products is sourced from the manufacturer's statements. The aforementioned applications include commercial products that are intended for industrial clients, such as textile additives or nanoengineered coating agents.

Nevertheless, textile coating or impregnation compounds that are intended for the end consumer are not included, as they are not classified as “textile products” [1].

The research on nanotechnology in the Web of Science is utilized to create a comprehensive range of functional materials that can be accomplished through nanoengineering. The text highlights the various NP and production processes that are presently being examined. The literature delineates the mechanisms that elicit the intended effects for each textile function, encompassing specifics regarding the NP/nanostructure, the textile matrix, the employed production method, and the form of the NP in the final fabric. The commercial utilization of various functional textiles relies on the findings presented in the analyzed research articles and on online searching for nanoengineered consumer products that are now available. The suggested products are categorized into the following product groups: Apparel, protective garments, interior trim and upholstery, sports and leisure, household, cosmetics, medical equipment, building materials, industrial purposes, and auxiliary/intermediate products for industrial operations [2]. The final product category encompasses all items that are not directly sold to the ultimate consumer but rather acquired by industrial customers and employed in the manufacturing process of a nanoengineered final product. Examples of such auxiliary or intermediate items include additives, textile composites that are further processed into garments or furniture, as well as licenses for the use of specific production procedures or technologies.

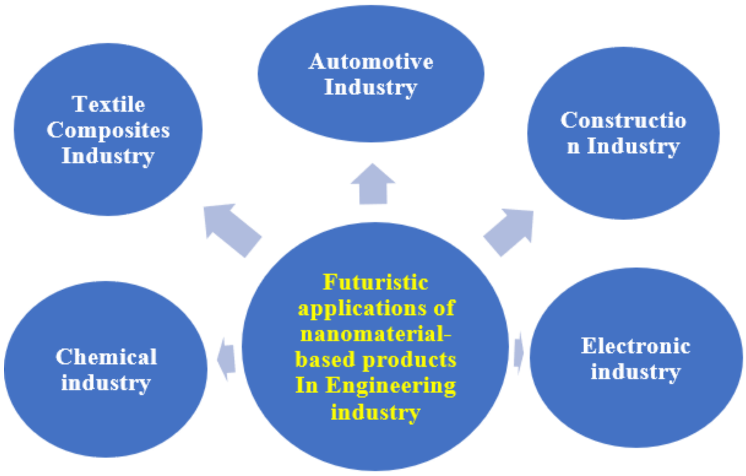

Figure 1. Overview of applications of nanomaterial-based products in different areas.

2. Nanoengineered materials for the automotive industry

Nanomaterials can be utilized in car bodies to create lightweight structures that maintain rigidity and crash resistance, reducing material usage and fuel consumption. This section discusses the integration of nanotechnology into the safety features and fuel efficiency of modern vehicles. It also highlights the significance of sustainable development in the application of these technologies and the analysis of the materials used in their life cycle. This is done to align with societal trends and meet customer demands for improved comfort, safety, and ecology. The present status and potential application of nanoparticles in automotive engineering are shown in **Table 1**.

Table 1. Potential application of nanoparticles automotive engineering.

Industry	Nanoparticles	Nanoparticle-based product/Conventional application	Potential industrial application
Automotive engineering	Carbon nanotubes Nano clay Silica Alumina Cerium oxide Platinum Graphene	Paints and coatings: Improve scratch resistance, UV protection, and color stability. Composites: Enhance strength, stiffness, and impact resistance in polymer matrix composites. Tires: Improve tread wear, traction, and fuel efficiency. Batteries: Increase energy density, power, and charging speed in lithium-ion batteries. Catalysts: Improve fuel efficiency, reduce emissions, and enhance catalytic converter performance. Sensors: Enable the development of smaller, more sensitive sensors for temperature, pressure, and gas detection. Fuel additives: Improve fuel efficiency, reduce emissions, and clean engine components. Self-healing materials: To create materials that self-heal cracks and damages.	Vehicle bodies and chassis Engine components (e.g., pistons, cylinders) Transmission and drivetrain components Battery electric vehicles (BEVs) Hybrid electric vehicles (HEVs) Fuel cell electric vehicles (FCEVs)

2.1. Lightweight body construction and Catalysts

The need for novel and sophisticated materials in automotive applications arises from vehicle safety, performance, and fuel efficiency requirements. Nanomaterials used in automotive applications aim to reduce engine emissions, enhance driving safety, minimize vehicle noise, and provide self-healing capabilities for vehicle bodies and windscreens. The concept of utilizing nano-fluids to enhance the efficiency of coolants was introduced a considerable time ago [3,4]. The suggestion resulted in a 100% improvement in liquid thermal conductivity by utilizing nanometer-scale particles, leading to a proliferation of scientific research efforts in this field [5,6]. Nevertheless, the enhancements in the performance of coolants may catalyze driving and inspire additional advancements in engine efficiency, as well as the reduction in size and weight of cooling systems. Additionally, there are ongoing investigations that specifically target the enhancement of thermal and rheological characteristics of lubricants by the use of nanoparticles [7]. Enhancing the decrease of weight in cars is a crucial concern for motor vehicles, as reducing weight is the primary method to enhance fuel efficiency. The increasing global standards for fuel efficiency and pollution in manufacturing and transportation are generating a need for affordable, high-performing lightweight materials as substitutes for metals. A nanocomposite refers to a solid matrix that contains nano-objects, such as a new type of polymeric materials that have exceptional mechanical, thermal, and processing capabilities. These materials are suited for replacing metals in several applications, including the automobile industry [8]. The nanoparticles are highly effective, typically requiring just 0.5%–5% of their weight to be added. A nanocomposite possesses qualities that surpass those of traditional microscale composites and may be synthesized at a low cost utilizing a straightforward process [9]. Nanocomposites are anticipated to enhance manufacturing speed, environmental and thermal stability, recycling, and weight reduction in automotive parts and systems. By restricting the use of this technique to non-essential structural components like front and rear sections, cowl vent grills, valve/timing covers, and truck beds, it is possible to achieve a significant weight reduction, amounting to several billion kilograms per year [8].

Nanotechnology is currently being employed in the mass production of car components. For instance, Audi and Daimler Chrysler utilize multi-layered nanocoating on glass instruments to provide an anti-reflection effect. General Motors Corp. has implemented a thermoplastic olefin (TPO) nanocomposite in an optional step-assist feature for the Chevrolet Astro and GMC Safari minivans. Replacing reinforced polymers in car body components is a viable strategy for reducing weight, but it is crucial to ensure that safety, affordability, and other desired qualities are not compromised [3]. Buses utilize sun protection glazing that has nanolayers inserted into glass sheets to reflect infrared rays. GMC utilizes thermoplastic nanocomposites with nanoflakes to manufacture rigid and lightweight external components, such as the step-assist. In their study, Presting and Koning [10] predicted that a 30% enhancement in roll resistance, air resistance, car weight, or powertrain might potentially lead to a reduction in fossil fuel consumption by 4%, 6%, 15%, or 28%, respectively. Therefore, carbon dioxide emissions will decrease. Nanotechnology can also play a role in enhancing fuel injection and reforming processes, improving hydrogen storage capabilities, optimizing cell electrodes, and enhancing the performance of proton exchange membranes (PEM). In addition, the application of nano jets can enhance engine combustion efficiency by reducing surface tension losses during aerosol production. Porous nanocomposites can also be utilized as pollution filters, effectively reducing the release of soot particles or harmful gases by mechanical means or catalytic reactions [3,4,11].

2.2. Automotive painting

The field of automotive painting has undergone significant advancements since its inception, transforming into a highly intricate procedure that not only boosts the visual attractiveness of automobiles but also offers vital safeguarding against environmental factors. The base coat clear coat paint method is a groundbreaking approach that has proved essential to the automotive industry.

Nanotechnology has been included in vehicle paints, leading to the development of nano-coatings. These coatings offer an extra layer of protection, providing resistance against scratches, chemical pollutants, and UV radiation. Nano-coatings not only increase the durability of the paint but also improve the gloss and shine on the surface of the car [12].

3. Nanoengineered materials for the chemical industry

3.1. Nanocomposite-based coating system

A nanocomposite coating is a substance consisting of a minimum of two phases that are incapable of mixing and are separated by a region known as the interface. The material must possess nanoscale dimensions in at least one dimension, with the primary component referred to as the matrix, within which fillers are scattered [13]. The categorization of nanocomposite coatings is determined by different approaches that consider either the type of nanostructured fillers or the type of matrix in which the filler nanostructures are distributed. There are three primary categories of nanocomposite coating, which are as follows [14]:

0D nanocomposite coatings consist of nanoparticles as fillers, which have diameters in the nanoscale in all three dimensions.

1D nanocomposite coatings consist of nanotubes or whiskers as fillers, which have dimensions on the nanoscale in two dimensions.

2D nanocomposite coatings consist of nanolayers as fillers, which have a dimension in the nanometer scale. There are two types of matrices: Organic matrix and inorganic matrix.

There are four primary categories of nanocomposite coating, classified based on the combination of matrix and nanofiller:

Coatings are made of a combination of organic and inorganic materials, known as organic/inorganic nanocomposite coatings (O/I nanocomposite coatings).

Coatings are made of a combination of organic materials, known as organic/organic nanocomposite coatings (O/O nanocomposite coatings).

