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Nanotechnology at the Frontiers of Societal Transformation: Opportunities, Impacts, and Future Directions

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Abstract- Nanotechnology has emerged as a transformative field with the potential to reshape multiple dimensions of society through the manipulation and application of materials at the nanoscale. The distinctive optical, electrical, mechanical, chemical, and biological properties of nanomaterials have enabled advances across healthcare, environmental sustainability, agriculture, energy, electronics, transportation, and consumer products. This review provides an overview of major nanomaterial classes, their synthesis, fabrication, and characterization, and examines their growing contributions to societal transformation. Particular attention is given to nanomedicine, targeted drug delivery, medical diagnostics, cancer therapy, nano-enabled agriculture, water purification, environmental remediation, nanoelectronics, energy generation and storage, and lightweight automotive materials. Beyond technological applications, the review discusses the broader socioeconomic and societal implications of nanotechnology, including employment opportunities, public acceptance, privacy, security, and environmental risks. Although nanotechnology offers considerable opportunities for improving human health, resource efficiency, environmental sustainability, energy performance, and economic development, its widespread implementation is accompanied by challenges related to nanomaterial toxicity, environmental fate and bioaccumulation, high production costs, technological scalability, uncertainty, public awareness, privacy, and security. Addressing these challenges requires interdisciplinary research, improved risk assessment and characterization methods, responsible innovation, effective regulation, transparent communication, and stronger consideration of the entire nanomaterial life cycle. The responsible development and commercialization of nanotechnology can contribute substantially to societal transformation while ensuring that technological progress is aligned with human health, environmental protection, security, and sustainable development

Keywords- Nanotechnology, nanomaterials, sustainability, societal impact, public acceptance

I. INTRODUCTION

Over millennia, scientists have envisioned technological and instrumental advancements enabled by nanotechnology, which involves manipulating matter at the atomic scale and has generated considerable expectations for scientific and technological progress [1]. Although the historical origins of nanotechnology remain debated, its conceptual development is commonly associated with early ideas concerning the manipulation of matter at very small length scales [2] and, more prominently, with Richard Feynman's 1959 lecture, "There's Plenty of Room at the Bottom," which highlighted the scientific and technological possibilities associated with controlling matter at extremely small dimensions [3, 4].

The development of nanoscale characterization, synthesis, fabrication, and manipulation techniques transformed these early concepts into a rapidly expanding scientific and technological field. Nanomaterials can be classified according to their dimensionality as 0D (e.g., nanoparticles), 1D (e.g., nanorods and nanotubes), 2D (e.g., graphene), and 3D (e.g., nanoprisms) [5]. Their distinctive characteristics arise largely from their high surface area, durability, and electrical conductivity [6]. These characteristics provide opportunities to tailor material properties through controlled synthesis, surface functionalization, nanofabrication, and structural organization.

For instance, gold nanoparticles exhibit a red color rather than the characteristic golden appearance of bulk gold, while aluminum, which is relatively stable at the macroscopic scale, can become combustible at the nanoscale [7]. Such size-dependent behavior has enabled nanotechnology to support the development of a wide range of applications, including cosmetic products [8-10], pharmaceuticals [11, 12], information and communication technology [13], defense, automobiles [14, 15], sports [16, 17], chemical synthesis [18], water purification [19, 20], magnetic and electrical applications [21, 22], food industry [23, 24], biotechnology [25].

The resulting technological advances have extended nanotechnology across diverse sectors with direct implications for everyday life and socioeconomic development. Beyond improving the performance of individual products, these developments have contributed to broader transformations in healthcare delivery, energy conversion and storage, environmental protection, manufacturing, communication, and food production [26].

However, the transformative potential of nanotechnology is accompanied by complex challenges. For instance, the rapid development and widespread application of nanotechnology raise important ethical, environmental, health, legal, and social concerns that must be carefully considered to ensure its safe, equitable, and responsible advancement. Thus, the societal transformation associated with nanotechnology cannot be evaluated solely in terms of technological performance or economic potential; it must also consider the broader consequences of its development, deployment, and integration into society.

Therefore, this review provides a comprehensive perspective on nanotechnology as a driver of societal transformation, highlighting its major opportunities and applications across healthcare, energy, environmental sustainability, food, agriculture, information and communication technologies, and other emerging sectors. Finally, the review discusses emerging trends, future opportunities, and the research, policy, and governance directions required to harness the transformative potential of nanotechnology while mitigating its associated risks.

