Nanomaterials: An Introduction

Tarun Kumar Barik, Gopal Chandra Maity, Pallavi Gupta, L. Mohan, and Tuhin Subhra Santra

Abstract  Nanotechnology offers a significant advantage in science, engineering, medicine, medical surgery, foods, packing, clothes, robotics, and computing from the beginning of the twenty-first century. As the potential scientific discovery always contains some good and bad effects on human civilization and the environment, nanotechnology is not an exception. The major drawbacks include economic disruption along with imposing threats to security, privacy, health, and environment. The introduction of the chapter discusses the historical background of nanotechnology. Later it also discusses the advancement of nanotechnology to date with its benefits. Major drawbacks of nanotechnology arise in human health due to the enormous involvement in medicine, food, agriculture, etc. This chapter also deals with environmental nano pollution and its effect on society, highlighting the social-economic disruption due to the rapid use of nanotechnology. Nano pollution affects not only human beings but also other living beings like microorganisms, animals and plants, which are briefly reviewed. This chapter also demonstrates the safety and security of nanotechnological developments, current policy and regulation status, challenges, and future trends. Finally, it is concluded, while nanotechnology offers more efficient power sources, faster and modern computers and technologies, life-saving medical treatments, but due to some negative impacts, it bounds us to think twice before any further advanced technological applications.

T. K. Barik (✉)
Department of Physics, Achhruram Memorial College, Jhalda, Purulia, West Bengal, India
e-mail: tarun.barik2003@gmail.com

G. C. Maity
Department of Chemistry, Abhedananda Mahavidyalaya, Sainthia, Birbhum, India

P. Gupta · L. Mohan · T. S. Santra
Department of Engineering Design, Indian Institute of Technology Madras, Chennai, India

L. Mohan
Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Japan

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1 Introduction

Nanotechnology is an emerging field of science and technology with numerous applications in biomedical and manufacturing engineering [1–3]. In the last two decades, nanotechnology integrates with mechanical and electronic engineering to develop Micro/Nano-electromechanical systems (MEMS/NEMS) devices, which have diverse applications in different fields of science and engineering. These devices are potentially applicable for various sensing, actuating, and biomedical analysis purposes [4–13]. Recently, quantum dots have increased much attention in biological fields due to their unique size, tunable light absorption, and emission properties [14]. Further, biocompatible nanomaterials have many applications in biomedical purposes such as orthopedic, cardiovascular, contact lenses, catheter, prosthetic replacement, etc., [15–21]. Among noble metals, Ag and Au nanoparticles synthesis via marine algae are used as a broad-spectrum antimicrobial agent towards a variety of pathogens in the biomedical field [22]. Nowadays, nanomaterials are produced by industries for commercial applications with enormous benefits. While there lies a vast potential of nanomaterials for fulfilling individual requirements, it also represents potential risks to human health [23].

The green synthesis of nanoparticles attracts many researchers and industries. Many microorganisms are utilized for the synthesis of nanoparticles. Biosynthesis of nanoparticles has been reported using photoautotrophic microorganisms such as cyanobacteria, eukaryotic algae, and fungi. The biogenic fabrication of nanoparticles via microalgae is a non-toxic, and eco-friendly, green chemistry method with a large variety of compositions and physicochemical properties. Biosynthesis of nanoparticles by plant extracts is currently under exploitation. Plant extracts are a better source of nanomaterials compared to the various biological processes often considered eco-friendly substitutes of chemical and physical methods [1, 17]. Seaweeds contain different organic and inorganic substances that can benefit human health [24]. The green seaweed is used widely in agriculture, pharmaceutical, biomedical, and nutraceutical industries for its presence of a high amount of vitamins and minerals [25]. Among several genera of microalgae, *Spirulina platensis* is blue-green algae of the cyanobacteria family grown in temperate water in the whole world. A blue-green alga has served as food with high protein content and nutritional value from ancient times [26]. The algae produce novel and potentially useful bioactive compounds [27, 28]. The bioactive materials have gained significant attention in recent years and have been used considerably in developing new pharmaceutical products, food products, renewable bio-energy, and biomedical applications [29–31]. However, a new global health problem has been arisen as in discriminant antibiotic use and the remarkable ability of bacteria to acquire resistance to lower these drugs’ effectiveness via genetic
mutation or gene acquisition. Therefore, new classes of antibiotics with novel structures are needed to combat this trend. Food preservation is now dealing with the severe concern of microorganisms mediated spoilage and fall in quality and nutrition worldwide [32]. Hence, increasing the continuous demand for pathogen control measures to combat resistant microorganisms against multiple antimicrobial agents. However, nanoparticles own large surface area to volume ratio, unique quantum size, magnetic properties, heat conductivity in addition to some catalytic and antimicrobial properties [33]. In this regard, nanomaterials, including metal nanoparticles, carbon nanotubes, quantum dots, and other active nanomaterials can be used to develop biosensors against a broad spectrum of microorganisms for the formulation of a new generation of antimicrobial agents.