Coatings are made from a combination of inorganic and organic materials, known as inorganic/organic nanocomposite coatings (I/O nanocomposite coatings).

Coatings are made from a combination of inorganic materials, known as inorganic/inorganic nanocomposite coatings (I/I nanocomposite coatings).

3.2. Exceptional characteristics of nano-coating

Thin films, nanoscale coatings, and nanostructured surfaces have extensive applications across various industry sectors and serve as excellent illustrations of how nanotechnology may enhance or disrupt existing technology sectors, as well as generate new ones. Nano coatings offer notable performance benefits compared to conventional coatings while also being more cost-effective in the medium to long run. Nanostructured materials significantly enhance various properties, including antimicrobial activity, product durability, thermal insulation, gloss preservation, resistance to dirt and water, hardness, corrosion resistance, flame retardancy, stability against ultraviolet radiation, improved energy efficiency, resistance to graffiti, self-cleaning ability, moisture absorption, gloss preservation, and chemical and mechanical properties.

3.3. Paper industry

The paper production business utilizes mechanical and chemical processes, known as pulping, to transform various materials into different types of board goods and paper [15]. Due to advancements in the paper industry, there has been an increased focus on manufacturing high-quality paper in a cost-efficient manner [16]. The ultimate characteristics of the paper, including its excellence, mass, sheen, evenness, and decreased ink absorption, are significant [17–19]. By incorporating nanostructured materials and small amounts of organic compounds into the paper formation, it is anticipated that the qualities of the resulting paper will be improved.

Nanotechnology is employed to modify the production process in response to shifts in resource-based and industrial knowledge, leading to corresponding adjustments, with a significantly heightened focus on stability. The core of the work revolves around the utilization of nanofibers, nanofillers, nanocomposites, and nanoscale compounds in paper applications. Scientists and researchers have been interested in using nano-additives in the paper industry because they significantly enhance the attributes of manufactured papers. These improvements include mechanical strength, printability, glossiness, and gas barrier capabilities. The alleged advantages of nano-additives are manifold, including a large surface area, strength, low weight, high stiffness, and sustained sustainability. Nevertheless, the implementation of nanotechnology in the paper sector has been hindered by several obstacles, including elevated expenses, inadequate compatibility between materials, and a gap in understanding.

The initial phase of the paper manufacturing process includes material preparation, pulp production, pulp bleaching, paper production, and fiber recycling [20]. The processed wood pulp, which may undergo bleaching if needed, is made as a thin mixture with various additions, particularly fillers, to achieve the desired paper quality.

Nanotechnology plays a crucial role in nearly all contemporary sectors, with a focus on achieving high-quality and efficient market opportunities [21–23]. The significant interest in the nanoscale range stems from the fact that nano additives exhibit superior characteristics in comparison to their bulk counterparts [22]. Nanotechnology is currently at the forefront of driving global economic growth and progress. Nano-scale techniques are widely used in various fields, offering insights into promising advancements in materials, electronics, and systems [23,24]. Nano-additives possessing distinctive benefits are anticipated to revolutionize the aspects of controlled technology. In this context, nanotechnology primarily aims to exercise control and manipulation over materials to achieve certain functionality. Nanotechnology advancements offer gradual and progressive improvements [25] and have recently become a valuable tool in various applications, including the pulp and paper industry.

The distinctive benefits and characteristics of the paper can be enhanced by the use of nano-additives. The progress in nanotechnology has led to the creation of several nano-additives, which are the outcome of considerable research in the field of nanotechnology. The size of nano-additives is substantial, as a result of many variables [23–26]. The light scattering properties are influenced by nano-additives, gloss and opacity, the calendaring process, the drying rate, and the ability of the paper to absorb ink. The nanoparticles tend to agglomerate [27]. Obtaining bigger-diameter nano-additives is challenging because of the limited specific surface area. For instance, furnishings that contain nano-additives with microscopic particles have a larger surface area that competes with the sizing agent, making them more resistant.

3.4. Switchable adhesives

Nano-based adhesive bonding incorporates the incorporation of nano-scale particles, such as nano-fillers and nanocrystals, to enhance the strength, flexibility, and durability of contemporary adhesives. These adhesive matrices, loaded with nanoparticles, possess improved characteristics in comparison to traditional adhesives [28–30].

3.5. Nanofillers in adhesives

The adhesive matrices, which are infused with nanoparticles, exhibit enhanced properties as compared to conventional adhesives. The use of nanofillers is an effective method for improving the performance of these base polymers. Nanofillers enhance the mechanical characteristics of polymeric adhesives, including their ability to withstand cracks, resist wear, and prevent corrosion [31]. Several types of nanofillers, such as nanoclays, carbon nanotubes, metal or metal oxide particles, ceramic fillers, and cellulose nanomaterials (CNMs), have been studied for their incorporation into polymeric adhesive nanocomposites. Studies have demonstrated that CNMs are especially proficient in improving polymeric adhesive matrices. Carbon nanomaterials (CNMs) possess the advantageous properties of reusability, biodegradability, non-toxicity, and lower energy requirements during the manufacturing process. An example of this is when the addition of 5 wt.% nano-silica to an epoxy coating resulted in a 30% reduction in mass loss during abrasive tests. Comparable enhancements were noted for acrylic adhesive composites reinforced with CNM, specifically with a fiber loading of 10 wt.% [32].

Due to their excellent crystallinity and aspect ratios, CNCs are much sought after as adhesive reinforcements. The use of CNCs in adhesive formulations enhances bond strength and enhances the resistance to joint creep and stiffness. The nanocrystals' high modulus of elasticity is crucial for improving the stiffness of the composite, making it essential for structural applications. Nanostructured epoxy adhesives are widely used because of their improved properties, including higher mechanical strength, enhanced heat and chemical resistance, and reduced curing time. Nanoscale materials enhance adhesion on uneven or rough surfaces as a result of their increased surface area-to-volume ratio. The adhesives supplemented with nanomaterials demonstrate a substantial enhancement in bonding strength, hardness, and durability. Their ability to cure quickly is extremely beneficial in businesses that require fast manufacturing procedures. In addition, the process of nano-structuring improves the ability of these adhesives to withstand harsh chemicals and high temperatures, thereby making them well-suited for challenging settings and maximizing their performance for specific industrial uses.

3.6. Nano-based adhesives in aerospace

The aerospace sector actively utilizes nano-based adhesives because of their exceptional tensile features, including fatigue resistance and improved mechanical properties. Nonetheless, the effectiveness of their performance in aircraft and space flight applications is heavily influenced by the specific nanoparticles or fillers utilized, their dimensionality, and the fabrication procedures applied. Carbon fibers have been integrated into adhesive epoxy matrices to provide lightweight and specialized structural materials that are specifically designed for modern spacecraft. These materials have demonstrated their suitability for use in aircraft applications (**Table 2**). The utilization of nanoparticles of various shapes, including planar, tubular, and spherical, in adhesives is a novel method for improving the characteristics of adhesive connections in contemporary airplanes [33].

Table 2. Potential application of nanoparticles in aerospace engineering.

Industry	Nanoparticles	Nanoparticle-based conventional product/Potential area of application
Aerospace engineering	Carbon nanotubes Graphene Nano clay Metal nanoparticles (e.g., silver, gold) Ceramic nanoparticles (e.g., silica, alumina)	Composite materials: Create lightweight, high-strength composites for structural components. Coatings: Provide corrosion resistance, thermal protection, and reduced friction. Energy storage: Batteries and supercapacitors to improve energy density and power. Propulsion: Fuel additives, propulsion systems, and rocket engines. Sensors: Detecting temperature, pressure, and chemical changes. Self-healing materials: Create materials that can self-heal cracks and damages. Thermal management: Improve heat transfer and thermal management in aerospace systems. Radiation protection: Create lightweight radiation shielding materials.

3.7. The futuristic nano-based adhesives

Due to current progress in manufacturing, adhesives are constantly enhancing, and the integration of nanoparticles is providing important characteristics. The present emphasis is on employing ecologically sustainable techniques to improve contemporary adhesives. Research in the field of bio-based adhesives enhanced with nanofillers is showing great potential. Continued advancements are anticipated in the realm of nano-based adhesives.

3.8. Magnetic fluids

The topic of magnetic soft materials is a rapidly growing interdisciplinary scientific discipline that has developed in the past several decades. The tasks largely involve condensed matter physics, magnetism, magnetic hydrodynamics, inorganic and organic chemistry, colloid chemistry, computational and computer modeling, acoustics, engineering, and applied sciences. Magnetically soft materials include magnetic fluids, magnetic elastomers, and magnetic gels that contain magnetic nanoparticles. These materials can be modified by adding different types of magnetic or non-magnetic substances.

Traditionally, magnetic fluids (MFs) were at the forefront, consisting of a colloidal system where nanoparticles coated with magnetic material were dispersed in a liquid medium. The magnetic fluid contains single-domain superparamagnetic nanoparticles, which are typically approximately 10 nm in size. The early materials mentioned here are recognized as the forerunners of intelligent nano-dispersed materials [34,35]. These materials have been extensively studied in scientific literature [36–38] and are used in a wide range of devices and technologies [39–42]. Magnetic fluid possesses a distinctive blend of fluidity and the capacity to react to an external magnetic field. As a result, it has been used in seals [40], controlled shock absorbers [39], diverse sensors [41], and acoustic systems [42]. The significant advancements in nanotechnology and the capacity to create materials and structures have allowed for the development of magnetic fluids as multiphase systems. In this particular situation, magnetic nanoparticles work as separate components with a regulated arrangement that can experience modifications on their surface with the help of particular surfactants. These modifications allow them to engage preferentially with specific biological entities or organic molecules [43].

