



Review

Advances with Molecular Nanomaterials in Industrial Manufacturing Applications

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Abstract: Molecular nanomaterials are of prodigious reputation for their uses in the numerous industries. This article highlights established industrial potential application areas for nanoparticles. The success of nanomanufacturing depends on the strong cooperation between academia and industry in order to be informed about current needs and future challenges, to design products directly translated to the industrial sector. The selection of the appropriate method, combining synthesis of nanomaterials with required properties and limited impurities as well as scalability of the technique, is of paramount importance. Varieties of molecular nanomaterials and their synthesis, characterization, and important applications are of current interest in several industries. Improved synthetic routes and advanced characterization methods will be important to advance molecular nanomaterials for their rapid translation to industries, manufacturing many useful products, and their implication in global economic development. Nanomaterials have emerging applications in almost all modern industries including construction, textile, water, aeronautics, food, medicine, environment cosmetics, machinery, oil and gas and computer. In the current review, we have chosen some leading industries world-wide that use nanomaterials. Besides the important applications of nanomaterials in almost all spheres of human life and environment, their toxicological effects must be addressed properly to utilize these applications. There are also some obstacles to a greater impact of nanotechnology in industry including its toxicological effects in human and surrounding environments and regulations of nanomaterials use. This review addresses molecular nanomaterials synthesis strategies, characterization methods developments, and their novel industrial and other relevant application fields.

Keywords: molecular nanomaterials; industrial applications; manufacturing



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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 TiO₂ nanoparticles (~20 nm) were delivered to the lung interstitium, which was cleared from the lungs more slowly than fine TiO₂ particles (~250 nm) in mouse model after the intratracheal administration of 500 µg of TiO₂. TiO₂ nanoparticles are of great importance in medical and pharmaceuticals industries. TiO₂ NPs or nanospheres generally have cytotoxicity. Spherical TiO₂ nanomaterials induced single strand breaks, oxidative damages to DNA, and oxidative stress in human lung carcinoma epithelial cell lines A549. 1-D, TiO₂ nanostructures including nanorods, nanobelts, and nanotubes are mostly synthesized and extensively investigated than 0-D TiO₂ NPs (nanospheres). The shape of TiO₂ NPs affects their deposition in the lung. Nanotoxicity studies for examining the impacts of TiO₂ crystal structures have shown to be associated with inflammatory responses, cytotoxicity and reactive oxygen species (ROS) formation. There are several studies on the cytotoxicity of rutile and anatase TiO₂ NPs with different cell lines. It was reported that anatase TiO₂ NPs induced cell necrosis and rutile TiO₂ NPs prompted apoptosis through the formation of ROS. TiO₂ NPs of 11 different crystal phase combinations at similar sizes were investigated, and a correlation between crystal phase and oxidant capacity was revealed. The ROS formation ability of anatase TiO₂ was found to be greater than that of anatase/rutile mixtures or rutile phase [15]. Nanomaterials are one billionth of a meter as claimed by size [16] and may be referred as nano object [17]. Nanomaterials can be divided into different categories according to their composition, performance, purpose and dimension [18]. Nanoparticles are usually four types according to their dimension (Table 1) [16,19].

Table 1. Dimensionality in nanoparticles.

Dimension	Ranges	Example
Zero-D	No dimensions are in the nanoscale range	Nanoporous material
One-D	One dimension is in the nanoscale range	Graphene sheets
Two-D	Two dimensions are in the nanoscale range	Nanowires, Biopolymers
Three-D	Three dimensions are in the nanoscale range	Quantum dots (QDs), Dendrimers

Zero-dimensional, one-dimensional, two-dimensional nanomaterials are also called low-dimensional nanomaterials and they may exhibit anisotropic or dimension-tunable properties [20]. Besides, there are also different molecular nanomaterials, such as carbon-based nanomaterials, metal and metal oxide NPs, semi-conductor NPs, polymeric NPs, lipid-based NPs etc. They generally differ in morphology, size, properties and the building block in them [16]. Generation based nanomaterials also exist, they are: second generation, third generation and fourth generation [17].

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 *Rhodospseudomonas 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 [21].

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 [21].

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].

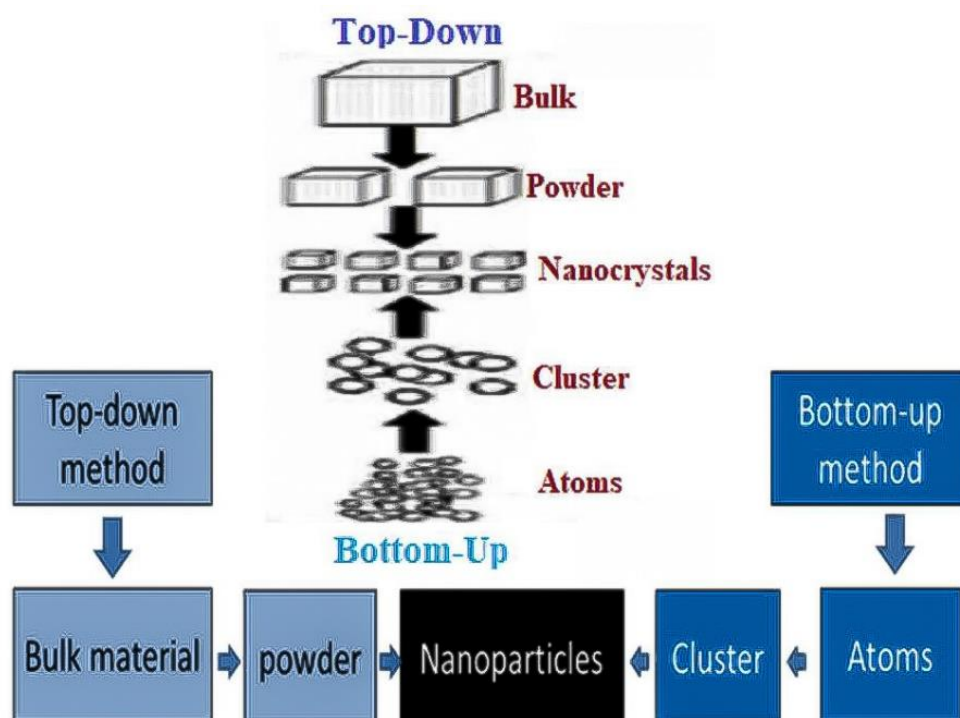


Figure 1. Physical methods for the preparation of molecular nanomaterials.