II. FUNDAMENTALS AND EMERGING NANOTECHNOLOGY PLATFORMS

A. Major Classes of Nanomaterials

Nanomaterials can be categorized according to the number of dimensions that extend beyond the nanoscale. Accordingly, they are generally classified as 0D (e.g., nanoparticles), 1D (e.g., nanorods and nanotubes), 2D (e.g., graphene), and 3D (e.g., nanoprisms) [5] Alternatively, nanomaterials can be grouped into five categories according to factors such as their potential toxicity, pore size, origin, structural configuration, and dimensionality or size [27]. Nanoparticles can also be classified according to their material composition. Based on the type of constituent material, they are broadly divided into carbon-based nanomaterials, metallic nanomaterials, ceramic nanomaterials, biomolecule-derived nanomaterials, and polymeric nanomaterials, as illustrated in Fig.1.

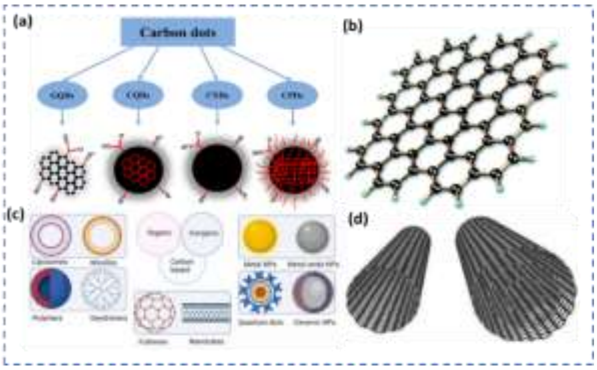

Figure 1. Types of nanomaterials (a) classification of carbon dots [28] (b) Graphene [29] (c) Illustration of different nanoparticles [30] (d) Carbon nanotubes [31]

(i) Carbon-based nanomaterials

Carbon-based nanomaterials are recognized for their outstanding properties and have found extensive applications across various fields. Among the most widely studied members of this category are carbon nanotubes (CNTs), graphene, and carbon quantum dots (CQDs) [32].

Carbon nanotubes

CNTs possess interior diameters on the nanometer scale and lengths that can extend to micrometers. They are among the most remarkable carbon allotropes and have a cylindrical structure formed by rolling graphene sheets into tubular configurations. This structural arrangement results in distortion of the sp2 hybrid orbitals and the formation of a σ-p rehybridized structure [33, 34]. CNTs can be synthesized through several techniques, including laser ablation, carbon arc discharge, chemical vapor deposition, and electrolysis. They are broadly categorized into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs consist of a single graphene sheet rolled into a tubular structure, whereas MWCNTs comprise two or more concentrically rolled graphene sheets. These structures can adopt three main configurations: chiral, armchair, and zigzag [34]. Adjacent graphene layers in MWCNTs are held together by van der Waals forces and separated by an interlayer distance of approximately 0.34 nm. Depending on the diameter and helicity of the graphitic rings, SWCNTs can exhibit either metallic or semiconducting behavior [35].

In addition, CNTs also possess high electrical conductivity, with reported values of approximately 102 to 106 S cm-1 for both SWCNTs and MWCNTs, together with exceptional thermal conductivity values of about 6000 W m-1 K-1 for SWCNTs and 2000 W m-1 K-1 for MWCNTs [36, 37]. Their high tensile strength makes them suitable as reinforcing agents in a wide range of composites and products. However, chemical treatment can deteriorate the properties of SWCNTs because defects may arise from the breaking of carbon-carbon bonds. In contrast, MWCNTs can largely retain their properties because chemical modification primarily affects their outer surface [38]. Although MWCNTs generally possess lower pore volume and specific surface area than SWCNTs due to their more complex structure, they offer several advantages, including lower production costs and the possibility of catalyst-free synthesis.

Graphene

Graphene has attracted considerable attention since its first synthesis through mechanical exfoliation in 2004. It consists of a one-atom-thick layer of sp2 hybridized carbon atoms arranged in a honeycomb-like crystal lattice [39, 40]. It exhibits very high thermal conductivity (5000 W m-1 K-1), excellent transparency (97.7%), outstanding carrier mobility (200,000 cm2 V-1 s-1), a high theoretical surface area (2630 m2 g-1), and excellent electrical conductivity (2000 S m-1) [41]. Graphene also demonstrates an extraordinary quantum Hall effect, high chemical and mechanical strength, and relatively low production cost [42, 43]. Graphene derivatives, including graphene oxide (GO), which is produced from graphite powder, and reduced graphene oxide (RGO), which is derived from graphene and contains oxygen-based functional groups [44], can be synthesized through chemical, electrochemical, or thermal processes. Graphene exhibits excellent performance in electrochemical applications and can be produced through various approaches, including exfoliation and cleavage, thermal or plasma-based chemical vapor deposition, chemical methods, thermal decomposition of SiC and other substrates, and CNT unzipping [45].