2 Historical Background of Nanotechnology

The first experiment of nanotechnology was shown in 1857 when Michael Faraday introduced ‘gold colloid’ samples to the Royal Society. He added phosphorous to a solution of gold chloride and, after a short while, noted that the blue color of the solution changed to a ruby red dispersion, without knowing the actual cause of color changing. Indeed, the resulting suspension of nanosized gold particles in solution appeared transparent at some frequencies, but others could look colored (ruby, green, violet, or blue). Since then, many experiments and theoretical studies have been carried out to explain similar systems’ unique properties, which in today’s terminology are called low-dimensional systems. Nearly after 100 years, in 1959, Richard Feynman inspired the field of nanotechnology in his lecture at the American Physical Society (APS) meeting, Caltech, saying the meaningful words “There’s Plenty of Room at the Bottom.” From the late 1980s, we find there is a growth of activity on these low dimensional materials. In general, low dimensional systems are categorized as follows: (a) two dimensional (2D) systems, in which the electrons are confined in a plane (e.g., Layered structures, quantum wells and superlattices); (b) one dimensional (1D) systems, in which electrons are free to move only in one dimension (e.g., linear chain-like structures, semiconductor quantum wires), and (c) zero-dimensional (0D) systems, where electrons are confined in all three dimensions (e.g., quantum dots, clusters, and nanosized colloidal particles) [34–41].

The dimension of these materials in the direction of confinement lies in the nanometer scale, given the name nanomaterials. In this length scale, classical physics fails to explain the behavior of these materials. Instead, one needs quantum mechanical concepts. Interestingly, due to quantum effects, the physical properties of nanomaterials change drastically from their corresponding bulk behavior. This unique feature of nanomaterials has been exploited by modern technology in various applications. The link between human life and nanotechnology is as old as Ayurveda, a 5000-year-old Indian medicine system.

Moreover, twenty-first century modern science marks the beginning of nanoscience, while it existed from ancient times of Vedas, much before even the
term “nano” was coined [42, 43]. As per strict nanometer terminology, any objects with dimensions in the nm range can be termed as a nanoparticle or a “nano” object, as TiO₂ dust in the study mentioned above [44]. Nanotechnology not only combines engineering, physics, and chemistry but also integrates with biology [45]. A physicist generally tries to identify and quantify nanomaterials’ fundamental interactions with different surrounding systems such as the thermodynamics, the interface of the nanoparticles with the liquid, and the role of mechanical properties (e.g., stiffness, elasticity, adhesion), etc.

Past three decades, extensive work has been performed to develop new drugs from natural products, because of the resistance of microorganisms to the existing drugs [46]. Researchers from the Indian Institute of Technology Bombay, India, have discovered that the age-old complementary medicines of Homeopathic pills and Ayurvedic Bhasmas are having metal nanoparticles such as gold, silver, copper, platinum, tin, and iron [46, 47]. Metallic nanoparticles (mainly silver and gold) have unique optical, electrical, and biological properties, that have attracted significant attention due to their potential use in many applications, such as catalysis, ultra-sensitive chemical and biological sensors, bio-imaging, targeted drug delivery and nanodevice fabrication [13, 48–57]. Recently, various industries like electronics, aerospace, cosmetics, textile, and even food use nanoparticles. Consequently, the chance of human exposure to nanoparticles rises, heading towards the time when nanoparticles are eventually present in blood circulation and interacting with immune blood cells.

Nanoparticles can be synthesized via various chemical and physical routes such as chemical reduction, [58–60] photochemical reduction, [61–65] electrochemical reduction, [66, 67] heat evaporation, [68, 69], etc. In all the above-mentioned methods, the reagents can be from different properties, i.e. inorganic such as sodium or potassium borohydrate, hydrazine, and salts of tartrate, or organic ones like sodium citrate, ascorbic acid, or amino acids, capable of getting oxidized. Various options are also available to work as a stabilizing agent. Several studies have reported shape and size dependency of silver nanoparticles formation on capping agents such as dendrimer, [70] chitosan, [71] ionic liquid, [72], and poly (vinylpyrrolidone) PVP [73]. These capping agents control the nanoparticle growth via reaction confinement within the matrix or preferential adsorption on specific crystal facets. Since these approaches are costly, hazardous, toxic, and non-environment friendly, hence, evaluation of the risk of these nanoparticles to human health becomes critical. Multiple studies have shown the increase in the number of leukocytes, mainly neutrophils, in the lungs and bronchoalveolar lavages during airway exposure of nanoparticles in-vivo models of inflammation. The neutrophil counts act as biomarkers for inflammation. Therefore, the selection of a synthesis route that minimizes the toxicity and increases nanoparticle stability leads to enhanced biomedical applications of silver and gold nanoparticles. The development of better experimental procedures for the synthesis of nanoparticles employing a variety of chemical compositions and controlled polydispersity offers considerable advancement [74]. Methods of nanoparticle production through different physical and chemical routes, as stated above, have their demerits as they produce enormous environmental contaminations.
and hazardous byproducts. Thus, there is a need for “green chemistry” that ensures clean, non-toxic, and environment-friendly nanoparticles production [75].

