# Molecular Nanomaterials in Industrial Applications

Subjects: Nanoscience & Nanotechnology

Contributor: Md Abdus Subhan

Nanomaterials have not only become one of the ‘hottest’ areas in research and development all over the world but also attracted numerous considerations in the industrial sectors. This technology can be primarily defined by their functional properties which determine how they interact with other disciplines. Recently, it becomes an evolving field in material science, materials processing technology, mechanics, electronics, optics, medicine, energy and aerospace, plastics and textiles etc. This technology not only establishes an interdisciplinary and emerging domain that embraces physics, chemistry, engineering but also contributes to detection of diseases, better therapy options, and remarkable reduced health-care expenses. Molecular nanomaterials can also be applied in manufacturing through ultra-precision, development of nano-metric microscopic devices, biological structures, nano robots, super computers, industries and genetics etc. All materials or devices which are nanometer scale (dimensions of roughly 1 to 100 nm) structured are included in nanomaterials.

molecular nanomaterials industrial applications manufacturing

## 1. Introduction

Nanotechnology is a field of advanced science and technology of governing matter on a nanoscale [1]. This nanoscale was first introduced in the famous lecture of Nobel Laureate Richard P. Feynman, “There’s Plenty of Room at the Bottom,” given in 1959 [2]. Nanomaterials have not only become one of the ‘hottest’ areas in research and development all over the world but also attracted numerous considerations in the industrial sectors [3][4]. This technology can be primarily defined by their functional properties which determine how they interact with other disciplines [5]. Recently, it becomes an evolving field in material science, materials processing technology, mechanics, electronics, optics, medicine, energy and aerospace, plastics and textiles etc. [6]. This technology not only establishes an interdisciplinary and emerging domain that embraces physics, chemistry, engineering [7] but also contributes to detection of diseases, better therapy options, and remarkable reduced health-care expenses [8]. Molecular nanomaterials can also be applied in manufacturing through ultra-precision, development of nano-metric microscopic devices, biological structures, nano robots, super computers, industries and genetics etc. [9]. All materials or devices which are nanometer scale (dimensions of roughly 1 to 100 nm) structured are included in nanomaterials [2][10]. Nanoscale, substances have a larger surface area to volume ratio than the bulk one which is the main reason for their increased level of reactivity, improved and size tunable magnetic, optical and electrical properties [11]. Nowadays, almost all developed nations have created nanomaterials-based research programs, fellowships, networks, research institutes, and educational enterprises aiming at understanding and leverage nanoscale discoveries [12][13]. Nanomaterials are now used in numerous industries all over the world. Nanofabrication, nanoparticles, nanorobot, nanocomputer, nanofertilizer, membrane-based nanoparticles, nano-engineered fiber, nanotubes, nanosensor, nanopesticides, nanoencapsulation, nano-ceramic tools, nanocatalysts etc. are used in industries to facilitate and develop improved industrial function and products. The structure in nanoparticles may rely on the method and conditions of particle preparation. The cohesive energies of the atoms inside nanoparticles and small clusters are additionally structure dependent [14]. When size approaches nanoscale the properties of particles change. The percentage of atoms becomes significant at the surface of nanoparticles, and there are numerous active sites on the nanoparticle surface. Many “nanotoxicology” researchers elucidated the interface of nanoparticles with bio-based systems and the mechanism of action. The $TiO_2$ nanoparticles (~20 nm) were delivered to the lung interstitium, which was cleared from the lungs more slowly than fine $TiO_2$ particles (~250 nm) in mouse model after the intratracheal administration of 500 µg of $TiO_2$. $TiO_2$ nanoparticles are of great importance in medical and pharmaceuticals industries. $TiO_2$ NPs or nanospheres generally have cytotoxicity. Spherical $TiO_2$ nanomaterials induced single strand breaks, oxidative damages to DNA, and oxidative stress in human lung carcinoma epithelial cell lines A549. 1-D, $TiO_2$ nanostructures including nanorods, nanobelts, and nanotubes are mostly synthesized and extensively investigated than 0-D $TiO_2$ NPs (nanospheres).

## 2. Fabrication and Characterization of Molecular Nanomaterials

The synthesis of nanoparticles is performed using several methodologies including biological methods, physical methods and chemical methods. In biological methods microorganisms such as bacteria, fungi, algae are used to prepare nanomaterials. In this case 10–20 nm size gold nanoparticles can be extracellularly prepared by using photosynthetic bacteria like *Rhodopseudomonas capsulate*. Moreover, by using Fusarium oxysporum fungus extracellular silver nanoparticles can be synthesized. Besides, by using Sargassum wightii algae within 12 h of incubation around 95% production of gold nanoparticles was obtained [15].

By using orange (*Citrus clementina*) peel biomolecule, silver nanoparticles can be fabricated. To synthesize AgNPs, orange peel aqueous extract (OPE) was mixed with aqueous solution of silver nitrate at room temperature. The color change from pale yellow to dark-reddish brown demonstrated the formation of the AgNPs. The formation of AgNPs was also observed spectroscopically by UV—visible spectroscopy at regular time intervals in the wavelength range of 300–600 nm [15].

In physical methods two routine approaches can be used to synthesis nano-structured materials, top-down technique and bottom-up technique (**Figure 1**). The major difference is based on the size of primary entities used to build nano materials with or without atomic level control [16].