Carbon nanodots (CNDs)

Carbon dots are zero-dimensional nanostructures with fluorescent properties and particle sizes below 10 nm. They were accidentally discovered during the purification of single walled carbon nanotubes [46, 47]. Carbon dots can be categorized into carbon nanodots (CNDs), carbon quantum dots (CQDs), and graphene quantum dots (GQDs) [28, 48]. CNDs are generally described as amorphous carbon nanoparticles without quantum confinement, whereas CQDs and GQDs possess crystalline structures and exhibit quantum effects. In general, all quasi spherical carbon nanoparticles can be classified as carbon dots [49].

CQDs contain oxygen and nitrogen based functional groups on their surfaces, including amino (−NH2), carboxyl (−COOH), and hydroxyl (−OH) groups, which contribute to their water solubility, most likely through hydrogen bonding [50]. In addition, carbon dots possess various surface functional groups capable of binding with ions, chemical molecules, polymers, DNA, and proteins. Such interactions can modify their properties, allowing functionalized carbon dots to be tailored for specific requirements in different applications. CNDs can be synthesized through numerous methods, including electrochemical synthesis, combustion, thermal, hydrothermal, and acidic oxidation, microwave and ultrasonic synthesis, arc discharge, laser ablation, and plasma treatment [48, 51]. Compared with conventional nanomaterials such as cadmium, lead, rare earth materials, and metal oxides, carbon dots exhibit superior photostability, higher quantum yields, lower toxicity, and excellent biocompatibility. Some can also be produced from abundant and inexpensive sources. These characteristics make them promising materials for applications in biomedicine, optoelectronics, sensing, and catalysis [52].

(ii) Metallic nanomaterials

Metal-based nanomaterials can be categorized into metal nanoparticles (NPs), metal oxide NPs, bimetallic NPs, and trimetallic NPs [53, 54]. Commonly used metal oxide NPs include Fe2O3, Al2O3, TiO2, SiO2, CuO, SnO2, and WO3.

Their distinctive physicochemical properties originate from their nanoscale dimensions and high density of surface sites located at corners and edges. Metal oxide nanoparticles are particularly important for applications in sensing, catalysis, energy storage, antimicrobial systems, medicine, and optoelectronics [55, 56]. They are commonly synthesized using sol-gel and hydrothermal methods. Similarly, Bimetallic nanoparticles, which consist of two different metals, have attracted greater scientific and technological interest than monometallic nanoparticles [33, 34]. They can be prepared by combining different metallic nanoparticle structures and exhibit size-dependent optical, electrical, thermal, and catalytic properties [57]. Bimetallization enhances nanoparticle catalytic performance, while electronic effects drive charge-transfer processes in bimetallic catalysts.

Trimetallic nanoparticles, in contrast, contain three different metals. Trimetallic catalysts generally exhibit superior performance compared with bimetallic catalysts because their catalytic properties can be more effectively tuned [58]. These nanoparticles can be synthesized through microwave-assisted methods, selective catalytic reduction, microemulsion, coprecipitation, and hydrothermal techniques. However, their unstable surface area and tendency to rapidly precipitate from liquids can restrict their catalytic activity [59]. Consequently, stabilizing agents such as block copolymers, organic ligands, surfactants, and dendrimers are commonly employed for trimetallic nanoparticles [59, 60].

Importantly, these different nanomaterial classes have been extensively utilized in diverse applications because their properties depend strongly on particle size and shape. For instance, AuNP solutions have been reported to exhibit a bright red color when the particle size is below 100 nm, whereas larger particles produce a dull yellowish color [61, 62]. Similar color variations can also occur between rod-shaped and spherical AuNPs. Compared with their bulk counterparts, certain metal nanoparticles, including Au and Ag, exhibit remarkable optical, electrical, and chemical properties because of their smaller particle sizes, larger surface areas, and higher reactivity. Owing to their specific antibacterial properties, AuNPs are commonly employed in optical sensing and imaging applications.

(iii) Ceramic-based nanomaterials

Ceramic nanomaterials generally consist of metal or metalloid oxides, carbides, phosphates, and carbonates, including materials based on calcium, titanium, and silica [63, 64]. Their nanoscale porous structures provide resistance against deterioration and degranulation. Nanoceramics can be classified into nanoparticles, nanoscaffolds, and nanoclays [65]. Their favorable characteristics, particularly high thermal resistance and chemical inertness, enable their use across a wide range of applications. They have received considerable attention in biomedical applications because their size can be controlled and their surfaces can be readily functionalized [66, 67]. In addition, ceramic nanomaterials possess excellent mechanical strength and resistance to changes in pH. They also exhibit high loading capacity and can be readily incorporated into both hydrophobic and hydrophilic systems.