The route of bottom-up method is from atom to clusters to NPs. The route of top-down method is from bulk material to powder to nanoparticles. The most commonly used bottom-up methods are Sol-gel, spinning, chemical vapor deposition (CVD) and pyrolysis. On the other hand, the nanolithography, laser ablation, sputtering and thermal decomposition are most common technique of top-down method. In sol-gel process metal oxides and chlorides or other metal salts are dispersed in a host liquid either by shaking, stirring or sonication to create nanoparticles. Spinning methods use a rotating disc inside a chamber/reactor. Here the physical parameters such as temperature are controlled. In this technique, the liquid flow rate, disc rotation speed, liquid/precursor ratio, location of feed, disc surface, etc. controls the nanostructures of nanoparticles. Besides, CVD technique produces a thin film of product on the surface of the substrate carried out in a

reaction chamber at ambient temperature by combining molecules in vapor phase. After reaction the produced thin film is recovered and used. Pyrolysis is the most frequently used process in industries for making large-scale NPs through burning a precursor using a flame. Nanolithography is the route toward producing a necessary shape or structure on a light delicate material that specifically eliminates a bit of material to make the ideal shape and structure. Laser Ablation Synthesis in Solution (LASiS) is additionally a typical top-down method for NPs preparation from various solvents in which the irradiation of a metal inundated in a liquid solution by a laser beam condenses a plasma plume to produce NPs. Another top-down method sputtering is typically a deposition of thin layer of NPs followed by annealing in which the thickness of the layer, temperature and duration of annealing, substrate type, etc. control the shape and size and morphology of the NPs. Another top-down method is thermal deposition, in which an endothermic chemical decomposition attained by heating breaks the chemical bonds of the precursors used [22].

Chemical method is important for gas and liquid phase production of molecular nanomaterials. Co-precipitation is a chemical method of synthesis of nanoparticles which involves the mixing of two or more water soluble salts of divalent and trivalent metals. The aqueous solutions are continuously stirred, which may or may not need the heat conditions, and use of reducing agents. Another chemical method is sonochemical method which can produce NPs by ultrasonication in a liquid medium [21]. Furthermore, inert gas condensation is also a chemical method in which material is evaporated in a cool inert gas usually He or Ar at low pressure. Here when pressure and molecular weight of inert gas are increased, the mean size of product (NPs) is also increased [23]. Another synthesis method is green method to reduce nanotoxicity. This method depends on organic extracts as reducing agent. Here in, various plants, amino acids, enzymes, flavonoids, aldehydes, ketones, amines, carboxylic acids, phenols, proteins and alkaloids provides electrons to reduce some materials (such as gold) into NPs. The ultimate size, shape and morphology of the product relies upon the concentration of plant extract, metal salt, pH of the reaction mixture, temperature and incubation time etc. [24]. Furthermore, microwave heating applied to chemical reactions also addresses a sustainable “green” chemistry by utilizing a secure solvents and reaction conditions, limiting accidents, preventing the waste or bi-products, and reducing the reaction time. For example, in various microwave frequencies, it is possible to synthesize NPs at shorter times than a traditional synthesis. In recent years, improved microwave devices have been designed for laboratories and industries to control temperature and other reaction parameters. However, the microwave heating depends upon the dipole moment of a given molecule, thus, a more polar reagent is needed in the reaction [25].

In nanofabrication, a thin film is a layer of material going from parts of a nanometer (monolayer) to a few micrometers in thickness. Thin films are made through an interaction called “deposition.” Deposition is a thin film coating system, which is accomplished by altering the four states of matter, solid, liquid, vapor and plasma. This can be cultivated through an assortment of vacuum system. Customary classifications of vacuum deposition system incorporate chemical vapor deposition (CVD), physical vapor deposition (PVD), evaporation through vacuum sublimation, or incidentally, a mix of these techniques. These models are only a couple of ways a thin film can be created.

Sputtering is a PVD class of thin film technology in which the material that will be covered (the sputtering target) is bombarded with plasma ions and the eliminated particles go into the gas stage. Condensation on the substrate surface and firmly adhesion in it is assisted by the vapor. Then the thin layer is exceptionally formed. It is a bottom up process. In the conventional top down, sputtering enables sputtering of only one material at a time due to the geometric relation between the magnetron and the substrate. For this kind of sputtering, it is important to have an objective material bigger than the substrate to get adequate film consistency. So, sputtering film deposition is bottom-up process from the

point of view of film formation, even if it could be interpreted as top-down technology from the point of view of removing atoms from the target and depositing on the wafer.

Molecular nanomaterials are generally characterized by DLS, XRD, SEM, TEM, LLS, AES, XPS and other methods. The most essential information usually obtained at the beginning of characterization of NPs is particle shape and size. XRD, XPS and electron microscopy techniques (SEM and TEM) are commonly used for revealing the details of the nanoparticle size, elemental compositions, phase, shape and surface morphologies etc. [26–29]. In sum, before an extensive and cost-effective applications of nanomaterials in all modern industries, advanced, environment-friendly synthesis methodologies, smart characterization technologies, and the scale-up process, concerning highest possible level of nanosafety are crucial for the industrial manufacturing uses of nano materials.

3. Industrial Applications

Molecular nanomaterials have numerous industrial applications in many industries [30]. Based on different important properties of molecular nanomaterials, we discuss the applications of nanomaterials in several industries.

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 [31]. Nanomaterials can act as superb filler in cement-based materials. The photocatalytic properties of the cement samples were enhanced through dispersing nano-TiO₂ by ultrasound. By the addition of nano-TiO₂, the total shrinkage of cement-based materials can be remarkably reduced. Nano-TiO₂ 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 [32]. By increasing the volume fractions of CNTs, the energy absorption capacity, the curvature ductility and the moment capacity of the CNT-reinforced concrete columns enhanced significantly [33]. 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 [34]. At early stages of hydration, the addition of nano-TiO₂ to cement increased the heat of hydration and also accelerated the rate of reaction [35]. When cement is substituted by nano-TiO₂, the strength of cement mortar at early ages increased a lot and the fluidity and strength decrease with time [36].

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) [10,17]. 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].