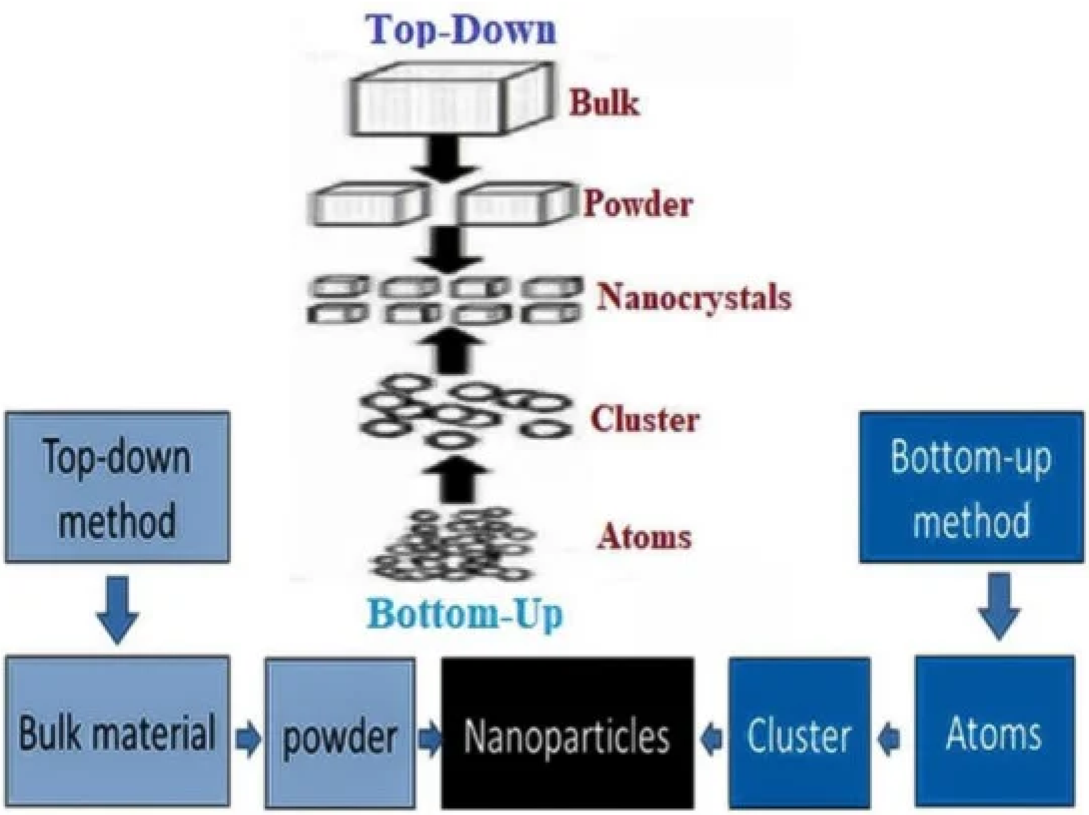


**Figure 1.** Physical methods for the preparation of molecular nanomaterials.

# 3. Industrial Applications

## 3.1. Construction Industry

An examination of expression of interests (EoI) submitted to the EC FP6 on 2002 in Europe found that there were 20 (out of an aggregate of 250) EoIs identified with nanomaterials application in development. Understanding and modeling of phenomena at nanoscale, developing nanoscale particles and fibers, nanostructure modified materials, functional materials, thin films and coatings/paints, energy efficient devices, and smart materials and integrated systems incorporating nano sensors/actuators are covered by EoIs. In 2002, the Nano House Initiative was introduced by Australian National Nanotechnology Network (ANN). They proposed to build a “nano house” using the developed nanomaterials and machineries. They think it will represent the best way in sustainable and environmentally sound housing. Moreover, Institute for Research in Construction (IRC), National Research Council Canada has taken a step to develop technology and products for construction industry based on nanomaterials. They provide importance on cements, cement-based products, admixtures and concrete [3]. Furthermore, by including nanoengineered fibers and polymers to the mix in the field using acoustic energy to ensure homogenous distribution or under more controlled conditions during the manufacturing process of cement and other concrete components, the performance of concrete could be improved. Nano-based enhancement of concrete products would offer much stronger and durable road and highway surfaces and potentially better driving conditions to reduce maintenance costs [17]. Nanomaterials can act as superb filler in cement-based materials. The photocatalytic properties of the cement samples were enhanced through dispersing nano-$TiO_2$ by ultrasound. By the addition of nano-$TiO_2$, the total shrinkage of cement-based materials can be remarkably reduced. Nano-$TiO_2$ also contributes to the reduction of the amount of mesopores. Besides, reinforced cement composites with nanomaterials, like CNT, nano-MgO, nano smectite-based clay exhibited lower autogenous shrinkage in comparison with those without NPs [18]. By increasing the volume fractions of CNTs, the energy absorption capacity, the curvature ductility and the moment capacity of the CNT-rein forced concrete columns enhanced significantly [19]. The heating performance of cement composites can be improved by adding CNTs. Cyclic heating by CNTs can reduce the heating and mechanical properties of CNT-reinforced cement composite in the long term [20]. At early stages of hydration, the addition of nano-$TiO_2$ to cement increased the heat of hydration and also accelerated the rate of reaction [21]. When cement is substituted by nano-$TiO_2$, the strength of cement mortar at early ages increased a lot and the fluidity and strength decrease with time [22].