(iv) Polymeric nanomaterials

Polymeric nanomaterials, with particle sizes ranging from 1 to 1000 nm in at least one dimension, have attracted substantial interest across numerous scientific fields, mainly because of their considerably increased surface area to volume ratio [68, 69]. Compared with bulk polymers, they exhibit improved optical, thermal, and electrical properties. Their major applications include drug delivery, separation, catalysis, nanoreactors, and surface coatings. They are ideal materials because of their controlled biodegradability and biological safety [70].

In drug delivery systems, polymeric NPs are commonly composed of biodegradable and biocompatible polymers. They function as drug carriers by encapsulating or entrapping therapeutic agents [71-73]. Examples of polymers include poly(D,l-lactide) (PLA), poly(D,L-glycolide) (PLG), polyalkylcyanoacrylates, and poly-Ɛ-caprolactone. These polymers are generally considered safe, and several biodegradable polymer compounds have been approved by the US Food and Drug Administration (FDA) and the European Medicines Agency (EMA) for pharmaceutical applications [74]. Pharmaceutical agents can be physically or chemically adsorbed onto the surfaces of polymeric NPs. Their small size, water solubility, low toxicity, long shelf life, and high stability make them effective drug carriers [72].

(v) Biomolecule-derived nanomaterials

Cellulose, keratin, collagen, and silk are readily available biological raw materials with attractive material properties. They constitute an important area of biomaterial research because of their favorable chemical, biological, and mechanical characteristics required for biomaterial processing and fabrication [75]. Consequently, proteins, lipids,

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polysaccharides, nucleic acids, and other biomolecules have been successfully employed in the synthesis of nanomaterials [76-78].

Although these nanoparticles previously received less attention than inorganic nanomaterials, increasing interest in biocompatible and biodegradable nanomaterials has led to their growing importance [79]. These materials, produced from biomolecules or combinations of biomolecules with synthetic materials, are commonly applied in biomedical fields, including drug delivery, cosmetics, and therapeutic systems, as well as in textiles, biofuels, pulp and paper production, and wastewater treatment [75, 80, 81]. The self-assembling ability of biomolecules such as DNA and proteins provides the foundation for their use in producing diverse nanostructures [82]. For example, nucleic acid conjugated nanomaterials can enhance molecular recognition in biosensing applications while incorporating the signal amplification capabilities of DNA probes into nanomaterials [83, 84].

B. Nanomaterial synthesis, fabrication and characterization

In general, nanomaterials can be synthesized using various techniques that are broadly classified into two main approaches: top-down and bottom-up. Within these approaches, chemical, physical, and biological processes can be employed as synthesis routes [27, 32], as illustrated in Fig.2. Key characteristics such as particle size, surface area to volume ratio, shape, morphology, surface coating, dispersity, reactivity, and compatibility play important roles in determining how nanomaterials interact with other structures, including cells, and consequently influence their functionality. Therefore, synthesizing and characterizing nanomaterials are essential stages in developing advanced materials at the nanoscale.

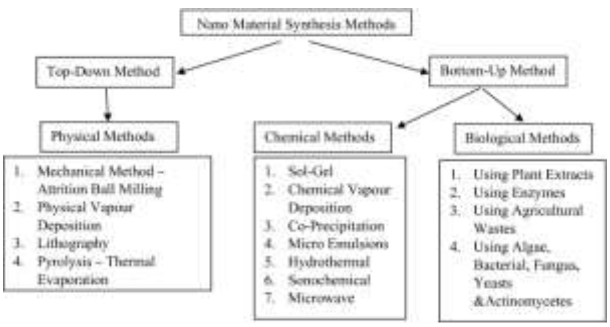

Figure 2. Synthesis methods of nanomaterials [86]

Several techniques are widely used for the physicochemical characterization of nanomaterials, particularly for evaluating their morphology, size, chemical composition, intermolecular forces, and surface charge. These include UV-Visible Spectroscopy (UV-Vis), Dynamic Light Scattering (DLS), Fourier Transform Infrared Spectroscopy (FTIR), Transmission Electron Microscopy (TEM), High Resolution Transmission Electron Microscopy (HR TEM), Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Energy Dispersive [87, 88]. In addition, other important characterization techniques can be employed to complement these methods depending on the specific properties and requirements being investigated. These include Nanoparticle Tracking Analysis (NTA), Atomic Force Microscopy (AFM), High Resolution Transmission Electron Microscopy (HRTEM), Energy Dispersive Spectroscopy (EDS), Selected Area Electron Diffraction (SAED), X-Ray Photoelectron Spectroscopy (XPS), Diffuse Reflectance Spectroscopy (DRS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES), Inductively Coupled Plasma Mass Spectrometry (ICP MS), Inductively Raman Spectroscopy (IRS) [87, 89, 90]. Table 1 presents the characterization techniques used to determine specific nanomaterial parameters.