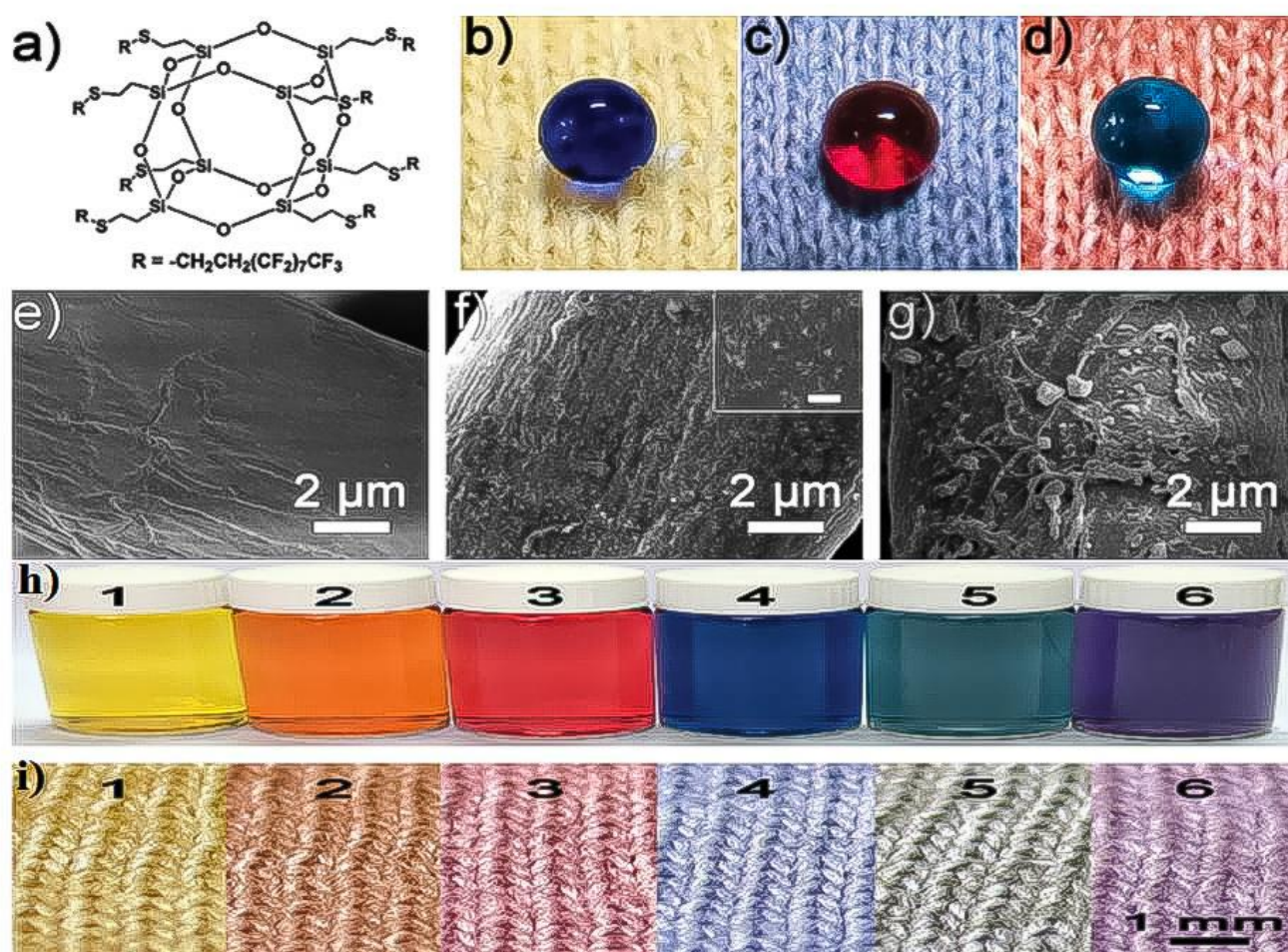


Figure 2. Fabric finishing using Ag-based nano-coating for enhancement of properties and performance. (a) Chemical structure of F-POSS, (b–d) Water droplets on F-POSS/AgNPs/PEI-coated cotton fabrics of (b) yellow, (c) blue, (d) and red colors. (e–g) SEM images of (e) pristine cotton fabric, (f) AgNPs/PEI-coated 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 [37]. Copyright John Wiley and Sons, 2015.)

In textile industries, CNT-reinforced polymer composite fibers have been created to improve strength and durability and to reduce weight. The CNTs integrated fibers has appeared to improve the strength and execution [38]. The color of a synthetic textile effluent can be removed by photocatalytic process by using TiO_2 suspensions under solar radiation [39]. The nanocomposites such as ZnO/CdO nanocomposite [40], ZnO/Ag nanocomposite [41], CuO-ZnO nanocomposite [42] and CuAu-ZnO-graphene nanocomposite [43], possess high efficiency to degrade textile effluent in ETP (effluent treatment plant).

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 [44]. 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 [45]. 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 [46]. 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 [47]. 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 [48]. Artemia eggshell- ZnO nanocomposites can be used for waste water treatment by photodegradation of methylene blue, Rhodamine B, and neutral red etc. [49].

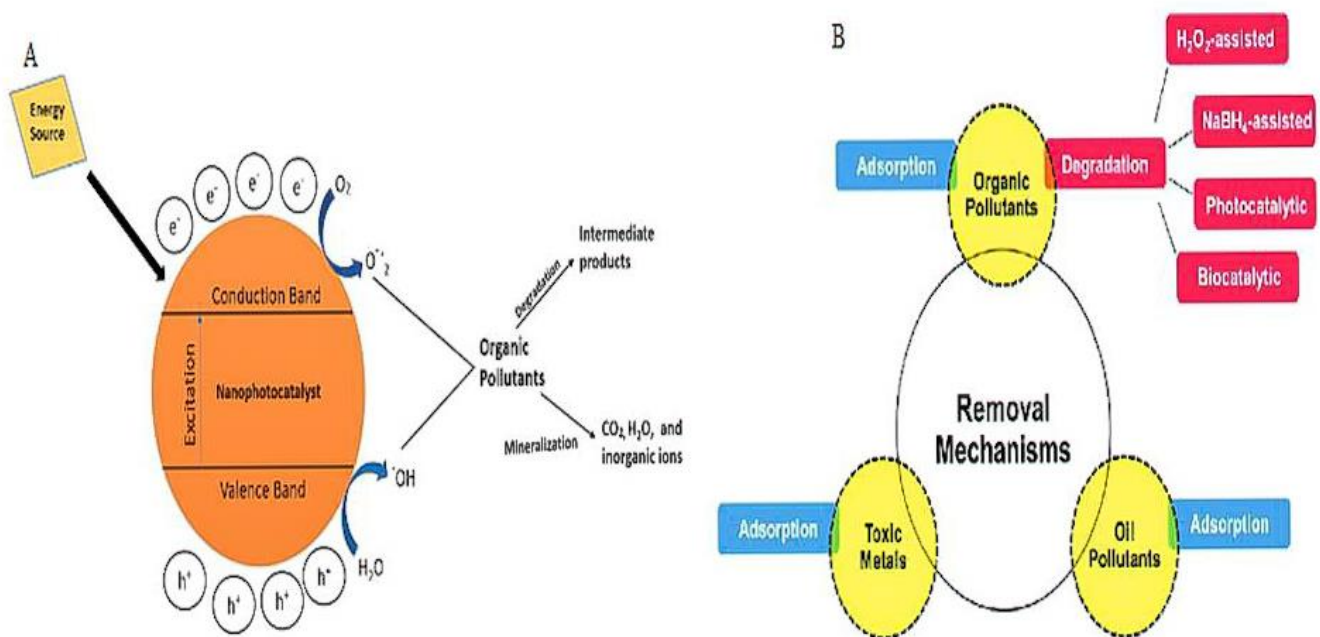


Figure 3. Mechanism of nanophotocatalysis for the treatment of environmental organic pollutants (A) and different pollutant removal techniques used by nano/micromotors (B). (Reproduced with permission of [44]. Copyright John Wiley and Sons, 2015).