### 3.2. Textile Industry

In textile industries to enhance textile features nanoparticle plays an important role. These features are fabric softness, durability, breathability, water repellency, fire retardant, anti-microbial properties (**Figure 2**) [10][23]. A Swiss company Scholler has built up a nano-based innovation to create another line of brand name fabric, for example, “Soft Shells,” functional stretch multi-layer fabrics [10]. In addition, nanocoating can develop multifunctional and smart high-performance textiles. Nanofibers can also be used in some technical application in textile industries, for example, filter fabric, antibacterial patches, night-vision uniform, tissue engineering and chemical protective suits. As nano-particles have a large surface area-to-volume ratio and high surface energy, nano based finishing improves affinity for fabrics leading to durable function. Wearable ‘smart’ nanomaterials have a great application in the textile industry. A wearable smart textile battery is rechargeable by sunlight and their interlaced sun-based cells transform T-shirts into power textiles. In this case graphene layers facilitate fabrication of energy storage textiles. Conducting polymers and graphene are fascinating for making textiles empower the consolidation of sensors and actuators. Nano-sized $TiO_2$ and ZnO are more proficient at engrossing and dissipating UV radiation than the bulk UV light protection of textiles [6].

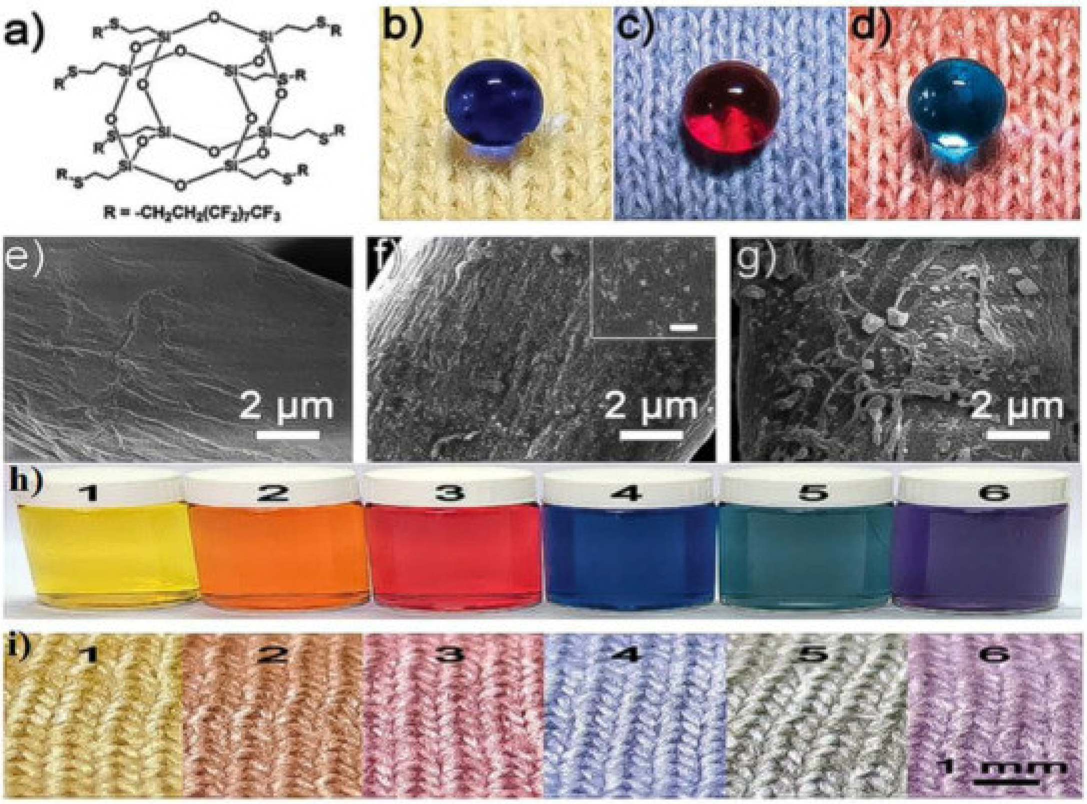


**Figure 2.** Fabric finishing using Ag-based nano-coating for enhancement of properties and performance. (**a**) Chemical structure of F-POSS, (**b**–**d**) Water droplets on F-POSS/AgNPs/PEI-coated cotton fabrics of (**b**) yellow, (**c**) blue, (**d**) and red colors. (**e**–**g**) SEM images of (**e**) pristine cotton fabric, (**f**) AgNPs/PEI-coated cotton fabric, and (**g**) F-POSS/AgNPs/PEI-coated cotton fabric. (**h**) shows different color AgNPs in colloidal form and (**i**) finishing of cotton fabrics using corresponding AgNPs. (Reproduced with permission of [24]. Copyright John Wiley and Sons, 2015.)

### 3.3. Water Treatment Industry

Nanomaterials offer new ways to upgrade both fundamental and advanced water treatment processes. Photocatalytic oxidation of organic pollutants is a process of water treatment that can be improved by NPs as demonstrated in **Figure 3** [25]. Here, nano-photocatalysts can improve treatment selectivity and ROS generation and utilization efficiency. By engineering nanoparticles using surface-modification strategies selective adsorption of foreign substances onto photocatalysts can be accomplished. Membrane separation processes for water purification and desalination can also be enhanced by nanomaterials. One methodology is to insert catalytic nanomaterials in the film as specific layer to degrade organic foulants on light irradiation or applied voltage. This way can reduce organic fouling [26]. Nanofiltration, another process of water filtration is the most energy efficient approach. Nanofiltration membrane, depend on a thin film composite (TFC) design, which deposits a polyamide (PA) active layer, formed by interfacial polymerization [27]. Depending upon the polymers used to cross-link the CNTs, the pore size in these films can go from 100 nm to sub-nanometer, making the materials valuable in biological treatment of industrial wastewater, desalination of industrial salt water etc. by functionalizing or doping the CNTs [28]. When irradiated by sunlight, zinc oxide/zinc tin oxide (ZnO/ZTO) nanocomposites showed 50%

photocatalytic degradation efficiency and 77% COD (chemical oxygen demand) removal of textile waste water [29]. Artemia eggshell-ZnO nanocomposites can be used for waste water treatment by photodegradation of methylene blue, Rhodamine B, and neutral red etc. [30].