Table 1. Summary of the various characterization techniques for nanomaterials

Type	Technique	Specific Purpose	Ref.
Nanoparticle formation	Ultraviolet-visible spectrophotometry	Provides information on nanoparticle size, structure, stabilization, and aggregation.	[90]
Morphology and particle size	Transmission Electron Microscopy	Determines shape, size (10^{-10} m), and morphology, crystallographic structure of the nanoparticles	[91-93]
	High-resolution transmission electron microscopy	Determines the arrangement of the atoms and their local microstructures, such as lattice fringe, glide planes, lattice vacancies and	[94]

		defects, screw axes, and surface atomic arrangement of crystalline nanoparticles	
	Scanning electron microscopy	Determines the morphology by direct visualization	[93, 95]
	Atomic force microscopy	Determines the size information (length, width, and height) and other physical properties (such as morphology and surface texture)	[96, 97]
	Dynamic light scattering	Determines the particle size distribution	[98, 99]
	Nanoparticle Tracking Analysis	Categorizes nanoparticles by size (30–1000 nm), with the detection limit depending on refractive index.	[100]
	Energy Dispersive X-Ray Spectra (EDX)	Detects X-rays emitted to balance the energy difference between two electrons.	[101, 102]
Surface charge	Zeta potential	Determines colloidal nanoparticle stability, surface charge, and the materials encapsulated or coated on the surface.	[103, 104]
	Fourier transform infrared spectroscopy	Characterizes nanoparticles by identifying functional groups and measuring emission, absorption, photoconductivity, or Raman scattering of a solid, liquid, or gas	[105, 106]
	X-ray photoelectron spectroscopy	Determines surface reaction mechanisms, elemental bonding, structure, and speciation in magnetic nanoparticles.	[107-109]
	Thermal gravimetric analysis	Confirms surfactant or polymer coatings and estimates surface-binding efficiency.	[110, 111]
Crystallinity	X-ray diffraction	Identifies and quantifies crystalline forms and elemental compositions of nanoparticles.	[112, 113]

III. NANOTECHNOLOGY AT THE FRONTIERS OF SOCIETAL TRANSFORMATION

Nanotechnology is facilitating the development of entirely new industries while also transforming existing markets [13, 114]. At the nanoscale, distinctive optical, electrical, and other properties have enabled advances across diverse fields, including electronics, transportation, materials science, agriculture and environmental science, energy, medicine, and consumer products [25, 115] (see Fig.3). As research and development in nanotechnology continues to expand, increasingly practical materials with novel and specialized applications are being developed. By 2015, nano-related products and services were projected to have a market value exceeding $1 trillion. Consequently, nanotechnology businesses were anticipated to become one of the fastest-growing.

industries in history, surpassing the combined growth of the telecommunications and information technology sectors [116]. Importantly, the commercialization of nanotechnology research has considerable potential to generate societal benefits while also providing economic opportunities [115]. Numerous products used in everyday life already incorporate nanotechnology, including computers, smartphones, pharmaceuticals, paints, and antibacterial materials [117]. Therefore, nanotechnology has become relevant to virtually every industry seeking to adopt advanced technologies and gain a competitive advantage. The rapid development and integration of nanomaterials and nanoparticles have consequently created potential applications across numerous sectors of society, and are discussed in detail below.

Figure 3. Application areas of nanotechnology [118]

A. Health

i. Nanomedicine and drug delivery

Nanotechnology and nanodrugs have generated a wide range of innovative applications in healthcare. Significant advances in nanomedicine have improved therapeutic approaches and patient outcomes, particularly in the treatment of inflammatory and degenerative disorders of the nervous system [119]. As a specialized area of nanotechnology, nanomedicine focuses on highly targeted molecular interventions to treat diseases and repair damaged tissues, including muscles, nerves, and bones. When appropriately designed, nanoparticles can be made compatible with the immune system and minimize unwanted immune responses. They can also function as drug carriers capable of selectively targeting damaged regions of the brain, thereby enhancing therapeutic effectiveness [120]. Consequently, the application of nanotechnology to nanomedicine and medical diagnostics has considerable potential to improve healthcare. Implanted nanosensors can monitor biomarkers and transmit health-related information, while magnetic nanoparticles facilitate highly sensitive imaging approaches for the early detection of cancer [121]. Additionally, nanoscale components incorporated into lab-on-a-chip systems enable the precise analysis of biomolecules from very small sample volumes [122]. These point-of-care nanodiagnostic devices can therefore provide rapid diagnostic results and support timely medical decision-making.