Due to lowering of bandgap of CuO nanoparticles in nanocomposite by the addition of reduced graphene oxide (RGO), the copper oxide/reduced graphene oxide (CuO/RGO) nanocomposite can serve as visible photo-driven catalyst for degradation of both ortho and para nitrophenols in 120 and 180 min, respectively. CuO/RGO NC can remove nitrophenols from waste water by degradation process [50]. The SWCNT/TiO₂ ultrathin film is valuable in treating emulsified wastewater produced in industry and everyday life and for decontamination of unrefined oil and fuel [51]. Au/ZnO hybrid nanostructures can be used for heterogeneous photocatalytic applications in water treatment [52].

3.4. Agriculture Industry

In agriculture industry, there are several applications of nanomaterials including nano delivery [53], nanosensors [53], nanoencapsulation of pesticides [53], nanopesticides [53], and nanofertilizers [54]. 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 [53]. 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 [55,56]. 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 [54]. Various sorts of nanoparticles like carbon nanotubes, Cu, Ag, Mn, Mo, Zn, Fe, Si, Ti, metal oxides, and nanoformulations of phosphorus, urea, sulfur, validamycin, tebuconazole and azadiractina have been transformed into nanopesticides and nanofertilizers [57]. 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 [58]. Nanofertilizer releases nutrients slowly through the lifecycle of the crop and increase efficiency of the elements. That's why the risks of leaching, adsorption, surface runoff, decomposition and toxicity of the soil can be reduced by using it [54,59]. Zinc nanofertilizer is an example of nanofertilizer that enables the plants to withstand lower air temperatures and helps in the biosynthesis of cytochrome [60]. In addition, nanoencapsulation of pesticides can control the outer shell properties of a capsule that can manipulate slow and controlled release of the active ingredient. The dispersion and wettability of agricultural formulations can be increased by using nanopesticides. It also can control unwanted pesticide movement [53]. The root growth of rye grass and pumpkin can be enriched by mixing Fe₃O₄ (100 mg/L) nanoparticles with soil [61]. By mixing 2.5% TiO₂ nanoparticles photosynthesis rate of plant is developed through the promotion of synthesis of chlorophyll A [62].

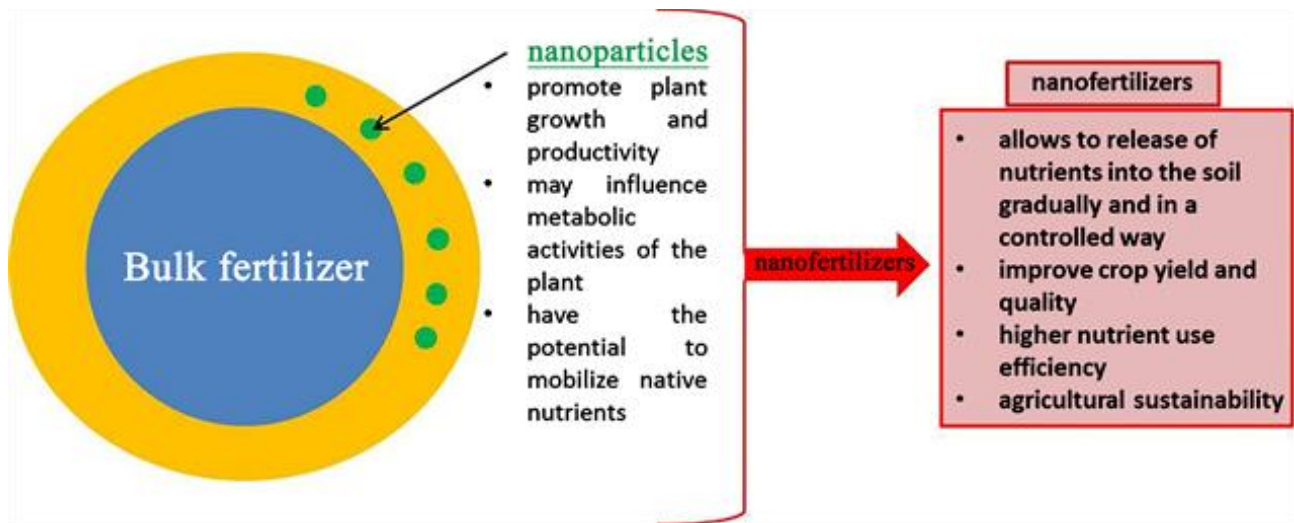
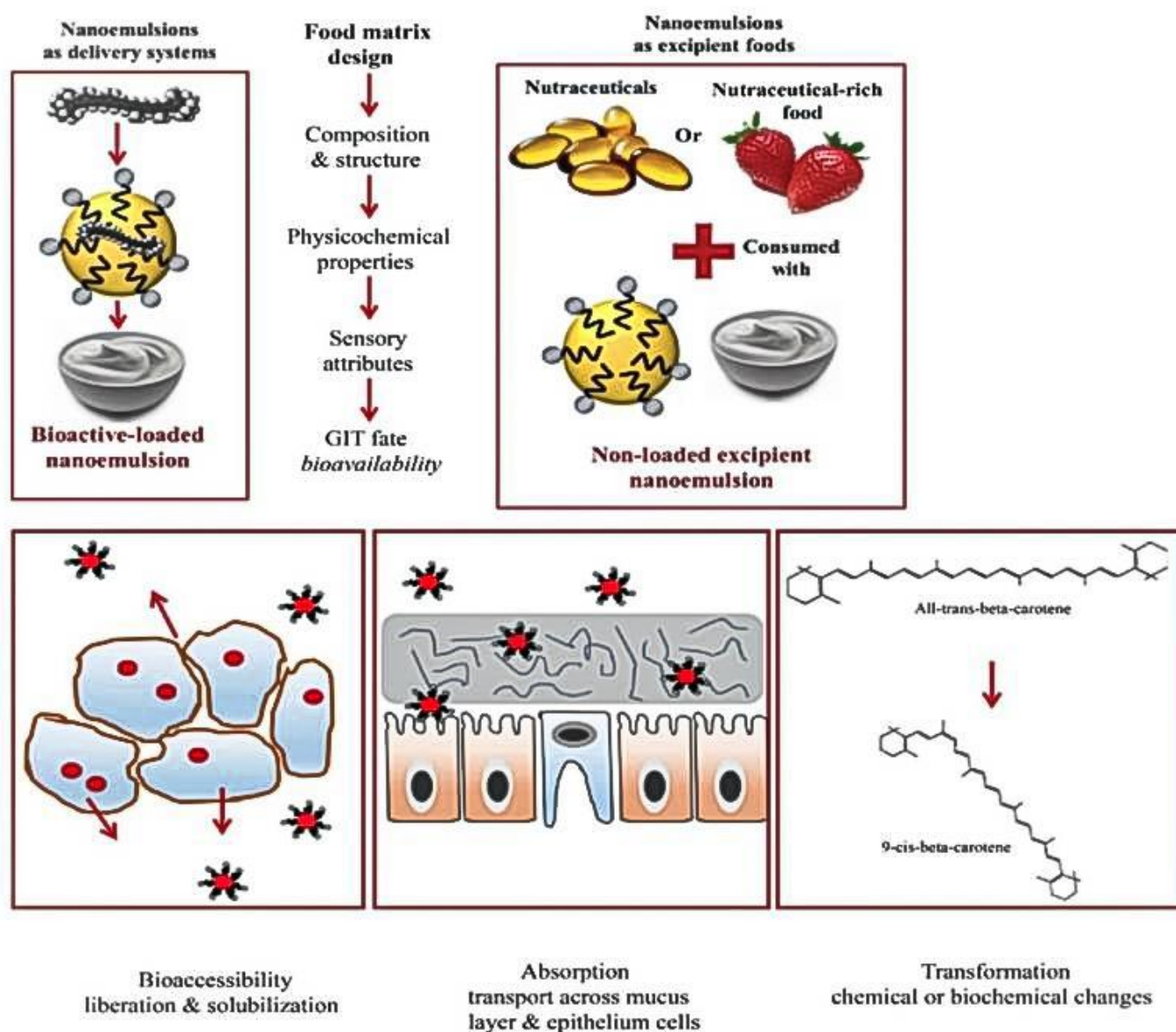