In recent years, environment-friendly approaches have been developed to fabricate stable nanoparticles with well-defined morphology and configured constricted sizes [76]. Additionally, owing to the high demand for precious metals (like silver and gold) and metal oxides in electronics, catalysis, medical, and other industrial applications, its recovery from primary and secondary sources is of considerable significance and interest. Biological recovery of these precious metals by preparing their nanoparticle is a green alternative to the conventional physical and chemical methods [77, 78]. Bio-inspired synthesis of nanoparticles is an advanced, cost-effective, environment-friendly approach over chemical and physical processes, without any inclusion of high pressure, energy, temperature, and toxic chemicals [79]. For example, the plant leaf extract is used for the biosynthesis of silver and gold nanoparticles for pharmaceutical and biomedical applications, without employing any toxic chemicals in the synthesis protocols [80]. An environmentally acceptable solvent system, eco-friendly reducing and capping agents are considered to be an essential element for an ultimately “green” synthesis [81]. The green synthesis techniques are generally utilizing relatively non-toxic chemicals to synthesize nanomaterials. The fabrication process also includes the use of non-toxic solvents such as water, biological extracts, biological systems, etc. In this technique, generally, microwave maintains a constant temperature of solvent systems. The conventional extraction technique using hexane, ethanol, and water was used to collect bioactive molecules [82]. However, they are immensely problematic due to instability as well as environmental and health hazards [83]. To overwhelm this problem, researchers developed a new approach, i.e., supercritical fluid (SCF) extraction technology for avoiding toxic organic solvents in green technology. SCF possesses physical properties intermediate between CO₂ gas and a liquid at a temperature and pressure above its critical point. Since supercritical CO₂ is non-polar, non-toxicity, non-flammability, and low critical temperature.

3 Benefits of Nanotechnology

Recently, research and development in nanotechnology have seen exponential growth due to advantages in different fields, i.e., drug delivery, cell imaging, material improvement, and medical devices for diagnosis and treatment. More powerful computers are being designed using nanomaterials in a smaller size, faster in speed, and consuming very less power, having long-life batteries. Circuits consisting of carbon nanotubes can maintain the computer system advancement. Carbon nanotubes are also commercially used in sports equipment, to increase their strength while maintaining a low weight. Nanoparticles or nanofibers in fabrics improve the water-resistance, stain resistance, and flame resistance, without putting on extra weight, stiffness, or thickness of the material. Nanoparticles are used in medical products for dermal, oral or inhalation applications, and pharmaceuticals. These are
also used in various consumer products, including cosmetics, food, and food packaging. The nanomaterials having potential uses in cosmetics include nanosilver, nanogold, nanoemulsions, nanocapsules, nanocrystals, dendrimers, fullerenes, liposomes, hydrogels, and solid lipid nanoparticles. Smaller the size, corresponding to the higher surface area of nanomaterials offer greater strength, stability, chemical, physical, and biological activity. Nanomaterials present in the human environment can be primarily classified into four categories: carbon-based nanomaterials, metal-based nanomaterials, dendrimers, and composites. The carbon-based nanomaterials (fullerenes and nanotubes) are employed in thin films, coatings, and electronics.

The metal-based nanomaterials (i.e., nanosilver, nanogold, and metal oxides (i.e., titanium dioxide (TiO$_2$)) are useful for food, cosmetics, and drug-related products. The dendrimers are nano-polymers, an ideal candidate for drug delivery. Composites such as nanoclays are formed with a combination of nanoparticles with other nanosize or larger particles. Many beverage bottles are made up of plastics with nanoclays. The nanoclay reinforcement increases permeation resistance to oxygen, carbon dioxide, moisture, and thus retaining carbonation, pressure with increased shelf life by several months. Nanoclays are also being used in packaging materials.

Different classes of nanomaterials are composed of nanoparticles with different shape, size, and chemistry and biology. Nanotechnology helps to improve vehicle fuel efficiency and corrosion resistance by building vehicle parts from Diamond-Like-Nanocomposite (DLN) materials that are lighter, stronger, and more chemically resistant than metal [84–88]. The DLN film exhibits biocompatibility in nature, which has potential applications as a coating material for biomedical purposes [89, 90].

A few nanometers wide water filters can remove nanosized particles, including virtually all viruses and bacteria, which can revolutionize the water filtration method. These cost-effective, portable water-treatment systems are ideal for the improvement of drinking water quality in developing countries. Nowadays, most sunscreens also contain nanoparticles for effective absorption of light, including the more dangerous ultraviolet range and passing the other wavelengths, which is healthy for the skin. Recently, nanosensors can be programmed to detect a particular chemical at low levels, such as a single-molecule detection, out of billions of molecules. This capability is ideal for security systems and surveillance at labs, industrial sites, and airports. In medical science, the detection of single biomolecules has tremendous DNA/RNA sequencing and disease analysis applications. The nanobiosensors can be used to precisely identify particular cells or substances in the body for different diagnostics purposes. Current research is focused on preparing the smaller, highly sensitive, and cost-efficient biosensors. The new biosensors are updated to even detect odors specific diseases for medical diagnosis, pollutant detection, and gas leaks for environmental protection. Figure 1 shows the technological tsunami that occurs due to nanotechnology in energy storage, defense & security, metallurgy & materials, electronics, optical engineering & communication, biomedical & drug delivery, agriculture & food, cosmetics & paints, biotechnology, textile, etc. [91]. According to Zion market research analysis in 2017 [92], there is a rapid increase of global nanomaterials market volume (in kilo tons) and revenue (in USD Billion), which is estimated from 2014 to 2022, is shown in Fig. 2a. Other statistical surveys
from two different agencies (see Fig. 2b and c (BCC research)) also confirmed the rapid increase of the global nanotechnology market of nanomaterials, nanotools, and nanodevices, etc. [93, 94].