A nano-dispersive magnetic fluid is a colloidal system consisting of magnetic nanoparticles (MNPs) with diameters ranging from 5 to 20 nm. The MNPs are covered with a stabilizing shell of a surfactant dispersed within a liquid carrier. Investigation and Academic Curiosity Surrounding Nano-Disperse Magnetic Fluids Article [44] provides a comprehensive explanation of the mechanism by which stable colloids are created from magnetic nanoparticles, which usually have a diameter of approximately 10 nm or greater. The name "magnetic fluids" was initially used to refer to these colloids [44], and their dynamics were referred to as ferrohydrodynamics [45]. Magnetic fluids are distinct materials that are artificially produced. Magnetostatic bacteria can detect magnetic nanoparticles (MNPs) [46], but there are currently no stable liquid systems that display ferromagnetic characteristics. During the early 19th century, renowned physicists Michael Faraday and Thomas J. Seebeck conducted research on the behavior of magnetic dust when subjected to external magnetic fields [47]. The system under investigation was characterized by instability and exhibited rapid settling. Elmore subsequently conducted measurements of the magnetization curves of micro-sized particles that were scattered in a carrier liquid [48]. The synthesis of magnetic fluids, as now investigated, originated in the United States approximately 60 years ago [34]. They were recognized as groundbreaking artificial nano-dispersed material and became the focus of scientific investigation [35]. Magnetic fluids have been utilized in much technical equipment [35,49,50], even before the word 'nanotechnology' was coined [51].

Nanotechnology has been evolving over the past 15 years, sparking renewed interest in magnetic fluids. Researchers have started viewing magnetic fluid from a different perspective. Currently, magnetic fluid is recognized as a multiphase system where magnetic nanoparticles exist as distinct elements with controlled structures and properties. Magnetic fluid and magnetic nanoparticles find numerous applications, particularly Magnetic fluid and magnetic nanoparticles find numerous applications, particularly in the field of biomedicine [52–54]. These particles serve as contrast agents in magnetic resonance imaging [55,56]. Researchers are actively investigating interactions between particles, the formation of chain aggregates and flexible clusters, and the impact of the microstructure on the macroscopic properties of magnetic fluid through both experimental and theoretical studies [57,58]. The development of magneto-fluidic systems has made it possible to significantly alter viscosity under the influence of an external magnetic field, showcasing a giant magneto-viscous effect.

Presently, the exploration of magneto-fluidic systems constitutes a multidisciplinary field, encompassing condensed matter physics, magnetism, hydrodynamics, inorganic and organic chemistry, colloidal chemistry, computational and computer modeling, acoustics, engineering, and applied sciences. Positive anisotropic MNPs are achieved through extensive efforts in refining production methods that control the material, size, shape, structure, and modification of the MNP surface [59–61].

4. Nanoengineered materials for the Engineering industry

Table 3 describes the potential application of nanoparticle mechanical engineering.

Table 3. Potential application of nanoparticles mechanical engineering.

Industry	**Nanoparticles**	**Application**	**Nanoparticle-based traditional product/Potential area of application**
Mechanical engineering	Titanium dioxide (TiO_2) Zinc oxide (ZnO) iron oxide (Fe_2O_3) carbon nanotubes (CNTs) Graphene Silver (Ag) Gold (Au)	Water treatment plants Air pollution control systems Soil remediation sites Wastewater treatment plants Environmental monitoring systems	Water Treatment: • Nanoscale's Water Treatment Systems (Nanoscale Corporation) • Nanostellar's Water Treatment Catalysts (Nanostellar Inc.) • Altair's Water Treatment Membranes (Altair Nanotechnologies Inc.) Air Pollution Control: • Nanohmics' Air Pollution Control Systems (Nanohmics Inc.) • Nanoscale's Air Pollution Control Catalysts (Nanoscale Corporation) • Komatsu's Air Pollution Control Filters (Komatsu Ltd.) Soil Remediation: • Nano remediation's Soil Remediation Systems (Nano remediation Inc.) • Nanostellar's Soil Remediation Catalysts (Nanostellar Inc.) • Altair's Soil Remediation Membranes (Altair Nanotechnologies Inc.) Wastewater Treatment: • Nanoscale's Wastewater Treatment Systems (Nanoscale Corporation) • Nanostellar's Wastewater Treatment Catalysts (Nanostellar Inc.) • Nanohmics' Wastewater Treatment Membranes (Nanohmics Inc.) Environmental Monitoring: • Nano sensor's Environmental Monitoring Systems (Nano sensor Inc.) • Nanostellar's Environmental Monitoring Sensors (Nanostellar Inc.) • Altair's Environmental Monitoring Membranes (Altair Nanotechnologies Inc.)

4.1. Wear protection for tools and machines

Nanocoating for external protection and building in addition to acting as corrosion inhibitors for reinforced steel, nanomaterials are especially well suited to shield the surfaces of many building materials, including glass, concrete, sand, limestone, and marble, from environmental factors like water staining, moss, and algae as well as soot and oil stains. Commercially available paints and surface coatings produce a low-energy face, making a building's surface extremely hydro and oleophobic, extending maintenance cycles and requiring less cleaning. The most common uses in the building and external protection sectors are photocatalytic coatings and dirt-repellent protective paints. Building upkeep is greatly hampered by dirt collection (buildup) on building exteriors. Typically, high-pressure water jets, scrubbing, wiping, and detergents are used to clean these types of building surfaces. These procedures have several drawbacks, including the need for chemical detergents, significant energy use, and labor costs. High maintenance costs follow naturally from this, which is why an efficient self-cleaning coating is preferred. Anti-fouling and easily cleanable coatings are manufactured by several major international corporations, such as Evonik Degussa, Dupont, Schott, 3M, and Corning, for a range of applications.

Recently, photocatalytic self-cleaning coatings have been developed. Titanium dioxide (TiO_2) has drawn a lot of interest from the industry. TiO_2 has two special qualities that it can achieve with the help of minimal UV light from a fluorescence source or sunshine.

- Strong oxidation power, and,
- Super hydrophilicity.

Strong oxidation power can be utilized to eliminate odors from toilet stains and kill microorganisms that have attached themselves to the wall (commercially available products include TiO_2-coated glass and tile). When a coating of this kind is put on external surfaces, its superhydrophilic qualities facilitate the easy removal of dirt and stains with water or sunlight. Because nanoparticle TiO_2 self-cleaning coatings eliminate the need for expensive surface cleaning, they are especially beneficial for skyscraper maintenance. By lowering the quantity of volatile organic compounds and other hazardous chemicals that people are exposed to in hotels, restaurants, commercial buildings, university laboratories, hospitals, and homes, photocatalyst coatings are also used to enhance indoor air quality. Because of their non-stick qualities, nano coatings make surfaces both inside and outside less stained and easier to clean. Because of their anti-graffiti qualities, stains like graffiti that formerly required thorough cleaning can be removed with a high-pressure hose.

Table 4. Potential application of nanoparticles biomedical engineering.

Industry	**Nanoparticles**	**Application area**	**Nanoparticle-based traditional products/Potential area of application**
Biomedical engineering	Liposomes Polymeric nanoparticles (e.g., PLGA, PEG) Metallic nanoparticles (e.g., gold, silver, iron oxide) Ceramic nanoparticles (e.g., silica, alumina) Quantum dots Carbon nanotubes Graphene oxide	Cancer diagnosis and treatment Neurological disorders (e.g., Alzheimer's, Parkinson's) Cardiovascular disease Infectious diseases (e.g., HIV, tuberculosis) Ophthalmic applications (e.g., glaucoma, age-related macular degeneration)	Drug delivery systems: To release drugs in a controlled manner, reducing side effects and improving efficacy. Diagnostic imaging: As contrast agents for MRI, CT, and PET scans, improving image resolution and accuracy. Biosensors: To detect biomarkers for diseases, such as cancer, diabetes, and infectious diseases. Tissue engineering: To create scaffolds for tissue regeneration and repair. Wound healing: To create dressings that promote wound healing and tissue repair. Implantable devices: To improve the biocompatibility and functionality of implantable devices, such as pacemakers and prosthetics. Cancer treatment: To deliver chemotherapy directly to cancer cells, reducing side effects and improving efficacy.

Commercially available are water-based, volatile organic compound (VOC)-free, transparent impregnating nanoparticle wood coatings with nanoscale UV absorbers. They offer enhanced water repellence, lower efflorescence, and noticeably better abrasion resistance. They are intended for use on masonry and concrete surfaces. New and creative coating applications are mostly driven by nanotechnology, and nanocoatings have seen significant growth in the last several years. High transparency, novel features, and high-quality performance are becoming more and more crucial needs in the coatings industry. However, protection from ice, pollutants, UV light, fire, heat, bacteria, marine life, touch, and corrosion is the main benefit that nanostructured coatings offer. These elements can be extremely dangerous to the public's health and cost the worldwide industry billions of dollars in lost production, maintenance, and downtime annually. For instance, worldwide, direct corrosion expenses represent 3%–4% of a nation's GDP. Extraordinary attributes Nanostructured surfaces, thin films, and nanoscale coatings are extensively used in several industry domains and serve as excellent illustrations of how nanotechnology may advance, upend, or even create new technology sectors. In the medium to long term, nano-coating is more cost-effective than standard coatings and exhibits notable performance advantages. Some applications of nanoparticles Biomedical engineering is mentioned in **Table 4**.