Figure 4. Advantages of nanofertilizers over bulk fertilizers. (Reproduced with permission of [55]. Copyright Scientific Research Publishing Inc., 2021).

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) [63]. 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 [53,63]. Integration of metal or metal oxide nanoparticles in polymer nanocomposites have been used for food packaging e.g., ZnO nanoparticle incorporated into polystyrene film [53,63], ZnO nanoparticles coated on polyvinyl chloride (PVC) films [64]. 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. Nanoencapsulation 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 CO₂ 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 [65]. TiO₂ nanoparticle-coated film is utilized for potential food packaging applications due to the photocatalytic antimicrobial property of TiO₂. Different concentrations of TiO₂ nanoparticles can be coated on food packaging film, especially in low density polyethylene (LDPE) film [66].



$$\text{Bioavailability} = \text{bioaccessibility} \times \text{absorption} \times \text{transformation}$$

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 [63]. 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. [17]. 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 [67]. 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 [68]. 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 [69]. Carbon nanotubes and organic matrix-based composites are continuously being utilized in spacecraft and aircraft industries in view of their strikingly high strength, modulus, lightweight, good fatigue life, high stiffness and excellent corrosion resistance [70]. When different types of CNT are incorporated in the resin at an equal concentration, they show improved mechanical and electrical property, consequently they are used in modern aircrafts [71]. For having high strength, lightweight, and high electrical conductivity epoxy/CNT composites are also used in aircrafts [72].

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 [73]. In addition, NPs are essential for diagnosis of diseases, cancer gene therapy, pulmonary diseases and inhibition of other infectious diseases [74]. Nanomedicines can be cleared by human body quickly yet they are exceptionally powerful in identifying and imaging disease like cancer [75]. 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 [76].

TiO₂ nanotubes (TNTs) have an ability to act as a drug carrier to the surrounding tissues, aiming to accelerate the tissue response regarding implant integration [77]. CuO nanoparticles are also used in drug delivery. These nanoparticles also have great biological properties including effective antimicrobial action against a wide range of pathogens and also drug resistant bacteria [78]. Novel multifunctional porous TiO₂ nanoparticles modified with polyethylenimine (PEI) can explore the feasibility of exploiting the photocatalytic property of titanium dioxide to achieve ultraviolet (UV) light triggered drug release. The PEI on the surface of multifunctional porous TiO₂ nanoparticles could adequately block the channel to prevent premature drug release, thus subsequently giving sufficient circulation time to target cancer cells [79]. Some nanocomposites are utilized in smart nano-drug delivery system such as ZnO-quercetin [80], Oxidized Starch/CuO Nanocomposite Hydrogels [81], polyvinyl alcohol/CuO nanocomposite hydrogel [82] etc.

Biosensors are extensively used in medical industry. Different nanomaterials are utilized as biosensors in such industries. Biosensor devices can detect a biological item [83]. Different types of TiO₂ nanomaterials have become forthcoming environment friendly electrode materials for biosensing applications [84]. Nanostructured ZnO can be utilized to build electrochemical biosensor for detection of biologically significant analytes like DNA, metabolites, cancer markers, and so on [85]. Colorimetric strategies based on gold and silver nanoparticles (NPs) are emerging quickly to distinguish metal particles in the watery stage, for example, gallic acid-functionalized AgNPs can be utilized as a colorimetric detecting test for identifying Al³⁺ with enhanced selectivity and affectability [86]. Aluminum is present in human brain tissue [87]. For this reason, brain tissue can be detected by gallic acid-functionalized AgNPs.