The nervous system is one of the most complex and sensitive systems in the human body and is protected by the blood brain barrier (BBB). The BBB consists of impermeable endothelial cells with tight junctions, enzymatic activity, and active efflux transport systems that regulate brain homeostasis. Overcoming the BBB to improve drug delivery and therapeutic efficacy remains a major challenge in drug development. Several systems have demonstrated the ability to facilitate drug transport across the BBB, including polysorbate 80/LDL, lactoferrin, and poly(butylcyanoacrylate) based nanoparticles. These systems can undergo receptor-mediated transcytosis and facilitate the delivery of agents such as doxorubicin, hexapeptide, dalargin, and melanotransferrin. Thus, nanomedicine provides promising approaches for the treatment of various serious diseases, including cancer, blood and lung diseases, diabetes, inflammatory and infectious diseases, Parkinson's and Alzheimer's diseases, neurological and neurodegenerative disorders, and orthopaedic conditions [123]. Numerous classes of nanotherapeutics are currently under investigation, and nanotechnology-based therapeutic products have also been evaluated in comparison with conventional pharmaceutical treatments [124]. Although nanomedicine remains an emerging field, it offers substantial opportunities for disease treatment, tissue repair, and early diagnosis.

Furthermore, PEGylation, which involves coating nanoparticles with poly(ethylene glycol) (PEG), can prolong their circulation time in the bloodstream and improve their accumulation at the desired site. For example, Hollis et al. investigated the biodistribution of paclitaxel in tumor bearing mice using paclitaxel nanocrystals containing both tritium labeled paclitaxel and fluorescent probe molecules [125]. Following intravenous administration through the tail vein, approximately 1% of the total administered paclitaxel was found to accumulate at the tumor site. Both Taxol, the solution formulation, and the nanocrystals exhibited comparable paclitaxel concentrations and similar activity within the tumor. In addition, trigger responsive systems have been developed for X-ray generated and magnetic field activated drug delivery [126, 127].

These stimulus responsive approaches enable therapeutic agents to be directed to specific locations and released when required through different stimuli sensitive mechanisms. The properties and structures of trigger responsive nanoparticles can be modified in response to endogenous or external stimuli, thereby enhancing cellular uptake and penetration. For instance, ultrasound activated sonosensitizers can be used to monitor and facilitate drug release at targeted sites. Notably, nanocrystal based drug delivery technologies have been used in the development of clinically effective drugs, including megestrol, paliperidone, fenofibrate, sirolimus, and aprepitant [128]. To eliminate the need for removing microparticles after their functional lifetime, biodegradable polymers can be used to develop long-acting microparticle formulations. This green chemistry approach to designing drug loaded nanoparticles is increasingly encouraged because it can reduce hazardous constituents during biosynthetic processes and consequently minimize adverse effects associated with drug delivery systems [129].

ii. Medical diagnostics and biosensors

Receptor functionalized micro and nanorobotic motors have introduced new capabilities for the binding and transport of biological targets. By employing specialized sensing mechanisms, nanorobots have demonstrated the ability to support accurate disease diagnosis through the isolation and identification of various biological targets, including proteins, nucleic acids, and cancer cells [130, 131]. Recent studies have developed customized nanorobots capable of interacting with cells at the subcutaneous and cellular levels [132]. Early detection of cancer is particularly important because nanorobotic systems designed to target tumors could potentially improve patient survival outcomes [133, 134]. Peng et al. [135], for example, developed a logic gate-based three-dimensional DNA nanorobot capable of recognizing two specifically overexpressed biomarkers on cancer cells. The DNA nanorobot can also execute Boolean logic operations on cancer cell membranes, providing considerable therapeutic potential for the treatment of malignancies. Similarly, Yang et al. [136] investigated Au-BP7@SP Janus nanohybrids and reported enhanced photothermal effects and active thermophoretic motion.

By converting mechanical energy into thermal energy, these Janus particles can increase the temperature of cells exposed to NIR light, promoting the destruction of malignant cells. Their active movement can improve the localization of cancer cells while minimizing damage to surrounding healthy tissues, thereby enhancing therapeutic benefits and reducing potential adverse effects. Such multifunctional nanodevices have the potential to integrate rapid diagnosis and personalized treatment within a single nanoparticle-based platform. In addition, the development of nanobiomaterials for precision medicine provides considerable opportunities for customization. Through careful nanoscale design, the pharmacokinetic behavior of therapeutic agents can be tailored according to specific requirements related to solubility, administration, and biodistribution, with successful applications already demonstrated [137]. Table 2 summarizes selected research findings concerning the application of nanotechnology in medical diagnosis.