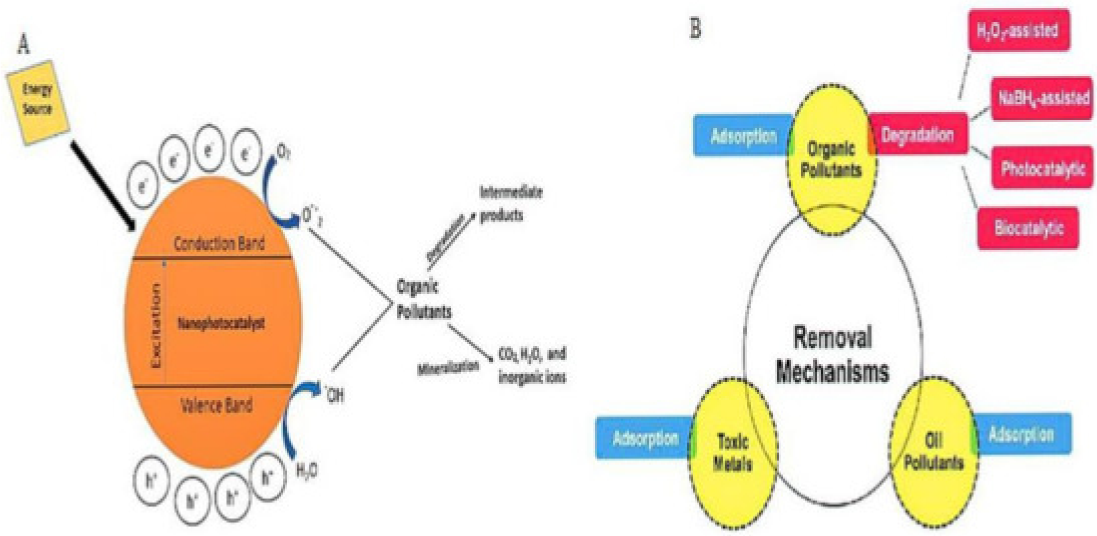


**Figure 3.** Mechanism of nanophotocatalysis for the treatment of environmental organic pollutants (**A**) and different pollutant removal techniques used by nano/micromotors (**B**). (Reproduced with permission of [25]. Copyright John Wiley and Sons, 2015).

### 3.4. Agriculture Industry

In agriculture industry, there are several applications of nanomaterials including nano delivery [31], nanosensors [31], nanoencapsulation of pesticides [31], nanopesticides [31], and nanofertilizers [32]. **Figure 4** shows advantages of nanofertilizers over their bulk counterpart. Nanodelivery is used for veterinary products in fish food and nanosensors are used for detecting pathogens, toxins in the water [31]. Nanosensors are also used for sensing nutrients, pesticides, contaminations, post-harvest management of agriculture products for enhanced shelf life. Nanoscale pesticides are used for effectively diminishing plant diseases, smart and targeted delivery of biomolecules and nutrients, agronomic fortifications, water sanitization and purification, nutrient retrieval, and smart fertilizers delivery [33][34]. In addition, site-specific water and soil conservation helps in the efficient utilization of natural resources. It can be controlled by the use of nanosensors in precision agriculture and Nanotechnology Applications in Crop Production and Food Systems (NACPFS) nanomaterials [32]. Various sorts of nanoparticles like carbon nanotubes, Cu, Ag, Mn, Mo, Zn, Fe, Si, Ti, matal oxides, and nanoformulations of phosphorus, urea, sulfur, validamycin, tebuconazole and azadiractina have been transformed into nanopesticides and nanofertilizers [35]. Actually, the idea of nanofertilizer theoretically includes the manure partners (industry, specialists, ranchers, and governments) taking a jump from mass scale mineral supplement creation and use to nanoscale creation, information, and practice, with concerns noted in regards to nanomaterial molecule size, process scaleup, and field application methodologies [36].

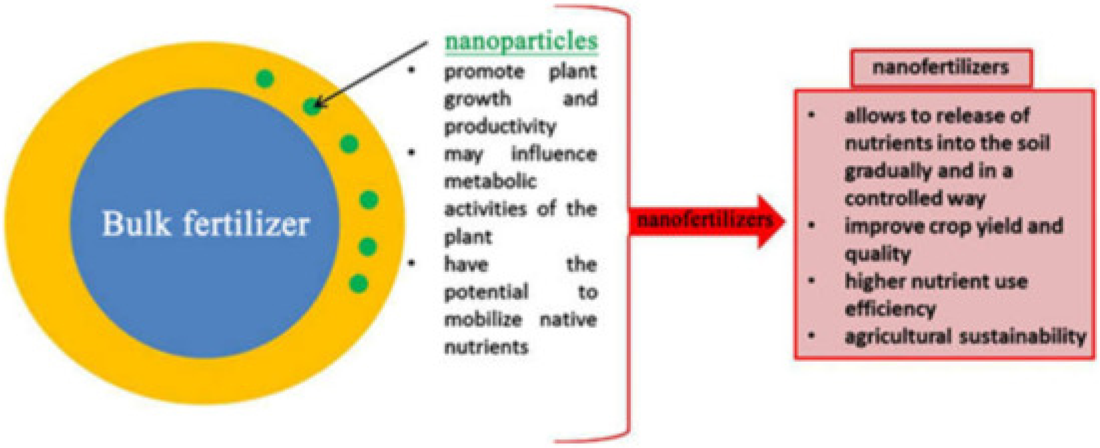


**Figure 4.** Advantages of nanofertilizers over bulk fertilizers. (Reproduced with permission of [33]. Copyright Scientific Research Publishing Inc., 2021).