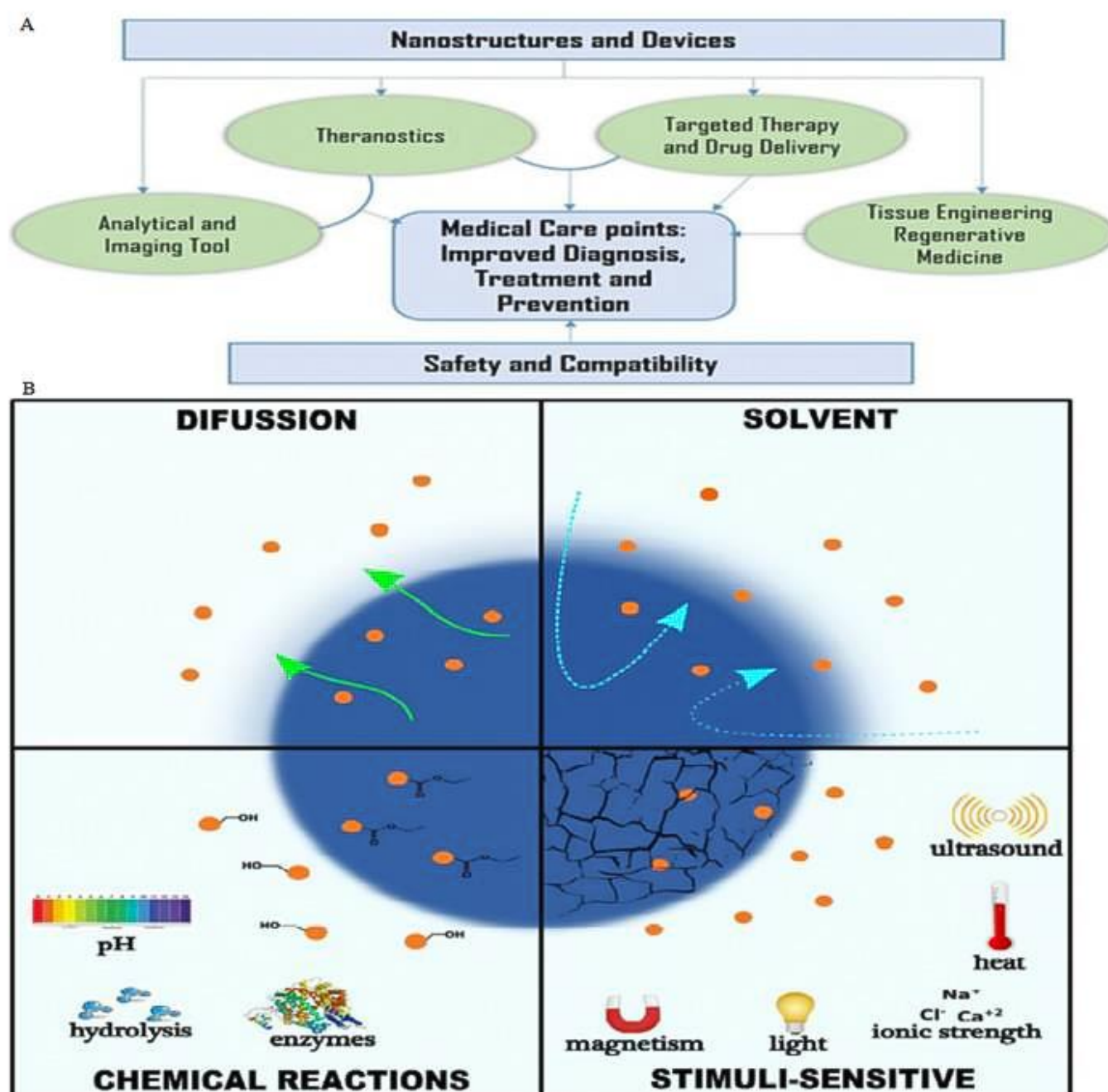


Figure 6. Application and goals of nanomedicine in different sphere of biomedical research (A) and mechanisms for controlled release of drugs using different types of nanocarriers (B) (Reproduced with permission of [76]. Copyright BioMed Central Ltd., Part of Springer Nature, 2021).

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, nanocatalysts 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 [88].

ZnO superstructures show excellent execution for hydrogen production through photoelectrochemical (PEC) water splitting in view of their specific beneficial properties like high internal surface area, enhanced scattering with improved light harvesting, reduced recombination rate, low charge transfer resistance, better crystallinity, channeled conducting pathways, and so on. These properties are significantly subject to the different morphologies of ZnO. In current time, energy demands of people have been expanding hugely. Thus, prime significance has been given to look through novel methods of energy transformation and capacity from renewable power sources. In the similar context, photoelectrochemical (PEC) water splitting by using semiconductor photoelectrode became well known because of its environmentally friendly nature. For PEC water splitting, ZnO is considered as one of the superior semiconductors due its high effectiveness and minimal expense. ZnO superstructures have shown astounding outcomes in PEC because of their outstanding physicochemical properties [89].

3.9. Cosmetics Industry

TiO₂ and ZnO nanoparticles are used in sunscreen [90]. Silica-coated nanosized TiO₂ [91] and α -bisabolol and phenylethyl resorcinol/TiO₂ hybrid composites [92] 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 [90]. ZnO nanoparticles are used in different eye shadow samples [93]. N-doped graphene/TiO₂ nanocomposite has antioxidant capacity, it can be used in screen-based cosmetics to maintain skin healthy and fair [94].

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 [95]. CuO nanoparticle suspension can be used as nanolubricant [96]. 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 [95].

Silicon-based nanoelectronics is a good proof of concept of nanotechnology, by pushing the Moore's law to the limits. In this case Moore's law depicts a drawn-out pattern throughout the entire existence of computing hardware which tell us that the number of transistors on a microchip increase twice per 2 years. In this case, Gordon Moore authoritatively perceived that the amount of transistors per chip had been multiplying per year, though the cost of computers is halved [97,98]. Moore's Law is around 60 years old, however, still strong. More than 60 years later from its statement, still the lasting impact and benefits of Moore's Law is palpable in many sectors including computing and electronics.

Experts agree that computers should reach the physical limits of Moore's Law at some point in near future. The high temperatures of transistors eventually would make it intolerable to create smaller circuits. This is because cooling down the transistors takes more

energy than the amount of energy that already passes through the transistors. However, the shrinking transistors have powered advances in computing for more than half a century, but soon engineers and scientists must find other ways to make computers more proficient. As an alternative of physical processes, applications and software may help improve the speed and competence of computers. Cloud computing, wireless communication, the Internet of Things (IoT), and quantum physics all may play a crucial role in the future of computer tech innovation.

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 [99]. In oil reservoir engineering the application of nanoparticles involves new types of smart fluids for improved oil recovery, and drilling [100]. 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. [101]. 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 [74]. 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 [102]. 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.