Nanostructured materials significantly improve a variety of properties, including antimicrobial, product longevity, heat insulation, gloss retention, dirt and water repellency, hardness, corrosion resistance, flame retardancy, stability against ultraviolet radiation, improved energy efficiency, anti-graffiti, self-cleaning, moisture absorbing, gloss retention, and chemical and mechanical properties. Primary markets for coatings with nanostructures are:

- Medical supplies (both long-term and short-term reusables).
- Producing food, leather and textiles.
- Coatings for Marine Use.
- Treatment of water.
- Taking care of the home.
- Building.
- Transport/Automobile.
- Engineering & Tools.
- Energy.

4.2. Lubricant-free bearings

Nanoparticles can be particularly useful as lubricating additives in lowering friction and preventing wear. The tribological characteristics of TiO_2 nanoparticles are good [62–67]. To comprehensively investigate the impact of particle size and shape on friction qualities, Hwang and Kalyani dispersed different carbon-based particles in mineral oil [68,69]. Numerous organic substances, including oxygen, nitrogen, sulfur, halogens, phosphorus, and sulfur, have been employed as anti-wear additives. Under lubricating circumstances, additives containing active elements are adsorbed on the metal's contact surface and form a tribochemical film. By lowering wear and friction, Kalyani, Zhou, and Tomala increased machine efficiency [70–72]. To reduce wear and friction under boundary lubrication conditions, Rabaso and Rapoport incorporated inorganic fullerene (IF) nanoparticles into their lubricants [73,74]. Pena-paras investigated the impact of Al_2O_3 and CuO nanoparticles on the load capacity and tribological characteristics of the GL4 and PAO 8 oils, respectively [75]. According to Liu's investigation of the mending properties of copper nanoparticles on contact surfaces, these particles indeed exhibit a very good mending effect [76].

Lee discovered that the lubrication enhancement of nano-oil was greatly enhanced by nanoparticles distributed in the mineral oil; the friction coefficient of the disc specimen submerged in the nano-oil was significantly lower than that of the disc specimen submerged in the mineral oil [77]. Hu produced the nanoparticles and carried out the experiment; the outcomes demonstrated that the addition of nanoparticles enhanced the 500 SN base oil's wear resistance and load-carrying capability while lowering its coefficient of friction [78].

Researchers have found SiO_2 to be a valuable common nanoparticle due to its superior controllability, dispersion, and confined distribution range. The tribological characteristics and anti-wear mechanism of water-based lubricants containing SiO_2 nanoparticles were studied by Wang and Zhu [79,80]. However, the relationship between surface roughness and nanoparticles has not been thoroughly examined. Peng's objective was to investigate the tribological characteristics of liquid paraffin, including SiO_2 nanoparticles as additives. The findings suggest that liquid paraffin containing appropriate quantities of SiO_2 nanoparticles exhibits superior tribological qualities in comparison to pure paraffin oil [81].

5. Nanoengineered materials for electronic industry

Electronic paper, Field Emission Displays (FEDs), Organic LEDs (OLEDs), and electronic devices are the three main types of display technologies, which are the visual devices used to display digital information, images, and videos (**Table 5**).

Table 5. Potential application of nanoparticle electronics engineering.

Industry	Nanoparticles	Application area	Nanoparticle-based traditional product/Potential area of application
Electronics engineering	Silver Gold Copper Carbon nanotubes Graphene Cadmium selenide Zinc oxide Titanium dioxide	Smartphones Laptops Tablets Smartwatches Televisions Solar panels Energy storage systems	Conductive Inks: • DuPont's Silver Nanoparticle Ink (DuPont) • Cabot's Silver Nanoparticle Ink (Cabot Corporation) • Nanograde's Copper Nanoparticle Ink (Nanograde Ltd.) Displays: • Samsung's Quantum Dot Technology (Samsung Electronics) • LG's Nano Cell Technology (LG Electronics) • Nanosys' Quantum Dot Technology (Nanosys Inc.) Solar Cells: • Nanosolar's Solar Cells (Nanosolar Inc.) • Solarmer's Solar Cells (Solarmer Energy Inc.) • Nanoco's Quantum Dot Solar Cells (Nanoco Group plc) Memory Devices: • Micron's Phase Change Memory (Micron Technology Inc.) • Samsung's Phase Change Memory (Samsung Electronics) • Intel's Phase Change Memory (Intel Corporation) Sensors: • Sensirion's Gas Sensors (Sensirion AG) • ABB's Temperature Sensors (ABB Ltd.) • Nanosensor's Biosensors (Nanosensor Inc.) Energy Storage: • Tesla's Battery Electrodes (Tesla Inc.) • LG Chem's Battery Electrodes (LG Chem Ltd.) • Nanotech's Battery Electrodes (Nanotech Industries Inc.) Thermal Management: • Nanocool's Thermal Interface Materials (Nanocool Inc.) • Indium's Thermal Interface Materials (Indium Corporation) • Nanotherm's Thermal Interface Materials (Nanotherm Ltd.) Printed Circuit Boards: • Dupont's Conductive Inks for PCBs (DuPont) • Fujikura's Conductive Inks for PCBs (Fujikura Ltd.) • Nanograde's Conductive Inks for PCBs (Nanograde Ltd.) Semiconductors: • Intel's Transistors • IBM's Transistors

More sophisticated, superior, and energy-efficient displays are made possible by the research and manufacturing of display technologies, which heavily rely on nanotechnology. Through careful engineering of materials at the nanoscale, scientists and engineers can attain enhanced performance and novel capabilities that are unattainable with traditional materials and production techniques. One kind of display technology that produces light using organic materials is called an organic LED. OLEDs are perfect for televisions, mobile devices, and other applications because they are thin, flexible, and have great contrast, quick response times, and wide viewing angles. Nanotechnology is employed to develop the organic materials in OLED displays that make images and emit light. Organic materials at the nanoscale are carefully designed to release light when an electric current is applied.

E-paper, or electronic paper, is a term for a kind of display technology that simulates the look of regular ink on paper. Because they are high contrast, low power consumption, and reflective, e-paper displays are perfect for wearable technology, digital signage, and e-readers, among other applications. To create electronic inks for e-paper displays, nanotechnology is employed. These inks can show text and images because they contain nanoparticles that, when exposed to an electric field, can change color. A sort of display technology called Field Emission Displays (FEDs) employs electron emitters to produce images on a screen. FEDs are the perfect choice for applications like projectors and large screen displays since they are light, thin, and have high brightness, quick reaction times, and wide viewing angles. Nanotechnology is utilized in Field Emission Displays to construct the electron emitters that generate images.

All things considered, display technologies have advanced significantly in recent years and are still developing, giving consumers a wider variety of choices for visual display.

5.1. Advanced OLETs and OLEDs

Organic light-emitting diodes, or OLEDs, hold great potential for a variety of useful uses. OLED technology is already utilized in small electronic device displays found in digital cameras, MP3 players, mobile phones, and some TV screens. It is based on the phenomenon that some organic materials generate light when fed by an electric current. Large-scale organic solar cells, windows that might be utilized as nighttime light sources, and ultra-flat, extremely bright, and power-saving OLED televisions are all achievable with more affordable and efficient OLED technology.

An OLED's emissive electroluminescent layer is made up of a thin layer of organic chemicals, as opposed to ordinary LEDs. OLEDs are very appealing since they don't need a backlight, which means they use less electricity to run. Moreover, because they're thinner than similar LEDs, they can be printed on nearly any surface. Nanomaterials and nanofabrication techniques are applied in the production of OLEDs in two areas: Transparent electrodes (where thin-film carbon nanotubes are becoming more and more popular) and coatings based on nanoparticles that are used to pack OLEDs to protect them from environmental damages (such water). Techniques for depositing materials based on nanoparticles may also be able to tackle unresolved problems with OLED manufacture, such as material damage, yield, and thickness uniformity.

Furthermore, a completely new design for OLEDs with a transparent conductor made of a few manometers of graphene has just been devised by researchers. This made it possible to produce OLEDs in big quantities at minimal cost on flexible plastic substrates that could be virtually put anywhere and rolled up like wallpaper. However, photon loss and exciton quenching still restrict the brightness and efficiency of OLEDs. Organic light-emitting transistors (OLETs) are substitute planar light sources that integrate an electroluminescent device's and a thin-film transistor's switching mechanism into a single architecture. OLETs therefore have the potential to usher in a new age in organic optoelectronics and act as experimental platforms for addressing broader basic optoelectronic and photonic problems.

5.2. Quantum dot LEDs, or QLEDs

One of the most promising optoelectronic materials, quantum dots (QDs), will be at the heart of next-generation displays due to their unique physical features and ability to be both photoactive (photoluminescent) and electroactive (electroluminescent). QD-based materials have cheaper manufacturing costs, longer lifetimes, purer hues, and lower power consumption than organic luminescent materials used in organic light-emitting diodes (OLEDs). Because QDs can be deposited on almost any substrate, you may expect printable, flexible, and even rollable displays of all sizes. This is another important benefit of quantum dot displays. An example of a passive matrix quantum dot light-emitting diode (QLED) display that is fully integrated with flexible electronics has been demonstrated by researchers.