Table 2: Summary of studies on nanotechnology in medical diagnosis

Nanomaterials/technology	Target for detection	Applications	Ref.
Computed tomography (CT)	Detects hypervascular hepatomas.	Medical imaging	[138]
Superparamagnetic iron oxide (SPIO)	Targets lung tumors using MRI.	Medical visualization	[139]
Quantum dots	Detects biomarkers.	Protein optical imaging and tumor visualization	[140]
Luminescent nanomaterials	Enables early-stage breast cancer detection.	Optical imaging of cells	[141]
Micelles in MRI	Detects unhealthy cells.	Medical imaging	[142]
Perfluorocarbon	Targets blood clots, cancer metastasis, and angiogenesis	Medical imaging	[143]

iii. Cancer therapy and regenerative medicine

Cancer is responsible for approximately one in every six deaths worldwide from health-related causes [144, 145]. It is therefore considered the second leading global cause of death [146]. Malignant tumors are generally associated with abnormalities in the mechanisms that regulate cell growth and proliferation [147], resulting in uncontrolled division and multiplication of damaged cells. However, conventional cancer treatments, including chemotherapy, can produce both off-target and on-target effects on healthy cells. Consequently, new therapeutic strategies are needed to improve selective targeting of cancer cells [144, 146, 148]. Advances in nanotechnology have demonstrated that nanoparticle-mediated drug delivery has demonstrated potential to improve tumor targeting while reducing systemic toxicity in preclinical and selected clinical settings. This has stimulated increasing research into nanomaterials as chemical biology tools for cancer treatment [149] (Fig.4). Through the enhanced permeability and retention (EPR) effect, nanoparticles can preferentially accumulate within tumor tissues, providing a platform for more efficient and targeted therapeutic delivery.

Similarly, several anticancer drugs, including vincristine, paclitaxel, doxorubicin, and daunorubicin, have been extensively investigated in liposome based formulations, with liposomal versions currently used in cancer treatment [150]. These formulations can reduce toxicity to healthy cells, improve drug delivery to tumor cells, and enhance treatment outcomes. For example, liposomes can provide stable and prolonged release of doxorubicin under acidic conditions through a pH gradient mechanism. Under neutral pH conditions, polymeric nanoparticles can provide controlled diffusion of paclitaxel while maintaining stability throughout the process. In contrast, dendrimers can undergo swelling under certain basic conditions and release methotrexate in a pulsatile manner [151]. Importantly, nanoparticles offer several advantages over free drugs because they can accommodate large pharmacological payloads, possess extended half-lives, exhibit reduced toxicity, and provide improved targeting efficiency [152].

Their small size also makes them suitable for producing high-quality images of tumor locations within the lymphatic drainage system. Gold nanoparticles (AuNPs) have been extensively investigated for both cancer diagnosis and treatment. Their chemical inertness contributes to reduced cytotoxicity, while their distinctive optical properties and localized surface plasmon resonance (LSPR) characteristics make them particularly useful for cancer applications.

In a study, gold nanoparticles are exposed to light at an appropriate wavelength, inducing an LSPR based photothermal response that selectively heats tumor tissues and destroys cancer cells [153, 154]. Similarly, Yezdani et al. [155] described research conducted by Professor Jennifer at Rice University involving 120 nm diameter gold nanoparticle coated nanoshells for eliminating malignant tumors in mice. Antibodies or peptides can be conjugated to the nanoshell surface to establish interactions with malignant cells. Consequently, irradiation of the tumor with an infrared laser produces sufficient heat from the gold nanoshells to destroy the cancer cells. In another study, a nanoscale delivery system known as a nanocell, consisting of a PLGA nanoparticle core enclosed within a PEG linked lipid envelope, was developed by Banerjee [152] for sequential targeting of cancer cells and tumor vasculature.

The outer lipid layer contained the antiangiogenic compound combretastatin, while the chemotherapeutic agent doxorubicin (DOX) was covalently attached to the internal PLGA core. The release of combretastatin resulted in vascular collapse and trapping of the nanoparticles within tumors, followed by the release of the chemotherapeutic drug in response to local hypoxia. This approach produced substantial regression of several tumors, including melanoma. In addition, QD-based biosensors have been investigated for the detection of cancer biomarkers [156]. A wide range of nanomaterials has also been studied for the identification of circulating tumor cells (CTCs), including graphene oxide, magnetic nanoparticles (MNPs), polymers, dendrimers, nanowires, nanopillars, silicon nanopillars, and AuNPs. These nanomaterials contribute to cancer detection and prognosis because studies have shown that they can improve the sensitivity and specificity of CTC isolation and detection systems.