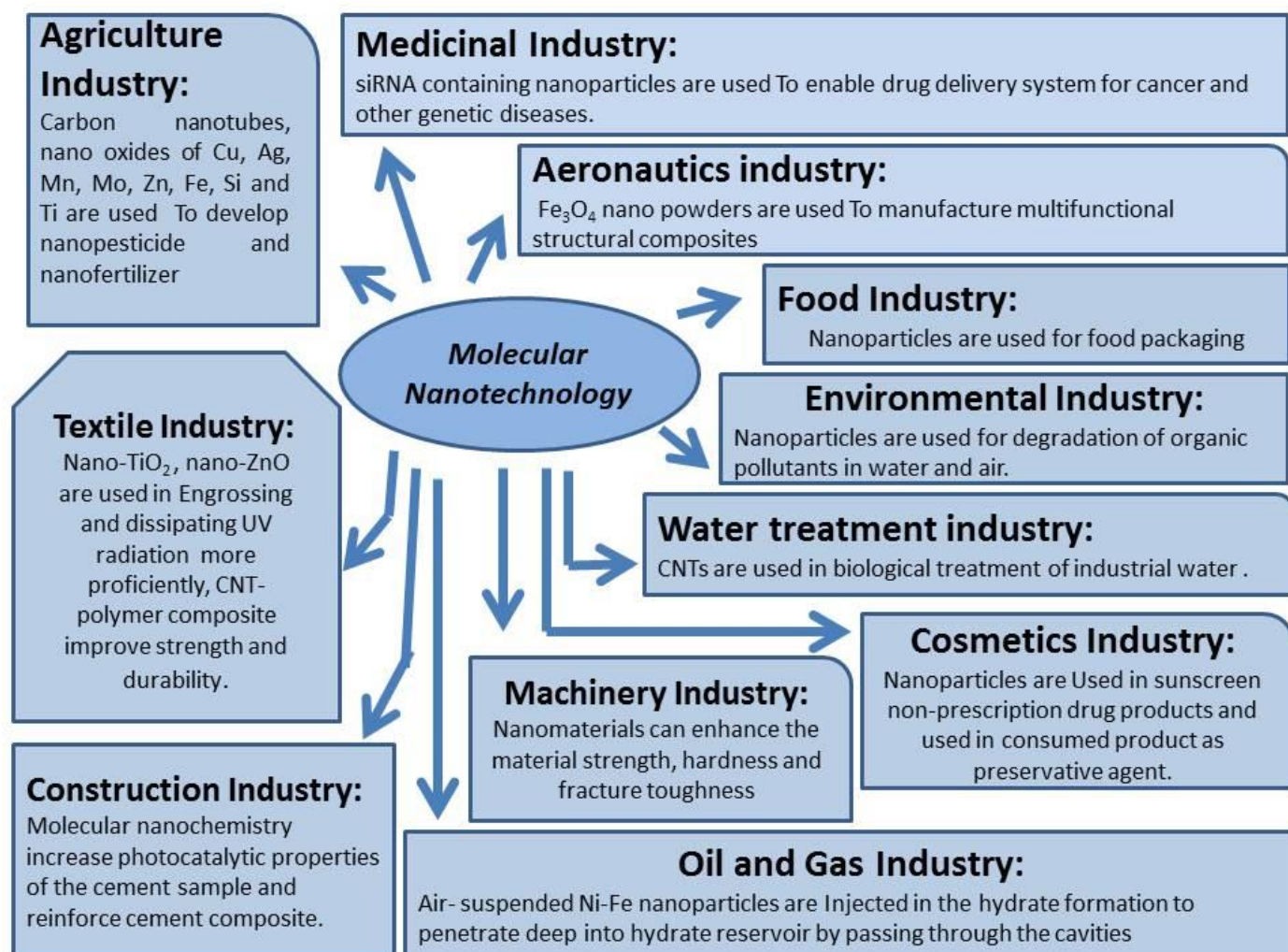


Figure 7. Applications of nanoparticle in industrial sectors.

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 [103]. 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 [104].

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 [105]. 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 [106]. 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]. As shown in Table 2, it summarizes industrial application of molecular nanomaterials.

Table 2. Summary of industrial application of molecular materials.

Industry	Molecular Nanomaterials Used	Applications	References
Construction Industry	Nano-TiO ₂	To increase photocatalytic properties of the cement sample.	[32]
	CNT, nano-MgO, nano-smectite-based clay	To reinforce cement composite.	[32,33]
Textile Industry	Nano-TiO ₂ , nano-ZnO	Engrossing and dissipating UV radiation more proficiently	[6]
	CNT-reinforced polymer composite fibers	To improve strength and durability and to reduce weight.	[38]
Water Treatment Industry	CNTs	In biological treatment of industrial wastewater.	[47]
Agriculture Industry	Carbon nanotubes, nano oxides of Cu, Ag, Mn, Mo, Zn, Fe, Si and Ti	To develop nanopesticide and nanofertilizer	[57]
Food Industry	ZnO nanoparticle with polystyrene film	Used for food packaging	[53,63]
	Silver nanoparticles and nanocomposites	Antibacterial agents for improving food safety	[53,63]
Aeronautics Industry	Fe ₃ O ₄ nano powders	To manufacture multifunctional structural composites	[67]
Medicinal Industry	siRNA containing nanoparticles	To enable drug delivery system for cancer and other genetic diseases	[73]
Environmental Industry	TiO ₂ and ZnO nanoparticles	Used for degradation of organic pollutants in water and air.	[88]
Cosmetics Industry	TiO ₂ and ZnO nanoparticles	Used in sunscreen non-prescription drug products	[90]
	Polycaprolactone (PCL) nanocapsules	To encapsulate elements for use in cosmetic items	[90]
	Silver nanomaterials	Used in consumer product as preservative agent	[90]
Machinery Industry	Nano-titanium nitride	To enhance the material strength, hardness and fracture toughness.	[95]
Oil and Gas Industry	Air-suspended Ni-Fe nanoparticles	Injected in the hydrate formatin to penetrate deep into hydrate reservoir by passing through the cavities	[74]
Computer Industry	Nanotube/carbon nanotube	Nanotubes are applied to manufacture smaller transistors or electronic devices	[107]
Medicine and Computer Industries	Flullerene	One of the most important medical application of fullerene is the controlled release of drugs for cancer and other diseases. In the electronic industry, it has useful applications in solar cells, diode, and semiconductors. Fullerene has potential applications in the pharmaceuticals as well as in nanomedicine.	[108–112]