5.3. Digital paper

Electronic paper reflects light like regular paper and can keep text and images endlessly without draining electricity, unlike standard flat panel displays that utilize a power-hungry backlight to illuminate their pixels. It also allows for image modification afterward. Electrophoretic displays are regarded as leading instances of the electronic paper category because of their ability to be manufactured on thin, flexible substrates and because of the way they resemble paper. There are currently commercially available electrophoretic displays, such as those found in the Sony Reader and Kindle; however, they are primarily black and white at this time. Color displays continue to have problems with quality and pricing. Researchers studying nanotechnology have demonstrated that organic ink nanoparticles may be able to improve the process of making electronic ink, leading to the production of e-paper with better brightness, a better contrast ratio, and a more affordable manufacturing cost.

5.4. Field-based emission displays

To develop a new type of vast area, high-resolution, low-cost flat panel displays, researchers have resorted to carbon nanotubes. Some predict that the largest challenge to LCD's hegemony in the panel display market will come from field emission display

(FED) technology, which uses carbon nanotubes (CNT) as an electron emitter. FED is also the preferred technology for ultra-high-resolution, wide-screen televisions.

FEDs can be thought of as a cross between liquid crystal displays (LCD) and cathode ray tube (CRT) televisions. By combining the dot matrix cellular structure of LCDs with the proven cathode-anode-phosphor technology found in full-sized CRTs, they profit from this technology. To produce colored light, the grid-mounted electron emitters are individually controlled by “cold” cathodes (in contrast to regular CRTs, which boil off electrons by heating the cathode). The narrow panel of today’s LCD is made feasible by field emission display technology, which also gives a broader field of view, great image quality comparable to that of CRT displays, and lower power consumption.

5.5. Optical switch

The development of an ultra-fast and ultra-small optical switch could hasten the day when photons take the place of electrons in consumer goods like cell phones and cars. Trillions of times every second, the new optical technology may be turned on and off. It is made up of discrete switches with diameters of just 200 nanometers, or one-fifth the width of a human hair. This size is significantly smaller than the optical switches of the current generation, and it readily overcomes one of the main technological obstacles to the widespread use of light-detecting and light-controlling electrical devices: The shrinking of ultrafast optical switch sizes.

A manmade substance with features not seen in nature is used to make the ultrafast switch. In this instance, the “metamaterial” is made up of nanoscale vanadium dioxide (VO_2) particles, which are coated with a “nanomesh” of minute gold nanoparticles and deposited on a glass substrate. VO_2 is a crystalline solid that can rapidly transition between an opaque, metallic phase and a transparent, semiconducting phase. The vanadium dioxide undergoes a phase change in a few trillionths of a second when hot electrons from an ultrafast laser are briefly exposed to the gold nanomesh. This process is attributed to the scientists.

5.6. Filters (IR-blocking)

Preventing infrared radiation from affecting a detector’s performance is crucial. Metal-mesh infrared-blocking filters have been developed as a highly efficient solution to overcome this problem for superconducting tunnel junction particle detectors. One of the better structures in this type is formed by freestanding Cr/Cu films that are 590 nm thick, a tiny membrane, and a sequence of circular holes that have a diameter of roughly 2 μm. A transmission of 300 K radiation is just 1%, according to the data transmission efficiency. From an alternative perspective, the ion transmission efficiency is close to 20%, which is consistent with values that are predicted geometrically. Because they can simultaneously analyze and elucidate ion charge states and mass values through kinetic energy measurement, superconducting particle detectors are thought to be extremely advantageous for mass spectrometry applications. This is not possible with traditional ion detectors like ion multipliers or microchannel plates. The quality of shielding radiation is essentially the main technology in mass spectroscopy using a cryogenic particle detector. In particular, until atoms or molecules may be received on the detector, there must be an open chamber for a flight path. As a result, when operating in a linear mode, the detector under cryogenic circumstances is exposed to 300,000 blackbody radiation throughout the flight. As a result, in the absence of radiation protection measures, the performance of cryogenic detectors based on superconducting materials is significantly impacted [82].

5.7. Antistatic and conductive coatings

Using advances in plastic anti-static coatings, OCSiAl created a concentrated graphene nanotube that offers thermoplastics-specific conductivity for electrostatic painting, allowing automakers to reduce costs by streamlining the painting procedure. The powder coatings created by Erie Powder Coatings in Canada utilizing TUBALL graphene nanotubes from OCSiAl are an additional illustration of an efficient anti-static coating for plastic materials. These coatings exhibit high resistance, conductivity, and static dissipative qualities, which eventually improve aesthetic performance.

Taking a closer look at anti-static coatings and additives for resins, anti-static resin flooring commonly seen in workplaces and factories, serves as an example. To prevent ESD, an anti-static resin coating is added to the flooring, which either inhibits or redirects electrical charges or produces no electrical charge at all. This eventually saves lives and is crucial in industry, especially in settings where volatile materials are used. Rubber anti-static matting and sheeting used in the electronics sector and the flooring business are two examples of industrial anti-static agents. Because graphene nanotubes may function at low working dosages while maintaining or enhancing the characteristics of rubber, they hold considerable promise as anti-static agents. The use of single-walled carbon nanotubes in static control flooring has several advantages, including increased quality and cost-effectiveness. Moreover, because they occupy less space in the coating, more materials with even more desirable qualities can be applied.

6. Nanoengineered materials for the construction industry

The construction sector is attracted to the remarkable features and characteristics of these materials. Although they are modest in size, they are well recognized and esteemed for their extremely commendable qualities in practically every domain nowadays. Nanomaterials are being extensively utilized in the construction industry, alongside other fields. They not only assist in the construction operations but also serve as a means of eliminating the spread of toxicity that occurs thereafter. Nanografi enhances the characteristics of construction materials by using nanotechnology, hence advancing the creation of cutting-edge materials.

The features of nanomaterials are exceptionally distinctive, encompassing both their physical and chemical characteristics. The materials at large and tiny scales exhibit significant differences due to the challenges faced by particles of such sizes in identifying their physical and chemical properties. The key factors include the obvious features such as the shape, size, surface qualities, and inner structure. They can also be referred to as aerosols, which encompass both solids and liquids suspended in the air. Additionally, they can be described as suspensions, indicating the presence of particles in liquids, and emulsions, which are mixtures of liquids. By introducing other substances, the characteristics of these materials can be modified and potentially impeded by certain deviations.

Creating a single nanoparticle requires a high level of intricacy, making the process of assembling one quite challenging. The interaction or combination of chemicals or particles is determined by their specific properties. The chemical processes they are involved in are mostly unknown due to their complexity and the need for meticulous attention and keen observations. Nanomaterials exhibit a wide range of distinct modes of interaction, both among themselves and with other substances. The decision to live freely or in groups lies entirely with them, contingent upon the nature of the forces acting upon them, which can be either enticing or repellent. Characterizing them is challenging due to their intricate relationships and the presence of dynamic factors. An inherent characteristic of nanomaterials is their ability to maintain a stacked arrangement when suspended in a gas, as opposed to when they are in a liquid form.

6.1. Applications of nanomaterials in the construction sector

Nanomaterials have made significant inroads into the construction industry, resulting in a profound transformation of products, services, and sectors, including construction. Recording the effects or impacts that they have on the environment and humans is of utmost importance.

The potential application of nanoparticles in civil engineering is shown in **Table 6**.

Table 6. Potential application of nanoparticles civil engineering.

Industry	Nanoparticles	Application area	Nanoparticle-based traditional product/Potential area of application
Civil engineering	Nano-silica Nano-alumina Nano-titania Nano-iron oxide Carbon nanotubes Graphene oxide Nano-clay	Buildings and bridges Highways and pavements Water treatment plants Dams and canals Environmental remediation Geotechnical engineering Structural health monitoring	Nanocrete: A concrete additive that improves strength and durability. Nano-sealants: Sealants that use nanoparticles to provide improved water resistance and durability. DuraBuild: A coating that protects concrete from corrosion and degradation. NanoGuard: Treatment that improves the durability of asphalt pavements. SmartCoat: Coating that provides self-healing properties for concrete structures. NanoCem: A cement additive that improves strength and sustainability. AquaShield: A water treatment system that removes contaminants and improves water quality. NanoSensors: Sensors that monitor structural health and detect environmental changes. EcoPave: An asphalt additive that improves durability and reduces environmental impact. NanoCon: A concrete additive that improves strength and reduces shrinkage.

Nanomaterials offer numerous advantages to the construction industry, and their remarkable ability to safeguard the ecosystem is remarkable. Nanomaterials possess a very small size, which enhances their performance in various areas such as catalysis, conductivity, magnetism, mechanical strength, and optical sensitivity. These properties contribute to a diverse variety of applications and are highly suitable for use in the construction sector and its associated operations. Hardened mixture of cement, sand, and water used in construction.

Concrete is one of the many applications of nanomaterials in the realm of building. Concrete exhibits the largest annual production among all other materials, mostly due to the incorporation of carbon nanotubes (CNTs) and nanosized SiO_2. These additives significantly improve the concrete mixture, including both the binding phase and the aggregates. Concrete contains a significant quantity of nanoparticles, which enhances its suitability for use in the building industry. Although their weightage is rather little, the collective impact of all the nanomaterials significantly influences the overall criterion and the scenario itself [83,84].