4 Nanotechnology in Health

4.1 Potential Routes for Nanomaterials to Enter into the Human Body

Nanomaterials can enter into the human body in various ways. Potential routes nanomaterials enter the human body are ingestion, inhalation, and skin absorption [95–97]. Many nanomaterials are employed in drug transport or cell imaging via intravenous entry to the human body. In the body, nanomaterials are translocated throughout the body by blood circulation. For the purpose, the nanoparticles must fulfill the requirement of permeability across the barrier of the blood vessel wall. Absorption through the skin serves as an alternate route of entry for nanoparticles inside a human body. The skin is the largest organ of the human body, provides a large surface area for interactions with the external environment. TiO$_2$ nanoparticles can take either
Fig. 2  a Rapid increase in global nanomaterials market volume (Kilo Tons) and revenue (USD Billion) for the period of 2014–2022 [92]. Source Zion market research analysis, 2017. b The global market value of nanotechnology from 2010 to 2020 (in Billion USD) [93]. c Global nanotechnology review for nanomaterials, nanotools, and nanodevices market from 2011 to 2017 (in Million USD). Source BCC Research [94]

route for entry, i.e., the lungs or gastrointestinal tract. Nanomaterials can enter the body through the skin for various reasons, such as the use of medicine, cosmetics, ointments, and use of clothes containing nanomaterials, occupational contact in the industry, etc. Soaps, shampoos, toothpaste, hair gels, creams, and some cosmetics containing the nanosilver, which can enter into the body through the skin.

Cream or solution containing Silver nanoparticles is used to treat wounds, burns, etc. to prevent infections and damaged skin. The penetrating ability depends on the size of the nanoparticles. The smaller the nanoparticle, has the more exceptional penetrating ability. The inhaled particulate matter gets accumulate in the human respiratory tract, while one significant portion of those inhaled particles gets deposited in the lungs. Nanoparticles also can travel across the placenta in pregnant women to the fetus along with other organs, i.e., brain, liver, and spleen. The effects of inhaled nanoparticles in the body may include lung inflammation and heart disease problems [95]. The pulmonary injury and inflammation resulting from the inhalation of nanosized urban particulate matter appear due to the oxidative stress imposed by these particles in the cells [98–101]. The first reported nanoparticle is nanosilver, which can damage DNA molecules. Silver nanoparticles have the most harmful effects on the most sensitive biological groups [98, 102–105]. This nanoparticle can enter into the blood through the skin. Silver binds with the thiol group of some proteins. If
silver complexes with thiol groups are located near-skin region, it gets readily available to get reduced either by visible or UV light into metallic nanosilver particles. Therefore, the immobilization of silver nanoparticles takes place in the skin. Further, the effect of nano copper-induced renal proximal tubule necrosis in kidneys has been reported by Liao and Liu [106].

4.2 Nanomaterials for Therapy and Diagnostics

Nanoparticles in pharmaceutical products facilitate improved absorption within the human body and easy delivery, often in association with medical devices. For example, magnetite, a metal oxide, has high potential applications in nanomedicine. Nanoparticles can assist the targeted delivery of chemotherapy drugs to specific cells, i.e., cancer cells. Superparamagnetic iron oxide nanoparticles (SPIONs) and ultra-small superparamagnetic iron oxide (USPIO) have also proved its significance for targeted drug delivery [107]. Nanoparticles improve the solubility of poorly watersoluble drugs, increase drug half-life, modify pharmacokinetics, improve bioavailability, diminish drug metabolism, assist controlled and targeted, and combined drug delivery [98, 108–111]. According to the International Agency for Research on Cancer (IARC) data, estimates of nearly 13.1 million deaths due to cancer by 2030. It is evident that the low survival rate occurs not because of the scarcity of potent, natural, or synthetic antitumor agents but owing to inadequate drug delivery systems. Hence develops the requirement of technology advancement to establish carriers and delivery systems capable of targeted and efficient delivery of the chemotherapeutic agents without unwanted systemic side effects [112]. The solid lipid nanoparticles and nanoemulsions are the most employed lipid-based drug delivery particles. However, nanosilver based commercial products are capturing the market. The newly developed nanomaterials for theranostics are being employed alone or in association with “classical” drugs, e.g., cytostatic drugs, or antibiotics. Theranostics is a combined term for nanomaterials with diagnostic and therapeutic properties [111].

5 Drawbacks of Nanotechnology

Nanomaterials are being employed in different industries and everyday life. Therefore, the interplay of nanomaterials and social surroundings is worth scientific exploration. Nanomaterials with several benefits can be toxic. Various studies also confer the effects, as mentioned above, indicating the potential toxicological effects on the human environment [98]. Different toxic and hazardous effects of nanotechnology are briefly discussed below.
5.1 Toxicity of Nanomaterials