4. Toxicity of Nanomaterials

Recently, toxicity of nanoparticles because of their minuscule actual measurements has been broadly perceived. An enormous number of non-harmful mass materials become toxic when their size is decreased to nanoscale [113]. There are numerous sources of nanomaterials in daily life including auto traffic, combustions, mining, energy generation, laundry, food and beverage, cosmetics, drug and medicine. The major toxicological concern is the way that a portion of the fabricated nanomaterials are redox active, and a few particles transport in different organs of human body including brain, lymphnodes, lung, liver, heart, spleen and kidney, and even across cell layers particularly mitochondria [114]. Carbon nanotubes and fullerene can be highly toxic, if these are inhaled into the lungs [113]. Adverse impacts of nanoparticles on human health rely upon individual factors such as genetics and existing disease, as well as exposure, and nanoparticle chemistry, size, shape, agglomeration state, and electromagnetic properties. Animal and human studies show that inhaled nanoparticles are less efficiently removed than larger particles by the macrophage clearance mechanisms in the lungs which cause lung damage, and that nanoparticles can transport through the circulatory, lymphatic, and sensory systems to numerous tissues and organs, including the brain. The way to understanding the harmfulness of nanoparticles is that their moment size, more modest than cells and cell organelles, permits them to enter these essential natural constructions, upsetting their typical capacity [115]. An extensive assessment of the biological and toxicological effects of nanomaterials is necessary for the design of products that are safe and operate as intended. As the toxicological tests are tedious and asset concentrated, the analysts are creating computational models to foresee the conduct of nanomaterials in biological systems [116]. Nannomaterials-based products are increasingly entering into the daily life of the human. The regulatory bodies including the Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) in the USA or the Health and Consumer Protection Directorate (HCPD) of the European Commission have been working with the likely risks of vast use of nanoparticles all over the world. However, neither engineered nanoparticles nor the numerous products and materials that comprise them are subject to any distinct regulation concerning production, handling or labelling. Currently, there is no recognized and unified regulation for nanomaterials use, and also there is no unique international organization for controlling it. Recently, international nations including fist-world countries are highly concerned about minimizing the toxicity effect of nanomaterials on humans and the environment through its journey towards modern advanced level applications in daily life.

5. Future Research Perspectives and Challenges

Aside its turn of events, there are a few struggles to an unrivaled effect of nanotechnology in industry. The absence of data, the chance of unfriendly effects on the climate, human wellbeing, security and maintainability, are as yet challenges [17]. There are numerous impediments to moving beyond the bench: an absence of subsidizing for an applied exploration, financial backer alert when managing new advances, and an absence of government direction in regards to administrative oversight of nanotechnology. Also, there is worry about the possible harmfulness of the nanomaterials themselves. This worry has incited broad examination concerning nanomaterial poisonousness, with considerations demonstrating that occupational exposure to nanomaterials can in reality be destructive. Be that as it may, the effect of delivering nanomaterials into the climate is more nuanced, especially if the nanomaterials are essential for a composite material; once in the climate, processes such as aggregation, adsorption to normal natural matter, sedimentation and oxidation change nanomaterials from their pristine structure, can adjust their harmfulness. A large number of the nanomaterials and nanotechnologies depicted here are not industrially accessible. The utilization of nanotechnology in modern water treatment holds the guarantee of changing large numbers of these cycles by bringing down the treatment cost and surprisingly empowering the treatment of already untreatable toxins. The modern water treatment

local area has explicit requirements, and it would profit the whole local area if analysts and end-clients could cooperate to foster answers for well-defined issues [47]. The whole range of nanotechnology will start various future precedents for smart vehicles. One of the changing characteristics of current vehicles is that, logically more parts are controlled electronically. For example, electronically controlled fuel infusion, exhaust emission, anti-lock braking system, automatic air conditioning, headlight brightness control, automatic adjustment of driver's seat, steering control, electronically controlled hanging, and so on. All the automotive subsystems may be an invention of nanotechnology. It incorporates utilizing progressed nanoparticles as a filler in vehicle tires, anti-reflective coatings for displays and mirrors, nanoparticle-reinforced polymers and metals, modified adhesive technologies and adhesive primers, improved fuel cell technology and hydrogen storage, catalytic nanoparticles as a fuel additive, and so forth [106]. A significant hypothetical advantage of nanotechnology examination is to decide if existing speculations are helpful indicators of what will occur in the enterprises where nanotechnology applications are being created and to change and expand existing hypothetical structures as justified by research discoveries. Speculations would then be able to be produced to expose existing hypothetical structures to thorough testing. Confronted with a gradual advancement, contest movements to item highlights and cycle efficiencies. Exercises that boost persistent improvement, including factual interaction control, measure advancement, preventive upkeep projects and worth designing, are significant. Robotic attributes of normalization, specialization and centralization ordinarily support effectiveness. Statistical surveying movement driven by client needs and input drive the association [117]. Finally, an international nanomaterials regulation is crucial for safe use of emerging, vast nanomaterials technologies world-wide.

6. Conclusions

Molecular nanomaterials have vast application in industries. Size makes them very valuable for all kinds of practical uses in industry. Industry use nanoparticles to improve their product, which is delivered to customer. Food based industries improved food quality with great smell and great taste by using nanoparticles. Agriculture industries use nanoparticles to make lands fertile, as insecticides and to eliminate their toxicity. Textile industry can produce special textiles with many functions by utilizing nanomaterials. The cosmetics industry can reduce toxicity of their products by using nanoparticles. Pharmaceuticals and medical industries have been using nanomaterials for formulating new drugs and improved treatment options for potential patient benefit and health-care. Others industries including energy and aeronautics industries, mechanical and machinery industries, construction industry, water and environmental-based industries, oil and gas industries are also developing their products and overcoming difficulties (if any) by using the nanomaterials. Nanoparticles are utilized in the development of industry since they can help with diminishing the utilization of regular materials by working on the exhibition of development materials and diminishing/reducing the utilization of energy. Nanomaterials with their remarkable multifunctional properties might change the working of avionics industry dramatically. Nanotechnology has set up itself as a key empowering innovation for a wide scope of uses, in this manner turning into a main concern for science and innovation strategies improvement, being now utilized in many items among the modern area, to be specific, electronic, space, medical services, food, beautifiers, composites and energy. The nanotechnology, up to now, has shown a major impact at the level of nanomaterials, and, excepting nanoelectronics where the results are spectacular, there is more to be done for its penetration at the system level. In summary, molecular nanomaterials bringing a revolution in industries including construction, gas and oil, food, medicine, aeronautics, environmental, machinery and computer industry etc. Finally, to ensure the emerging nanomaterial-based industrial applications and consumer benefit nation-wide, implicating its impact in human life and environment, and overall in modern

civilization process, an internationally recognized, rigid, nanosafety regulation is crucial for sustainable development.

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