Steel is a versatile material that is commonly utilized in the construction industry for building structures and bridges. These encounter hurdles in terms of strength, resistance, and formability. This is attributed to their incorporation into the realm of metal nanoparticles (NPS). In addition, copper particles are utilized to reduce surface roughness, hence enhancing anti-corrosion properties.

Transparent material is used to cover openings in buildings, allowing light to enter while keeping out the elements. Window glass, like concrete and steel, can serve several purposes when TiO_2 and SiO_2 nanoparticles are added. By applying a photochemical method, TiO_2 nanoparticles can be coated onto windows. This coating enables the nanoparticles to effectively react with sunshine and indoor light, resulting in the elimination of dirt and bacterial films, if present. The silica layers or sheets, in the form of nanoparticles, are utilized to make windows fireproof and are quite reliable. The extensive promotion of nanoparticles is attributed to their properties and many factors [85].

Reducing the impact on the environment: While there are certainly advantages, it is important to acknowledge that there are also potential negative consequences associated with the products and materials employed in this particular industry. Nevertheless, nanoparticles exist in the form of nano-electromechanical and micro-electromechanical systems (NEMS and MEMS). These sensors are composed of either nano- or micro-sized materials, which have recently received significant interest. Nanomaterials are extensively employed to safeguard both the environment and humans from potential harm resulting from excessive use. It is worth noting that nanomaterials themselves serve as a protective measure to mitigate adverse environmental effects.

6.2. Nanomaterial-enriched concrete

Common nanomaterials used in concrete to improve density, strength, and ultimately fire resistance include silica, titanium dioxide, iron oxide, and carbon nanotubes [86–88]. Concrete is made denser and less porous by adding silica particles to fill the spaces between the cement grains. Increased mechanical strength is the outcome of this [88]. Silica fume and nano-silica, sometimes referred to as “fumed silica”, are the two forms of nanoparticles used in concrete [89]. Concrete that is self-cleaning and toxin-free can benefit from the use of nanosized titanium dioxide [87].

Abrasion resistance and compressive strength can be increased by using iron oxide nanoparticles [88]. It has been determined that the presence of carbon nanotubes (CNTs) in concrete can result in robust, electrically conductive, and self-healing concrete [87]. The use of nanomaterials to help with post-fire curing of concrete that improves the capability to recover strength post-fire event [90,91] is a novel and promising development in nanotechnology in concrete. Using carbon nanotubes or carbon black nanoparticles, these nanoparticles can impart self-sensing properties that have implications for better assessing a building's structural safety during or after a fire [92–94].

6.3. Advanced glass and windows

Glass can have its insulating, self-cleaning, and fire-resistant qualities enhanced by a nanomaterial layer [86,87]. Another kind of nanomodified material is fire safety glass, which forms an intumescent layer between two glass plates and can offer high levels of fire protection by utilizing either nano-silica or silica fume [86,87]. The intumescent layer offers a high degree of integrity and insulation during a fire by expanding and becoming opaque. For more than 30 years, this kind of glass has been available, although mostly for applications requiring a high degree of thermal insulation, including escape routes [86].

6.4. Nanomaterials for insulation

Aerogels based on silica are excellent thermal insulators that can be utilized in vacuum-insulated panels, translucent windows, and insulation blankets [89]. These materials are not commonly utilized and are expensive to produce [86,87]. One more thing preventing them from being widely used is their low mechanical strength [95]. However, as demand for energy-efficient building materials rises, costs may be lowered with better production techniques and scale. Although the application of nanotechnology as an insulator depends on its capacity to lower the thermal conductivity of the building material, some applications of nanomaterials in construction may raise thermal conductivity, which could be dangerous in the event of fire protection unless the material composite additionally possesses fire-retardant qualities.

6.5. Advanced steel

Steel can have nanomaterials integrated into its construction or applied as a nano-coating. The use of coatings and nanocomposite polymers on steel structures can lower the warmth and enhance fire resistance [96]. Through the process of refining materials to the nanoscale and eliminating impurities such as carbides, steel is enhanced in strength, corrosion resistance, and tensile strength, which can reach 100 times that of regular steel [96]. According to manufacturers, employing nanomaterial in steel is more cost-effective and equally effective than using stainless steel. More efficient than more conventional techniques for shielding steel against corrosion, like coated with epoxy [86]. Steel constructions lose some of their strength and stiffness when exposed to high temperatures. Structural steelwork typically needs fire-resistant materials, such as cement-based sprays, boards, batt materials, and intumescent coatings, to protect occupants and minimize loss; however, steel coatings often lose their endurance [97]. Nanomaterials with Good fire resistance can be achieved with structural steel [97,98]. When a structure reaches a critical temperature in a fire, it may collapse. Better steel integrity can guarantee the integrity of the structure both during and after a fire, making it safer for rescue personnel. This would offer inhabitants more time to leave during a fire and cause less harm to property.

6.6. Nano-coated wood

In North America, wood is the most often used building material for residential construction and one of the most extensively used building materials overall. As a building material, timber has excellent mechanical qualities, and if forest resources are maintained well, they can be an endless renewable supply with the capacity to store atmospheric carbon for lengthy times if the lifespan of timber goods is prolonged [99]. Nevertheless, wood is a little more durable and fireproof than non-renewable building materials like steel and concrete. Untreated wood burns quite easily. Building standards restrict the use of wood in residential buildings because, unless it is coated with fire-resistant materials, it has a low fire resistance. Conventional chemical fire retardants can be used to increase fire resistance. Still, conventional fire-resistant coatings can release harmful gas [100]. The substances are connected with dangers to the environment and human health, and they are less effective than nanomaterials found in wood composites or nanocoatings consisting of SiO_2 and TiO_2 oxides and nanoclay [101]. Better technologies are required because most fire-retardant coatings are not very resistant to weathering and environmental influences [102]. The APP/PER/MA intumescent method for wood discovered is the most dependable and financially feasible, and evidence suggests it could be improved with the production of nano clay, nanostructured carbon [100], or amorphous silicon dioxide. Researchers have developed nano-coatings that can offer fire-resistant qualities without endangering human health, and they are working on nanotechnology wood coatings that have bestowed on wood fire-resistant qualities [103–107]. One intriguing breakthrough in a wood structure fire safety measure is the hydrothermal synthesis of $MnFe_2O_4$ onto the wooden surface, producing an electromagnetic wave-absorbing and fire-resistant layer covering [108]. From a safety standpoint, this could be a good alternative because manganese ferrite is already used in medications based on nanoparticles and is soluble, meaning it won't stay in the respiratory system if ingested, and there's proof that the body can get rid of it without harming any organs [109]. The application of an environmentally friendly polyelectrolyte complex that gives wood self-extinguishing and fire resistance when coated is another intriguing, advanced behavior, a longer igniting period, and a lower peak heat release rate [110]. This layer enhanced the wood's strength as well. These prospective innovations in building materials could have a significant positive impact on society by making wood more fire-resistant, which can save financial loss and avoid injuries and fatalities. In all things considered, using nanoparticles in wood construction can make fire-resistant building materials better and more sustainable, but further study is required to fully comprehend their lifetime and toxicological consequences.

6.7. Nanocomposites and nanocoating in architectural materials

A variety of architectural materials can be coated with nano-coatings. They create an intumescent coating on drywall and paint. The intumescent layer charges when it comes into contact with heat. Because char is a poor conductor, it provides better fire protection for the substance behind it, acting as a fire retardant. It was discovered that adding nano- and micron-sized boron nitride (BN) as fillers to fire-resistant coatings improved the coatings' thermal stability, particularly at high temperatures [111]. Wang et al. [98] compared the expanding and char structure of organic and inorganic intumescent coatings and discovered that while organic intumescent coatings produce smoke and solvent-toxic gas during a fire, they also have a good expanding effect. Inorganic intumescent coatings, like salt silicate coatings, have low levels of smoke and harmful gas emissions during application. They also don't produce organic solvents when heated.

Nevertheless, only at low temperatures do inorganic intumescent coatings provide fire protection and are susceptible to moisture [95]. Further investigation is required to comprehend the life cycle of the product and the toxicological consequences of nanocoating [112]. The use of nano-coating materials has far-reaching consequences. The usage of nanocomposites, like nanoclay, can strengthen construction materials and help in resistance against fire. Nanoclays have use in coatings and as construction material composites. The advantages of construction materials' strength and density have risen thanks to nanoclays [113]. Although there are currently no goods available for use in building, nanoclays can be synthetic or naturally occurring, created with layers of silicate-based materials, and employed in polymers to improve functioning in various ways [89]. If nano clay brick is put into the construction material market, it could have a significant positive impact on fire safety [87].

7. Nanoengineered materials for textile/non-woven industry

Nanotechnology possesses significant commercial possibilities for the textile sector. This is mostly due to the fact that traditional techniques employed to bestow various features on fabrics sometimes fail to provide lasting results and tend to lose their functionality after laundering or use [114]. Nanotechnology enhances fabric durability due to nanoparticles' substantial surface area-to-volume ratio and elevated surface energy, resulting in improved affinity for fabrics and increased functional longevity. Furthermore, the use of a nanoparticle coating on textiles will not compromise their breathability or tactile quality. Consequently, the interest in employing nanotechnologies within the textile business is on the rise. Coating is a prevalent method employed to deposit nanoparticles onto fabrics. Various techniques can be employed to impart coatings onto fabrics, including spraying, transfer printing, washing, rinsing, and padding. Among these strategies, padding is the most frequently employed.