Greater human exposure of nanomaterials presents in the environment; more significant is the harmful effect on human health. The assessment of the cytotoxicity of nanomaterials assists in the proper elucidation of the biological activity. Gerloff et al. reported the cytotoxicity of various nanoparticles, such as zinc oxide (ZnO), SiO$_2$, and TiO$_2$, on human Caco-2 cells [113]. Shen et al. [114] showed the human immune cells are prone to toxicity due to ZnO nanoparticles [115]. The ZnO nanoparticles damage mitochondrial and cell membranes in rat kidney, ultimately leading to nephrotoxicity [115]. Generally, the nanomaterial toxicity mechanism comprises reactive oxygen species formation and genotoxicity. However, as described earlier, the toxicity of ZnO nanoparticles mainly affects immune cells. Various nanomaterials with their diverse sizes alter mitochondrial function. For example, ZnO nanoparticles generate Zn$^{2+}$ ions, which disrupts charge balance in the electron transport chain in the mitochondria and therefore triggers reactive oxygen species generation. Nanosilver particle has a genotoxic effect. A 20-nm nanosilver has a genotoxic effect on human liver HepG2 and colon Caco2 cells. It has also increased mitochondrial injury and the loss of double-stranded DNA helix in both cell types [116]. Inhalation of TiO$_2$ nanoparticles resulted in pulmonary overload in rats and mice with inflammation [117, 118]. The cytotoxic and genotoxic effects of TiO$_2$ nanoparticles on the human lung were reported by Jugan et al. [119]. TiO$_2$ nanoparticles are genotoxic, and it can induce pathological damage of the liver, kidney, spleen, and brain. Du et al. reported cardiovascular toxicity of silica nanoparticles in rats [120]. The surface coating of quantum dots causes toxicity to the skin cells, including cytotoxicity and immunotoxicity [121]. Nanosilver is used in wound dressings, affects both keratinocytes and fibroblasts. Fibroblasts show higher sensitivity towards nanosilver than by keratinocytes. Again, iron oxide nanoparticles rapidly get endocytosis on cultured human fibroblasts and interrupt the function. Citrate/gold nanoparticles have shown toxicity on human dermal fibroblasts [122]. Carbon nanotubes have high toxicity and produce harmful effects on humans. The nanoparticles can penetrate the lungs, then reached the blood and acted as a barrier for the circulation of blood into the brain. They can also enter inside other organs like bone marrow, lymph nodes, spleen, or heart. Sometimes, nanoparticles can incite inflammation, oxidant and antioxidant activities, oxidative stress, and change in mitochondrial distribution. These effects depend on the type of nanoparticles and their concentrations [101]. Copper nanoparticles (diameters 40 nm and 60 nm) harm brain cells at low concentrations. It activated the proliferation of the endothelial cells in brain capillaries. Ag nanoparticles (25, 40, or 80 nm) influenced the blood-brain barrier, causing a pro-inflammatory reaction, which might induce a brain inflammation with neurotoxic effects [123]. Smaller Ag nanoparticles (25 nm and 40 nm diameter) can induce cytotoxic effect at a higher rate than larger nanoparticles. Nanoparticles also have harmful effects on the brain cell of the mouse and rat. The high concentration of nanoparticles can affect brain blood fluxes, with consequent cerebral edema. Pathogenic effects of Ag-nanoparticles (25, 40, and 80 nm diameter), Cu-nanoparticles (40 and 60 nm), and Au-nanoparticles
(3 and 5 nm) on the blood-brain barrier of the pig have been reported [124]. Silver nanoparticles (45 nm) influenced the acetylcholine activity via nitric oxide generation; it induces hyperactivity of rat tracheal smooth muscle [125]. It is also reported that Ag- nanoparticles (25 nm) produced oxidative stress after the injection into the mouse. The nanoparticles were aggregated in the kidneys, lungs, spleen red pulp, and the nasal airway, with no observable morphological changes apart from the nasal cavity [126].

Very few cells do not undergo morphological changes after withstanding the air-liquid interface culture for an extended duration. Au-nanoparticles (5 nm and 15 nm diameter) penetrated the mouse fibroblasts, where they remained stocked. Only the presence of 5 nm Ag-nanoparticles disrupted cytoskeleton resulting in narrowing and contraction of cells. Many engineered nanomaterials, such as TiO2, magnetite iron, CeO2, carbon black, SWCNTs, and MWCNTs, also might cause different levels of inflammatory reactions, including enhanced pro-inflammatory cytokines expression, target inflammation-related genes, and micro-granulomas formation [127, 128]. The intra-tracheal administration of MWCNTs with variable length and iron content in hypertensive rats Led to the lung inflammation with increased blood pressure and lesions in abdominal arteries along with accumulation in multiple organs i.e., liver, kidneys, and spleen post seven days and 30 days exposure [129]. Maneewattanapinyo et al. studied acute toxicity of colloidal silver nanoparticles administered in laboratory mice and observed no mortality any acute toxicity symptoms after a limited dose of 5.000 mg/kg post 14 days of oral administration. No differences could be observed among groups after hematological and biochemical assessment and the histopathological study. The instillation of silver nanoparticles at the concentration of 5.000 ppm developed a transient eye irritation for 24 h. The application of these nanomaterials on the skin did not produce any micro or macroscopic toxicity [130]. The schematic mechanism of silver nanoparticle’s toxicity in the human body is shown in Fig. 3 [131]. The liver and spleen are maximum exposed organs to nanomaterials owing to the prevalence of phagocytic cells in the reticuloendothelial system. Also, the organs with high blood flow, such as kidneys and lungs, can be affected.