### 3.5. Food Industry

Nanomaterials can not only improve the quality, safety and nutritional value of food but also reduce costs. By using nanoemulsion technology food industry can create low-fat mayonnaise, spreads and ice cream (**Figure 5**) [37]. An important current nanomaterial application is nanoencapsulation of food ingredients and additives to control the release of certain active ingredients (i.e., proteins, vitamins, minerals, enzymes and preservatives), mask the undesirable odors and flavors (such as fish oils), enhance the shelf-life and stability of the ingredient and the finished food products, and also enhance the uptake of encapsulated nutrients and supplements. Nanoparticles and nanocomposites have antibacterial properties that can be used for improving food safety e.g., Ag NPs and nanocomposites [31][37]. Integration of metal or metal oxide nanoparticles in polymer nanocomposites have been used for food packaging e.g., ZnO nanoparticle incorporated into polystyrene film [31][37], ZnO nanoparticles coated on polyvinyl chloride (PVC) films [38]. Nanomaterials also enhance processing, solubility, stability and shelf life of fresh products, consistency and texture, color and flavor, encapsulation of bioactives and better bioavailability of products in food industry. Nanostructuring of food offers new tests, improved consistency and texture. Nanocapsulation is also important in food industry. Fruit juice was absorbed better by the body when beta-carotene nanoencapsulated in starch and added to the juices (**Figure 5**). In addition, nanoemulsions incorporated into juices and beverages impart antimicrobial properties and improve the quality of products. Nanosensors assist to monitor quality, detect the level of $CO_2$ released from a food, track the consignment during various stages of logistics, prevents contamination and guarantees a quality item. In some situations, clarification and concentration of raw juices are done by nanofiltration in food industry [39]. $TiO_2$ nanoparticle-coated film is utilized for potential food packaging applications due to the photocatalytic antimicrobial property of $TiO_2$. Different concentrations of $TiO_2$ nanoparticles can be coated on food packaging film, especially in low density polyethylene (LDPE) film [40].

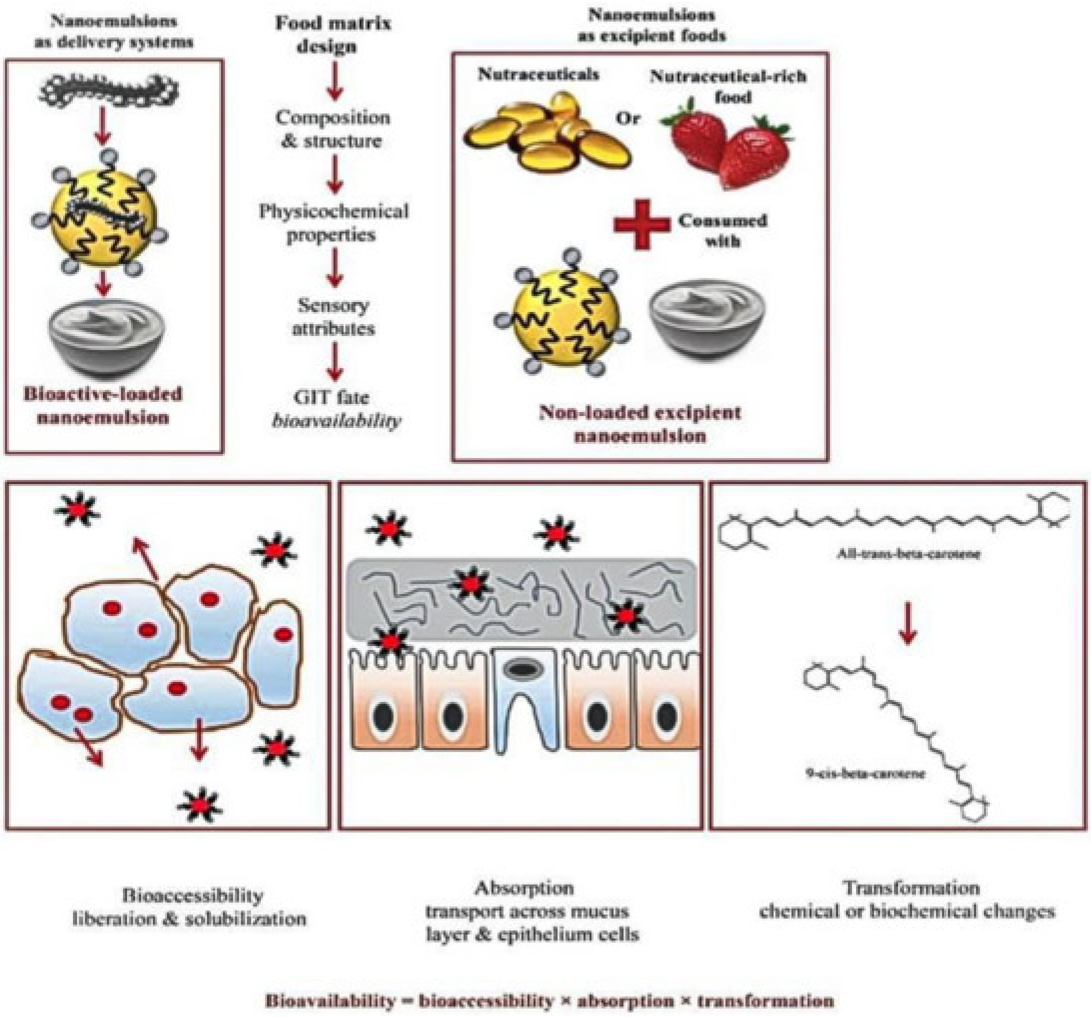


**Figure 5.** Schematic diagram showing the delivery of bioactive components in food. The overall oral bioavailability of bioactives is preserved by three major factors: bioaccessibility, absorption, and transformation. GIT: gastro-intestinal tract. (Reproduced with permission of [37]. Copyright Elsevier Taiwan LLC., 2016).