Nanotechnology bestows textiles with attributes such as water repellence, soil resistance, wrinkle resistance, antibacterial qualities, anti-static characteristics, UV protection, flame retardancy, and enhanced dyeability, among others. This paper emphasizes some notable qualities conferred by nano-treatment in the textile sector, amidst the diverse prospective uses of nanotechnology.

- Water repellence.
- Thermal protective finish.
- UV-protection.
- Easy care finish.
- Anti-bacteria.
- Flameproof and retardant finish.
- Anti-static.
- Wrinkle resistance.
- Self-cleaning textiles.
- Odor control finish.
- Hydrophilic nano finishes.
- Lotus effect.

Nanoparticles possess a high surface area-to-volume ratio, facilitating their adhesion to fibers or fabrics and enhancing the longevity of the capabilities conferred by the particles. The nanoparticle coating does not compromise the breathability or tactile quality of the material. The most prevalent functions include wrinkle resistance, stain and soil repellency, water repellency, as well as anti-static, anti-bacterial, and anti-ultraviolet protection.

7.1. Nano-enhanced wrinkle resistance textiles

Wrinkling transpires when the fiber is significantly wrinkled. When fiber or fabric is flexed, hydrogen bonds among the molecular chains in the amorphous regions fracture, permitting the chains to slide past one another. The linkages are reformed in new locations, and fiber or fabric maintains increased configurations. The drawbacks of traditional resin applications encompass a reduction in fiber strength, abrasion resistance, water absorbency, dyeability, and breathability.

7.2. Nano-enhanced stain resistance textiles

Fabric staining results from the re-deposition of soil during laundering or dry cleaning, the accumulation of airborne dry soil, or contact with extraneous substances. Silicon compounds and fluorochemical coatings can verify resistance against soil, water, and oily stains. The stain-resistant textiles from Nano-Tex consist of billions of minuscule fibers, each about nanometers (0.0000004 inches) in length, integrated within conventional cotton or linen. The waterproof fibers, referred to as “nanowhiskers” by Nano-Tex, enhance the fabric’s density, elevating surface tension to prevent liquid absorption—similar to raindrops on a newly waxed automobile. The firm asserts that this Nano-Care treatment will endure 50 home launderings before its efficacy diminishes. The most advanced application of nanotechnology in textiles is presently focused on stain, oil, and water repellency, stain release, and wrinkle resistance. Nanotechnology can be utilized to apply stain resistance, stain repellent, and dual-action repel-and-release coatings.

Repellent treatments reduce the crucial surface tension of the fabric, preventing it from attracting stains or dirt. Oil and water bead up and roll off the fabric. When a repellent finish is applied to textiles, the imperceptible treatment offers enhanced water and oil resistance, as well as protection against spills and stains.

Stain-release materials permit stains and spills to penetrate the fabric; oil and water may bead slightly, and when stains are introduced, the fabric exhibits minor oil/water repellency. However, the imperceptible stain-release finish facilitates the effortless removal of embedded stains during laundering. This concludes with the incorporation of a hydrophilic component that facilitates the removal of absorbed stains by conventional laundering. The Dual Action Repel and Release is the latest stain release finish in the industry. The finish amalgamates the benefits of both stain release and repellent finishes into a singular formulation. This dual protection provides a distinctive equilibrium of repellency that operates in conjunction with an improved stain release, effectively eliminating the most stubborn stains, including entrenched ones. Featuring dual-action repel and release finishes, this fabric provides consumers with double the stain prevention in a single, easy-to-maintain material.

7.3. Nano-enhanced water repellent textiles

Water-repellent coatings alter the fiber's surface without obstructing the interstices. Consequently, the fabric allows the passage of air and water vapor. Initial water-repellent coatings were readily detachable for dry cleaning or laundry. Currently, wax emulsions, pyridinium compounds, N-methylal compounds, silicones, and fluorochemicals are employed to enhance water repellency in both natural and synthetic fibers. Recently, various products have been produced to enhance wrinkle resistance, stain resistance, and water repellency. The nano whisker introduced by Nanotex is among the most superior alternatives. They are permanently affixed to the cloth, in contrast to the conventional topical coatings or cumbersome laminated fabrics formerly employed for this purpose. The whiskers are hydrocarbons incorporated into the fibers within an aqueous solution. The modifications to the fibers do not impact the inherent tactile quality and breathability of the fabric. The fabric has excellent wrinkle resistance, the processing is imperceptible, and a "peach fuzz" look has been noted. The finish can be applied to textiles by a nanoscale emulsification technique that is more complete, uniform, and precise than conventional approaches. Woven cotton fabric rolls from textile mills are submerged in liquids containing trillions of nanowhiskers. They possess waterproof properties and enhance the fabric's density. The treated cotton is subsequently dried in ovens, adhering the minute fibers to the significantly larger cotton strands. This enhances the surface tension of the fabric's outer layer, preventing liquid absorption. Although the end product appears unaltered, it offers an almost impermeable barrier against liquids and wrinkles, for example. Nanowhiskers ensure uniform application without altering surface qualities, in contrast to conventional finishes. Nanoparticles are minuscule, rendering their incorporation into fabric imperceptible to tactile examination [115].

Nanoparticles incorporated into textile materials are imperceptible to the naked eye, therefore preserving the original color of the products. Nanoparticles create a protective coating on the surface of textile materials without altering their chemical properties; hence, they do not release harmful compounds and exhibit no adverse consequences. Textile items treated with nanoparticles exhibit greater durability compared to conventional finishes after multiple washes. Nano-finishes can enhance fabrics by providing both wrinkle and stain repellency in a single treatment. Nano-tech clothes may exhibit suboptimal performance if not adequately maintained. Appropriate maintenance for these outfits entails utilizing gentle machine washes and drip drying, refraining from dry cleaning, and eschewing chlorine bleach and wringing of the fabric.

7.4. Nano-enhanced anti-static textiles

Static commonly builds up in synthetic fibers such as nylon and polyester because they absorb little water. Traditionally, surfactants are employed to distribute a minimal quantity of moisture over the fiber's surface to facilitate charge dissipation. Silver is among the most effective electrically conductive nanoparticles. Silver nanoparticles easily remove static charge [116,117].

7.5. Nano-enhanced anti-bacterial textiles

Quaternary ammonium compounds are frequently utilized as antibacterial agents. Numerous chlorinated organic chemicals and organometallic compounds, including copper, silver, iron, manganese, or zinc, enhance the antibacterial resistance of fabrics. The use of nanosilver particles provides a long-lasting antibacterial treatment for textiles [118–120].

7.6. Nano-enhanced ultraviolet protective textiles

Various nanocompounds or nanoparticles can be utilized to provide UV protection to textile materials. The most prevalent nanocompounds utilized are titanium dioxide and zinc oxide in nanoscale dimensions. They offer a protective advantage by reflecting, scattering, or absorbing detrimental UV radiation [121].

At present several research organizations and industries are offering nanotechnology and its application techniques for textiles. Some of them are as follows:

- NanoTex, LLC, Greensboro, N.C., USA.
- Texcote Technology (International) Ltd, Sweden.
- Schoeller Textiles AG, Switzerland.
- Beijing Zhong-shong Century Nanotechnology Co. Ltd, Beijing, China.

8. Environmental aspects and health safety

The anticipated widespread application of nanotechnologies in the textile industry, along with other sectors utilizing nanotechnology, is raising environmental and health safety concerns. Nanoparticles have a large surface area relative to their volume, which makes them more adsorbent to other materials and increases the duration of their effects. In this regard, it consumes less material compared to the bulk or conventional material required for the same industrial application. The distinctive characteristics of nanomaterials have captivated not only scientists and researchers but also enterprises, due to their significant economic potential. The National Science Foundation indicates that nano-related products and services will expand to a market value of 1 trillion dollars by 2015. This sum exceeds the total of the telecommunications and information technology sectors. It is projected that nanotechnology will generate several hundred billion euros during the next decade. The nanomaterials market may reach 4 billion dollars by 2007. It was anticipated that 2 million new job opportunities would be generated to satisfy the global annual production need of 1 trillion dollars within 10 to 15 years [122].

Due to the less surface-active energy, the bulk materials utilized in traditional procedures reduce performance, lead to increased material consumption, and eventually contribute to increased energy consumption and environmental degradation. On the other hand, nanotechnology may positively influence the environment as well. Nanotechnology has the potential to conserve raw materials and enhance the quality of life by utilizing fewer resources without compromising performance. **Table 7** illustrates the prospective utilization of nanoparticle environmental engineering.

Table 7. Potential application of nanoparticles environmental engineering.