5.2 Health Hazards in Human

Despite having many benefits and using nanomaterials, it may cause health hazards to humans due to a tiny size. The broad absorption surface of the lung, the thinner air–blood barrier, and comparatively less inactivation of enzymes leads to faster entry for particles into the systemic blood circulation at higher drug concentrations. Additionally, intended uptake, exposure of airborne particles from the environment, and nanoparticles released during the manufacturing process may also cause health hazards for humans. Usually, nanomaterials’ biological effects are based on their size, composition, shape, and even on their electronic, magnetic, optical, and mechanical
properties. Presently, the influence of nanotechnology on human health and the environment is still controlled. Most of the studies assessed the outcomes of unintentional and accidental exposure (inhalation, medical procedures, or accidental ingestion) and focused only on local effects [98, 99]. Though, along with introducing nanomaterial-based biomedical methods, it is mandatory to analyze their toxicity at a systemic level. Centuries before, Paracelsus said, “everything is a poison, and nothing is a poison, it is only a matter of a dose.” For nanomaterials, it is applicable in both the aspects of dose and particle size [100]. There is a massive demand for nanomaterials in various applications, ranging from diagnostic technology, bio-imaging, to gene/drug delivery [132–145]. Therefore, intended or unintended human exposure to nanomaterials is unavoidable and has higher prospects of exposure. Thus, a branch of science is developing, named “nanotoxicology”, the study of the toxicity of nanomaterials. Nanotoxicology assesses the role and safety of nanomaterials on human health. Several anthropogenic sources, like power plants, internal combustion engines, and other thermo-degradation reactions also generate nanoparticles and develop the need to assess them [101].
5.2.1 Hazards in Nanomedicine

The nanomaterials represent a variety of biomedical applications. However, there is some potential risks factor related to the toxic issue. For example, oxidative stress, cytotoxicity, genotoxicity, and inflammation have been reported on in vitro and in vivo models for testing nanoparticles. The difference in the size of nanomaterial and bulk comes with the differences in properties and toxicity. Nanomaterials are tremendously beneficial yet can be toxic. Ag, ZnO, or CuO nanoparticles are frequently used as bactericides [102]. Nevertheless, waste disposal in the environment can also negatively affect non-target organisms.

5.2.2 Hazards in Medical Instrumentation

Nanomaterials are involved in medical interventions like prevention, diagnosis, and treatment of diseases. More functional and accurate medical diagnostic equipment are being designed for easy and safe operation. The lab-on-a-chip technology facilitates real-time point-of-care testing, enhancing the standards of medical care. Nanomaterial based thin films on implant surfaces improve the wear and resist infection. However, until now, these medical nanodevices are not 100% hazard free due to manufacturing processes, not following guidelines of nanotoxicity, and operating without the assessment of long term effects of nanotoxicity.

5.2.3 Hazards in Food Product

Nanotechnology is used to produce advanced food products and smart packaging technology [146–148]. In this way, the possibility of direct exposure to nanomaterials with human beings is enhanced, and different types of long-term or short-term toxicity may occur [149–151]. Nanoparticles and diamond-like nanocomposite (DLN) thin films are used in food packaging to reduce UV exposure and prolonged shelf life. Due to very few articles being reported in this area, further research is needed to fully explore the potential use of these nanoparticles for food products and medical treatments.

6 Environmental Nanopollution and Its Effect in Society

Environment conservation is a challenging task. Its vastness and complexity make this even more difficult. As nanomaterials’ production is growing, multiple issues concerning nanotechnology arise as environmental pollution and industrial exposure. Nanoparticles serve as pollutants in diesel exhaust or welding fumes, presenting new toxicological mechanisms [152, 153]. It also makes us face pollution in macro, micro,
and nanoscale. New branches of electronics are also creating new sources of occupational exposure hazard. The circumstances produce new challenges for both classical toxicology and nanotoxicology. Though nanotechnology improves the living standard, a simultaneous increase in water and air pollution has also occurred. As the origin of this pollution lies in nanomaterials hence termed “Nanopollution.” Nanopollution is exceptionally lethal to both underwater flora and fauna and organisms living on soil. The pollutants can enter the human body in multiple ways. Cellular mechanisms can get affected by nanomaterial toxicity, which mainly comprises reactive oxygen species generation and genotoxicity [153–155]. The nanoparticle’s exposure on humans can occur accidentally by environmental particles (e.g., air pollution) and intentionally because of a variety of consumer products, cosmetics, and medical products containing nanoparticles. The release of nanoparticles during the manufacturing process may result in exposure to workers via dermal, oral, and inhalation routes. Exposure to air pollutants, such as ultrafine particles, is known to cause inflammatory airway diseases and cardiovascular problems in humans [156]. Pope et al. [157] stated that even low levels of ambient nanoparticle exposure have a significant effect on mortality. To decrease nano pollution, scientists and researchers used nanotechnology to develop nanofilters, eliminating almost all airborne particles [158].

7 Social-economic Disruption Due to Rapid Use of Nanotechnology

As the speed of nanotechnology development is growing, as a consequence, the job opportunities are decreasing, arising the problem of unemployment in fields like industrial sector, manufacturing, and traditional farming [159, 160]. Nanotechnology-based devices and machines have replaced humans to furnish the job more rapidly and efficiently, which has pointed out the importance of human resources in practical work. Increasing growth and instant performance of nanotechnology have compromised the worth of commodities like diamond and oil. As an alternative technology, i.e., Nanotechnology has a detrimental effect on demand as substitutes have more efficiency and do not need fossil fuels. Diamonds are losing the worth due to greater availability from nanotechnology-based fabrication methods. Currently, manufacturing companies are equipped to produce the bulk of these products at a molecular scale, followed by disintegration to create new components.