### 3.6. Aeronautics Industry

Molecular nanomaterials have been used in wide variety of materials, processes and devices with huge opportunities for applications relevant to NASA's missions. In aeronautics industry, nanomaterials are used to produce lighter materials without compromising strength and other mechanical properties, and also used to form electronics and displays with low power consumption, sensors, paints etc. [23]. Multifunctional structural composites are used in engineering applications in aeronautical industries. Here in, $Fe_3O_4$ nano powders are used to manufacture multifunctional structural composites [41]. In Mexico, there is a wide practice of models identified with the foundation of advancement areas which may likewise be characterized and analyzed under the cluster framework technology. Under this framework, the process of agglomeration take place, e.g., the agglomeration of aerospace and nanotechnology industry in Queretaro and Monterrey. It is necessary not only for the presence of technological opportunities but also for technological capabilities [42]. In aeronautics, nanoparticles are used for development of a new class of high-performance structural composites with enhanced damping properties. This could substitute the expensive acoustic treatments currently being used as alternatives in the fuselage structure. Thus, nanomaterials can decrease weight and cost in the aircraft design process [43].

### 3.7. Medicinal Industry

Nanomaterials are utilized toward enhancing the delivery of the drug to diseased tissues. There have been numerous research efforts for the utilization of nanomaterials in drug design, delivery and medication. The essential goal is the acceleration of the discovery process than the advancement of the drug as a nano-medication as such. The assumption from this translational research is to focus on key properties and better drive the science endeavors to choose drug candidates. Nanomaterials are suitable candidates for their applications in treating diabetic, cancer and many other genetic diseases. For example, siRNA containing nanoparticles enable the drug delivery system [44]. In addition, NPs are essential for diagnosis of diseases, cancer gene therapy, pulmonary diseases and inhibition of other infectious diseases [45]. Nanomedicines can be cleared by human body quickly yet they are exceptionally powerful in identifying and imaging disease like cancer [46]. **Figure 6** demonstrated applications and goals of nanomedicine in different domain of biomedical research and mechanisms for controlled release of drugs using different types of nanocarriers [47].