Industry	Nanoparticles	Application area	Nanoparticle-based traditional product/Potential area of application
Environmental engineering	Titanium dioxide (TiO_2) Zinc oxide (ZnO), iron oxide (Fe_2O_3) and carbon nanotubes (CNTs) Graphene Silver (Ag) Gold (Au)	Water treatment plants Air pollution control systems Soil remediation sites Wastewater treatment plants Environmental monitoring systems	Water Treatment: • Nanoscale's Water Treatment Systems (Nanoscale Corporation) • Nanostellar's Water Treatment Catalysts (Nanostellar Inc.) • Altair's Water Treatment Membranes (Altair Nanotechnologies Inc.) Air Pollution Control: • Nanohmics' Air Pollution Control Systems (Nanohmics Inc.) • Nanoscale's Air Pollution Control Catalysts (Nanoscale Corporation) • Komatsu's Air Pollution Control Filters (Komatsu Ltd.) Soil Remediation: • Nanoremediation's Soil Remediation Systems (Nanoremediation Inc.) • Nanostellar's • Soil Remediation Catalysts (Nanostellar Inc.) • Altair's Soil Remediation Membranes (Altair Nanotechnologies Inc.) Wastewater Treatment: • Nanoscale's Wastewater Treatment Systems (Nanoscale Corporation) • Nanostellar's Wastewater Treatment Catalysts (Nanostellar Inc.) • Nanohmics' Wastewater Treatment Membranes (Nanohmics Inc.) Environmental Monitoring: • Nanosensor's Environmental Monitoring Systems (Nanosensor Inc.) • Nanostellar's Environmental Monitoring Sensors (Nanostellar Inc.) • Altair's Environmental Monitoring Membranes (Altair Nanotechnologies Inc.)

8.1. Potential impact of nanomaterial on environment

The extensive application of nanoparticles inevitably results in heightened emissions into the environment via air, groundwater, and soil. The unique characteristics of nanoparticles may lead to adverse environmental impacts if released into the ecosystem. Furthermore, in addition to possessing inherent hazardous effects, nanomaterials, owing to their unique morphology, surface characteristics, or charge, may interact with molecules in an undesirable manner or sequester nutrients.

Nanomaterials may infiltrate the environment throughout their lifespan. The duration of their survival and the manner in which they persist remain subjects of inquiry, with estimated ambient nanoparticle concentrations anticipated to be in the mg/L range in air, soil, and water. Compared to existing toxicity data for lethal and sublethal effects, these doses were markedly lower than those expected to induce biological consequences, suggesting a minimal risk threshold. It is essential to acknowledge that as novel particles and applications are created, and as additional information on their fate, behavior, uptake pathways, and atmospheric entry emerges, these predictions may evolve. Furthermore, once nanomaterials infiltrate the environment, they possess the capacity to accumulate inside environmental organisms. The exposure pathways arising from production, processing, and utilization necessitate the monitoring of the initial products of nanoscale compounds and their transformation products (life-cycle studies, exposure scenarios) within the designated compartments. It is essential to adhere to several steps: First, identify the nanoparticles that persist and accumulate in the environment using appropriate measurement methods for detection in water, soil, and sediment; next, analyze the behavior of the nanomaterials post-use, during disposal, landfilling, incineration, or reutilization; finally, conduct ecotoxicity testing throughout the entire lifecycle.

The stability of nanoparticles is a critical aspect in assessing the danger of exposure to nanomaterials; specifically, it is essential to evaluate their stability and longevity, as well as the conditions in which they may undergo alterations upon entering the environment. Knowledge regarding the potential fate scenarios of nanoparticles in the environment is progressively emerging. Recent studies have emphasized that the behavior of nanoparticles in the environment is influenced not only by the physical and chemical properties of the nanomaterial and their concentration but also by the characteristics of the receiving environment. Due to their small size, nanoparticles can be extensively dispersed through the air, allowing for the partial application of research findings regarding the behavior and effects of natural ultrafine dust or ultrafine dust generated during incineration. Groundwater is at risk from nanoparticles in soil because of their broad, active surfaces, which can bind and mobilize contaminants like organic materials or heavy metals. If nanomaterials are not broken down or dissolved, they will eventually tend to collect and settle onto the substrate, depending on the receiving environment. Typically, industrial products and waste are disposed of in waterways that eventually flow into the ocean. Upon the discharge of water, dispersed nanoparticles are anticipated to exhibit behaviors consistent with the principles outlined in colloid science. The assessment of concentrations, surface characteristics of nanomaterials, and the physicochemical features of the aqueous phase are critical elements in ascertaining the interactions of these nanoparticles with organic matter and their potential for adsorption.

There is less published research on the absorption or interaction of nanoparticles with plants; however, it details the creation of cadmium nanocrystals on phytoplankton. A nearly linear correlation was observed between toxicity and the release of silver ions from the particles, which accumulated in the phytoplankton. It has been proposed that plant tissues could serve as a scaffold for the in situ aggregation of metallic nanoparticles and that lipophilic nanoparticles, such as carbon nanotubes, may be absorbed by microbial communities and root systems, leading to their accumulation in plant tissues. In conclusion, understanding the behavior and impacts of nanoparticles in the environment and living creatures is rapidly expanding due to significant interest from the scientific community and greater financing. Nevertheless, the field is far from being mature. Current forecasts indicate that environmental concentrations are expected to be substantially lower than those that induce biological effects in laboratory settings, and the probability of considerable ecotoxicological harm is minimal. The impact of nanoparticles utilized in food packaging on the overall ambient concentration appears to be insignificant. Furthermore, the presence of nanoparticles in the environment may also be advantageous. Numerous studies are emerging about the application of nanotechnology for the remediation and detoxification of environmental toxins. The in situ method known as nanoremediation involves the utilization of reactive nanomaterials to facilitate chemical reduction and catalysis for the remediation of targeted pollutants, without the extraction of groundwater for surface treatment or the relocation of soil for treatment and disposal.

Nanoremediation is purported to have the capacity to lower the overall expenses associated with the remediation of extensive contaminated sites, decrease cleanup duration, obviate the necessity for the treatment and disposal of contaminated dredged soil, and diminish certain contaminant concentrations to nearly zero, all achievable in situ. To mitigate any detrimental environmental repercussions, a comprehensive review, including extensive ecosystem-wide studies of these nanoparticles, must be conducted prior to the widespread application of this technology. Using nanoparticles as ‘nano-additives’ for two opposing purposes—the breakdown and stabilization of polymers under different environmental circumstances and durability under varied environmental conditions—is another intriguing aspect of nanoparticles’ impact on the environment. A new study summarizes the current state of research on this novel use of nanoparticles, which has the potential to be extensively used in the near future.

8.2. Possible impact of nanomaterial on human health

Three distinct methods of nanoparticle entry into the organism are possible: Inhalation, dermal penetration, and ingestion. Increasing scientific data indicates that unbound nanoparticles can traverse biological barriers, and exposure to some nanoparticles may result in oxidative damage and inflammatory responses. Concerns with nanomaterials in food packaging primarily revolve around the possibility of indirect exposure stemming from the potential migration of nanoparticles from the packaging. The inhalation and dermal penetration of nanoparticles in food packaging predominantly concern workers in factories that produce these substances. It is advisable for these personnel to utilize personal protective equipment, including gloves, goggles, and masks equipped with high-efficiency particulate filters.

There is less knowledge regarding the consequences of nanomaterials entering the human body. The risk evaluation of nanomaterials upon consumption has been examined for only a limited number of nanoparticles utilized in food packaging.

Research indicates that TiO_2, Ag nanoparticles, and carbon nanoparticles/nanotubes can penetrate the circulatory system from the gastrointestinal tract. The processes are likely contingent upon the physicochemical parameters of the nanoparticles, including size, and the physiological condition of the entrance organs [123]. The translocation fractions appear to be quite low; yet, this is the focus of ongoing rigorous investigation. Upon entering the bloodstream, the liver and spleen serve as the primary organs for nanoparticle distribution. The circulation time significantly rises when nanoparticles are hydrophilic and possess a positive surface charge. Certain nanoparticles pose a risk to all organs, as the chemical makeup of the nanoparticles or the nanoparticles themselves have been discovered in every organ examined, showing their diffusion to these organs. The organs encompass the brain and testis, as well as the reproductive system. Fetal distribution in pregnancy has also been documented. Given the poor understanding of the long-term behavior of nanoparticles, a cautious estimate must posit that insoluble nanoparticles could collect in secondary target organs over prolonged exposure, with ramifications that remain unexamined. There is a particular concern over the potential migration of nanoparticles into the brain and the developing fetus. Investigations in both domains must be undertaken to either validate or refute the idea regarding the relationship of nanoparticles with various neurological disorders. The impact of various particles utilized in food packaging on health is now being examined, including ZnO nanoparticles and fullerenes [124].

9. Summary

The advancement in the utilization of nanoparticles, nanocomposites, and nanospheres has accelerated significantly in recent years, especially within the domain of textile finishing. Nanoscale materials can improve the physical attributes of traditional textiles, including antimicrobial efficacy, water repellency, soil resistance, antistatic characteristics, infrared resistance, flame retardancy, dyeability, and tensile strength. In the future, the utilization of these remarkable nanoparticles may be expanded to create textiles with healthcare and wound-healing capabilities, as well as self-cleaning and self-repairing properties.

Future developments of nanotechnologies in smart materials will have a twofold focus:

1) Upgrading existing functions and performances of materials.
2) Developing smart and intelligent engineering materials with unprecedented functions.

The latter is more urgent from the standpoint of homeland security and the advancement of technology. The new functions with nano-enriched material to be developed include:

a) Wearable solar cell and energy storage,
b) Sensors and information acquisition and transfer,
c) Multiple and sophisticated protection and detection,
d) Healthcare and wound healing functions, and,
e) Self-cleaning and repairing functions.

Undoubtedly, nanotechnology holds an enormously promising future for smart engineering materials. It is estimated that nanotechnology will bring hundreds of billions of dollars of market impact on new materials within a decade.

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