At present, nanotechnology involves high investment technologies, raising the cost daily. The high price is the result of intricate molecular structure and processing charges of the product. The whole process makes it difficult for manufacturers to produce dynamic products using nanotechnology randomly. Currently, it is an unaffordable business owing to the massive pricing of nanotechnology-based machines. Hence, nanotechnology can also bring financial risks as manufacturers have to invest a large sum of money for setting up nanotech plants. The manufacturers have to
face a considerable loss if, by any chance, the manufactured products fail to satisfy the customers. Alternate options such as the recovery of the original product or maintenance of the nanomaterials are also a costly and tedious affair.

Further, nanotechnology does not leave any byproducts or residues, generally based on small industries, therefore creating a considerable risk of extinction for small scale industries. As an outcome, the quantity of sub-products of coal and petroleum is deteriorating. Another massive threat, like the Covid-19 pandemic situation, may be born with the arrival of nanotechnology. It can make the easy accessibility of biochemical weapons or nano-bio engineered biological weapons. Nanotechnology is making these weapons more powerful and destructive. Unauthorized criminal bodies or corrupt politicians can steal the formulations and may reach these dangerous weapons easily, and they can quickly destroy our civilization [161].

8 Effect of Nanotechnology on Microorganisms, Animals, and Plants

Some nanomaterials are hazardous to human beings and are also harmful to the existence of different microorganisms, animals, and plants. Human-made nano pollution is very unsafe for living microorganisms, animals, and plants under the water or on the earth. As a result, many of microorganism’s families have entirely disappeared from the world. Due to the rapid application of nanotechnology in the agriculture sector without proper nanotoxicological analysis, many plants are directly exposed to nanotoxicity, and animals are indirectly exposed. Thus, in the last two decades, a vast number of valuable plants and animals are entirely disappeared from our world.

9 Safety and Security of Nanotechnological Developments

Nanotechnology is an extensively expanding field. Researchers, scientists, and engineers are getting high success in producing nanoscale materials and taking advantage of enhanced properties, such as higher strength, lighter weight, increased electrical conductivity, and chemical reactivity compared to their larger-scale equivalents [162, 163].

Human health concerns are also growing due to nanomaterials. The attempts of technological manipulations raise the vocational risk to the workers in case of accidental exposures. The ethical issues regarding the poisoning of mass material are processed at a nanoscale, causing adverse effects on the health and industry. Mass poisoning occurs in the case of toxic micro particles coatings on the products. These microparticles penetrate inside the brain, while in contact with humans. Academic and industry experts suggest that there exists ambiguity regarding the toxic effects of releasing nanoparticles into the environment. It is also noteworthy that there is a lack
of knowledge of nanoparticles interactions with humans and the environment. Similar to most of the emerging technologies, nanotechnology, and nanochemistry industries have both benefits and challenges. To obtain maximum benefits, the problems must be overcome, managed, and endured. In combination with other inorganic or organic counterparts, mesoporous silicates have been extensively explored for targeted drug delivery and cancer treatment. Even though the long-term toxicity of the nanoparticles is subjected to controversies and doubts, the use of gold and silver nanoparticles have provided more advantages in comparison to other actual alternatives (cytostatics).

Consequently, there is a growing interest in developing in vitro assays for nanotoxicology study [164]. It is strongly encouraged to use primary human cells as a source for in vitro study with nanoparticles since different origins of cancerous cell lines complicate data interpretation for human risk evaluation. Till now, the environmental effects and the toxicity of nanomaterials to organisms are in the infancy state. The evaluation methods need to be cost-effective rapid, and quantity efficient.

10 Current Policy and Regulation Status

The social implications of nanotechnology comprise many fundamental aspects like ethics, privacy, environment, and security. Occasionally, the negative impacts on the environment are too averse to handle that the people simply give up. However, nanoscience researchers are still optimistic about seeing the light of hope on the other side of the tunnel. Environmental clean-up is possible via the design and manipulation of the atomic and molecular scale of materials. It would develop cleaner energy production, energy efficiency, water treatment, and environmental remediation. Nanoscale fluid dynamics decipher the flow of nanoparticles in the environment as a result of interactions with biological and ecological systems. Researchers are keen to understand the transportation of nanomaterials in association with environmental contaminants through groundwater systems. For food authenticity, safety, and traceability, every food company should need to use smart labels at more robust and innovative functional lightweight packaging. Each developed and developing countries have a separate policy and regulation for the use of nanotechnological products and applications. Explicit initiatives on nanotechnology must be needed to promise that the opportunity provided by nanotechnology is not misused, and research does not become fragmented. The uncertainty, complexity, and diversity of nanotechnology mean that any initiative should not be a strictly preconceived closed program. Flexibility will be needed to stay side by side of development as they arise.
11 Challenges and Future Trends in Using Nanomaterials in Humans