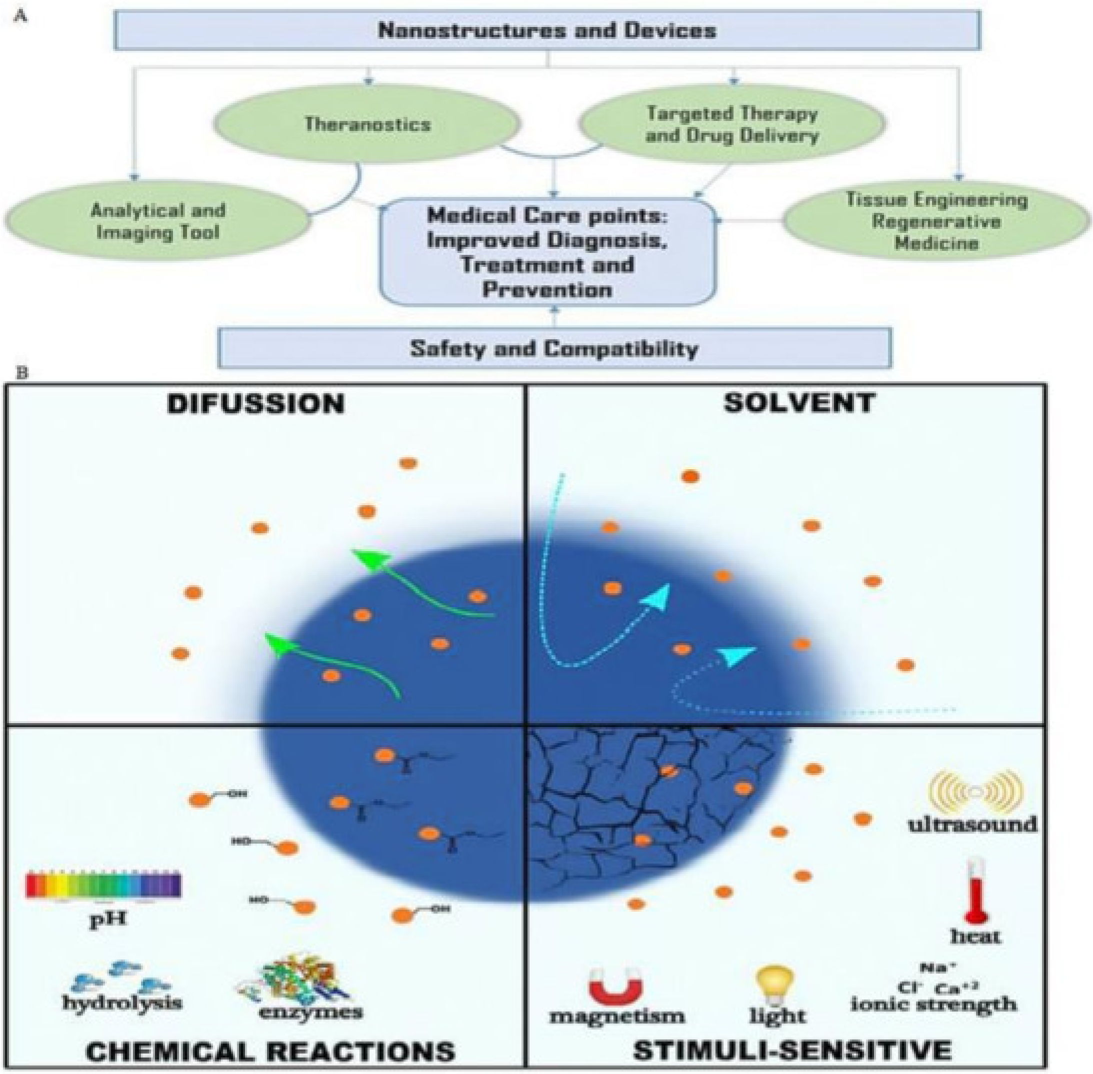

**Figure 6.** Application and goals of nanomedicine in different sphere of biomedical research (**A**) and mechanisms for controlled release of drugs using different types of nanocarriers (**B**) (Reproduced with permission of [47]. Copyright BioMed Central Ltd., Part of Springer Nature, 2021).

### 3.8. Environmental Industry

In the environmental industry, nanoadsorbents, nanocatalysts, nanoparticles, nanomembranes, nanomaterials are used for many purposes. Nanoadsorbents, which have large surface area, small size, and large number of active adsorption sites can be used for wastewater treatment. These nanoadsorbents are carbon-based, polymeric, magnetic, or nonmagnetic and metal oxide-based including modified compounds. In water treatment, for degradation of organic pollutants, nanocatalyts are widely used. $TiO_2$ and ZnO nanoparticles and nanocomposites are used for degradation of organic pollutants in water and air. In addition, nanomembranes have replaced reverse osmosis process which used in waste water treatment. Because these bring some facilities over reverse osmosis such as reduced operational costs and fewer energy consumption, higher flux rates etc. In production of efficient fuel cells nanomaterials can be used. These nanomaterial-based fuel cells can be an alternate clean energy source devices such as environmentally benign batteries [48].

### 3.9. Cosmetics Industry

$TiO_2$ and ZnO nanoparticles are used in sunscreen [49]. Silica-coated nanosized $TiO_2$ [50] and α-bisabolol and phenylethyl resorcinol/$TiO_2$ hybrid composites [51] are also used in sunscreen. Silver nanomaterials have antibacterial properties. So, it is used in consumer product as preservative agent. Other than these solid lipid nanoparticles (SLN) and nanostructured lipid transporters (NLT) are also used to prevent decay on the skin surface. Polycaprolactone (PCL) nanocapsules are polymer nanoparticles that have been utilized by L'Oréal and others to encapsulate elements for use in cosmetic items [49]. ZnO nanoparticles are used in different eye shadow samples [52]. N-doped graphene/$TiO_2$ nanocomposite has antioxidant capacity, it can be used in screen-based cosmetics to maintain skin healthy and fair [53].

### 3.10. Machinery Industry

In the machinery industry, nano-machines can be manipulated with a micro molecular finger, and command fingers to work and find the necessary raw materials. Actually, micro-mechanical field, micro-nano-bearings, metal nano-ceramic tools, nano-magnetic fluid sealing ultra-fine grinding machine, nanomotor, nano generator, nano lubricants are useful in machinery industry [54]. CuO nanoparticle suspension can be used as nanolubricant [55]. Micro nano bearings can tolerate high temperature and that is why it can be a good feature including the good wear resistance, anti-characteristics in this industry. In addition, nano-titanium nitride are refined grains, the small grains help to enhance the material strength, hardness and fracture toughness. Nano-motors are short in size and it can load 4 kg, mainly used for toys and power windows on cars. Utilizing the nano materials as a lubricant, the parts would not need successive substitution, and transport serviceable life will be the longer [54].

### 3.11. Oil and Gas Industry

In oil and gas industry, nanomaterials are utilized to develop geothermal resources by enhancing thermal conductivity, improving down hole-separation, and aiding in the development of noncorrosive materials. This could be used for geothermal-energy production. Nanomaterials could be used to improve the prospects of developing unconventional and stranded gas resources. Nano-tubes have numerous applications in the oil industry. Nanoparticles could help improve oil and gas production by making it simpler to separate oil and gas in the reservoir—for example, through improved understanding of processes at the molecular level. Nanomaterials have been applied to improve oil recovery in the form of tailoring surfactants which can be added to the reservoir in a more controlled way than with existing substances, thereby releasing more oil [56]. In oil reservoir engineering the application of nanoparticles involves new types of smart fluids for improved oil recovery, and drilling [57]. Nanoparticles have special properties like adsorption, wettability, alteration and surface area play an important role in upstream oil and gas industry to increase the production. Nanoparticles are also utilized in drilling and completion in oil and gas industry, for example, clay stabilization, enhanced viscosity of drilling fluids, and fluid loss control, sloughing (wall collapse) control, stability of well bore, torque and drag friction, hydraulic fracturing and cementing etc. [58]. Furthermore, in gas industry air-suspended Ni-Fe nanoparticles injected in the hydrate formation to penetrate deep into hydrate reservoir by passing through the cavities. These nanoparticles also cause a temperature rise up to 42 °C leading to disturbance in thermodynamic equilibrium and can cause the water cage to decompose and release methane [45]. Finally, nanoparticles can address the issues related with accessing stranded natural gas resources by creating nanocatalysts and nanoscale membranes for gas-to-liquids production and making nanostructured materials for compressed natural gas (CNG) transport or significant distance power transmission [59]. CNTs are robust and proven as promising building blocks for oil/water separating membranes. Therefore, CNT-based membranes are used extensively in oil/water separation industry [60]. Nanomaterials are widely used in numerous industries to invent, and enhance the quality of products emerging rapidly into the markets. Useful applications of the nanoparticles in different industrial sectors all over the world is displayed in **Figure 7**.