Nanotechnology-based production uses minimal human resources, land, maintenance, and it is cost-effective, high productivity with modest requirements of materials and energy. The extensively growing field offers scientists and engineers an excellent opportunity to manipulate or alter the nanoscale materials to yield benefit of enhanced material characteristics like increased strength, lightweight, higher electrical conductivity, and chemical activity in comparison to their large-scale counterparts. However, for biomedical applications, the toxicity evaluation of nanomaterials should be performed. Broadly, detailed physicochemical characterization of nanomaterial should be performed before and during any toxicity study. Essential properties can control nanomaterial-induced toxicity, including size and shape of the nanomaterials, coating, chemical composition, crystal growth, nanomaterials purity, structure, surface area, surface chemistry, surface charge, agglomeration, and solubility should also be taken care. Measurements should be performed in a sufficiently stable state of nanomaterials in the most suitable test medium, i.e., aggregation status and ion release from metallic nanomaterials. Various engineered materials should be tested for their multidisciplinary tiered toxicity using diverse models and experiments [165, 166]. Therefore, the first step in genotoxicity is an assessment of the physicochemical properties of nanomaterials. The validation of the proposed tiered approaches still waits for the future. The researchers are continuously trying to increase the relevant database with an increasing number of publications (papers, reviews, or even patents) every year [167], particularly the market share of the nanotechnology products is also growing up to thousands of billions of Euros [168]. Balanced use of the nanotechnologies/nanomaterials must be arranged to optimize the opportunities/risks factors.

Further studies related to the influence of size and shape, capping agents, receptors immobilization onto the metal nanoparticles are still necessary. Varying sizes can tune surface plasmon resonance, the shape of the nanomaterials and different surface functionalization of both silver and gold nanoparticles can reduce the toxicity and enhance a variety of biomedical applications in the future. For example, CNT toxicity can be reduced via functionalization, surface coating, and stimulation of the autophagic flux. The amino functionalization decreases the CNT toxicity to the cells [169] and albumin coating for SWCNTs [170]. We have summarized some comparative points about the advantages and disadvantages of nanotechnology discussed throughout our review in the form of the following Table 1.

12 Conclusions

Nanoparticles can enter and get distributed around the human body very easily. After entering into humans, it moves within the body and creates cellular toxicity. Then it attacks the respiratory system, cardiovascular system, brain, skin, gut, and other
| Advantages                                                                 | Disadvantages                                                                 |
|----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Early-stage detection of some diseases                                    | Still at its infancy stage                                                     |
| Reduction of the size of any material, machine or equipment               | More research and developmental work need to be done                           |
| Reduction of the amount of energy and resource                            | Expensive technology till now                                                  |
| Helps to clean up the existing nano-pollution                             | Creates environmental nano pollution                                           |
| Able to secure the economy once it can be fully implemented               | It can create social-economic disruption in society                            |
| Applicable and implementable to most of the applications ever existed     | The huge initial cost for implementation                                        |
| Can alter the basis of technology for human, in its matured phase         | Resistance from a culture perspective, activists, journalists and even within the government |
| Improvement of the therapeutic drug index by increasing efficacy and/or reducing toxicities | Knowledge limitation from many industries and misperception among many fields about its capabilities. |
| Targeted delivery of drugs in a tissue-, cell- or organelle-specific manner | The government does not regulate nanomaterials                                 |
| Enabling sustained or stimulus-triggered drug release                      | Requirement of significant investment and research but yield is still a limiting factor |
| More sensitive cancer diagnosis and imaging                               | Some nanoparticles may be toxic to humans                                      |
| Better pharmaceutical properties (i.e. stability, solubility, circulating half-life and tumor accumulation) of therapeutic molecules | Nanotechnology made weapons are more powerful and more destructive by increasing the explosion potential |
| Provision of new approaches for the development of synthetic vaccines     | Lack of employment in the fields of traditional farming, manufacturing, and industrial sector |

organs. Some nanomaterials kill harmful bacteria within the body, and some kill good bacteria and live-cells of the human body. Nanoparticles with different substances are used in SIM cards of cell phones or sunscreens. When these are used, free nanoparticles get released in the environment (air, water, or soil). Engineering fields like civil and electronics also create new occupational health risks, making new, potentially toxic nanomaterials. The toxicity of nanoparticles depends on their shape, size, and chemical composition. Centuries before, Paracelsus quoted, “everything is a poison, and nothing is a poison, it is only a matter of a dose.” In regards to nanomaterials, the quotes hold value for both dose and particle size. The new interdisciplinary investigations explore the potentially harmful effects of these useful NPs and help in environmental preservation. Owing to a smaller size, the inhalation of nanomaterials imposes an adverse impact on human health. The inhalation causes severe injury to the lungs and can also become fatal. The deterioration of lungs can be observed even after the 60s of nanoparticle inhalation. Therefore, for sustainable nanotechnology development, it is mandatory to evaluate and spread knowledge about the short term and long term exposure benefits and hazards for nanomaterials.
To conclude, nanotechnology has the potential to impact society, both positively or negatively. Its consumers, producers, and dealers include all the community members and all stakeholders, so we should collectively raise the voice in its various growth and commercialization phases. Nanotechnology is currently in its infancy stage, with a significant lack of awareness about its effects on humans and the environment. As civilization moves forward, the vital query is: how should we manage the risks and uncertainties of this emergent technology? Is anyhow the COVID-19 pandemic situation human-made? If not, we can face such circumstances due to the careless application of nanotechnology in different fields.

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