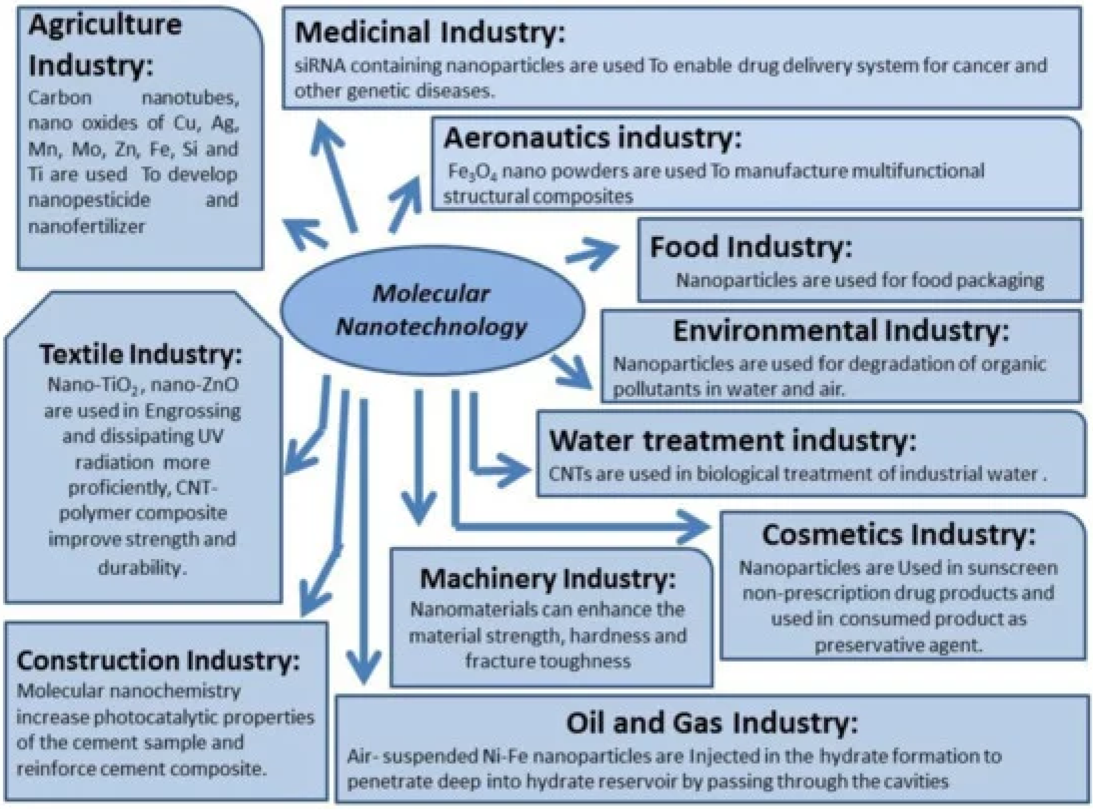


**Figure 7.** Applications of nanoparticle in industrial sectors.

### 3.12. Computer Industry

Nanomaterials and the propensity to miniaturization in the manufacturing industry are recognizable in the computer industry. The fundamental thought for the advancement of nanomaterials research comes from the area of microelectronics and its applications in computer systems. As per this manufacturing idea, when the particles are smaller, manufacturing cost can be reduced and their productivity become higher [61]. Furthermore, nanomaterials can be utilized for planning and assembling electronic segments and devices appropriate for making more modest, quicker and reliable computer. Nanoparticles has its effects in various fields, for example, computing and data storage, in the improvement of high-speed processors, decreasing energy consumption. In addition, nanotubes can substitute silicon chips, however, this technology is no longer used as an approach. The electronic nanocomputer is a device where the information is stored and addressed as an electrostatic charge with the assistance of basic components made of soft materials like organic molecules, semiconducting polymers or CNTs. Additionally, chemical nanocomputers can store the process data as chemical structures. Here the inputs are encoded in the formation of the molecular structure of the reactants whereas the output can be decoded or extracted from the structure of the products. Nanocomputers can store the information as atomic quantum states [62].

### 3.13. Miscellaneous Applications of Molecular Nanomaterials

In the chemical industry, nanoparticles are used as catalysts. Nanoparticles can enhance atom efficiency, can permit the replacement of toxic modifier, extend lifetime and ensure the recyclability of catalyst [63]. Besides industrial applications, there are some other applications of nanoparticles. Rubber fillers is similar to carbon black and silica as nanostructured materials. These have been used as essence of automotive tire sector for many years. For safety technologies and increasing comfort features, cars are heavier because of addition of new electronic components. Incorporation of nanoparticles has made possible to alleviate this. This incorporation of nanoparticles can reach the mechanical resistance and lighter weights with less amount and lighter material. There still remains a vast area where nanocoatings are needed to pave its way. Numerous coatings have been around for quite a while and still keep on having used and function in the automotive marketplace. Hard coatings of ceramics improve wear and friction characteristics of components. It also has the specialty of detecting even fractional concentrations of gas in vehicle interiors. Furthermore, the electro-chromic coatings are prophetic of the enormous boon for future vehicles [64]. The ideal supporting components of modern fibers are nanotubes. A potential application is in supporting long-span or high-rise structure cables. For recently proposed space elevators these cables can be a material of choice [2].

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