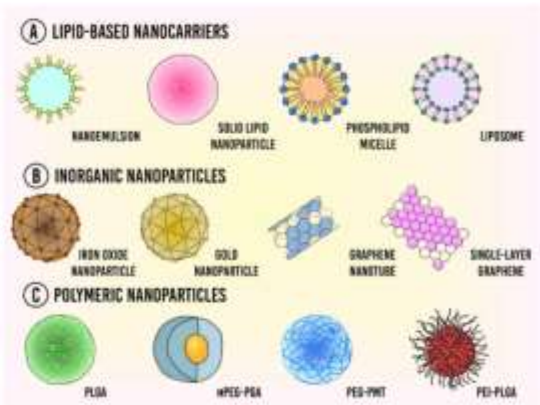

Figure 4. Types of nanocarriers used for drug delivery in cancer therapy. (a) Lipid-based nanocarriers; (b) Inorganic nanoparticles; (c) Polymeric nanoparticles [149].

B. Environmental sustainability

i. Nano-enabled agriculture and food systems

Nanotechnology offers several potential benefits for agricultural applications. For example, nanocapsules can be used for the efficient delivery of nutrients, herbicides, and other agricultural products [157]; while nanoparticles can assist in detecting sanitizers and diagnosing infections in plants and animals [158]. The use of nanocapsules can also improve nutrient absorption, bioavailability, and distribution. Furthermore, nanoparticles can be employed to detect foodborne pathogens and can subsequently be utilized for antifungal and antimicrobial purposes [159]. The importance of nanotechnology in agriculture and food production is particularly evident given the serious challenges facing these sectors. Soil degradation, food shortages, hunger, and declining wildlife populations continue to increase these challenges. In the food sector, nanotechnology-based sensors combined with nanoparticle-based inks may also enable the rapid identification of products [160].

ii. Water purification and desalination

Water purification and access to clean and safe water are essential for sustaining life, maintaining human health, protecting ecosystems, and supporting economic development. With continued global population growth, water demand is increasing, particularly in regions affected by water scarcity [161]. This situation has encouraged the investigation of alternative water resources, including seawater and and wastewater. However, conventional treatment approaches such as filtration, reverse osmosis, chlorination, and ozonation are becoming increasingly inadequate because new industrial pollutants are continuously being released into the environment. Addressing these emerging challenges therefore requires the development of innovative water purification technologies capable of efficiently removing contaminants while remaining cost-effective, environmentally sustainable, and energy-efficient.

iii. Environmental remediation and climate control

Human activities, industrial operations, and agricultural practices release chemicals and other harmful substances into the environment, disrupting ecosystems and adversely affecting living organisms. Various remediation technologies have therefore been developed to address environmental pollution, with bioremediation being particularly attractive because of its environmentally friendly principles. Bioremediation uses biological agents to address environmental contamination either directly at the contaminated site or at an off-site location. Although it offers advantages over conventional remediation approaches, bioremediation is limited by relatively slow processes and difficulties associated with treating certain compounds [162].

Nanotechnology provides opportunities to enhance conventional bioremediation strategies by exploiting the distinctive properties of nanoscale materials. The increasing application of nanoparticles and nanomaterials in bioremediation is largely attributed to their ability to penetrate contaminated regions that may be inaccessible to larger particles and their enhanced reactivity toward pollutants [163]. Nanotechnology-based environmental remediation has been applied to processes such as denitrification, dechlorination, degradation of organic pollutants, removal of heavy metals, and anodic remediation. For example, the successful degradation of hazardous compounds such as carbon tetrachloride using oxide-coated iron nanoparticles demonstrates the potential of nanotechnology for environmental remediation [164]. Studies have further confirmed that nanoscale iron particles can transform and detoxify a variety of environmental contaminants, highlighting the promising role of nanotechnology in addressing environmental pollution [165].

C. Energy, electronics, and IoTs

i. Electronics and computing

Nanoelectronics is enabling the continued miniaturization of electronic and computing technologies while simultaneously improving their performance. These materials include nanoparticles (NPs), which possess at least one dimension below 100 nm [166, 167]. The importance of nanoscale materials became evident when researchers established that particle size can influence the physicochemical properties of materials, including optical characteristics that can be exploited in applications such as bioimaging [168]. Examples include carbon-based nanoparticles such as carbon nanotubes, quantum dots, and metal nanoparticles. Carbon nanotubes and graphene exhibit substantially higher electron mobilities than silicon, making them promising materials for high-speed transistors [169, 170]. One-dimensional semiconductors and metals have unique structural, optical, and electrical capabilities, making them the building blocks for a new generation of electronic, sensor, and photonic materials [171, 172]. Similarly, nanowires and quantum dots can support dense, low-power memory and logic devices for computing architectures beyond conventional CMOS technology [173].

Consequently, technologies such as faster computer processors and higher-density solid-state drives are becoming increasingly available, while ongoing research continues to explore smaller transistor dimensions and alternative computing concepts. Additionally, nanophotonics research involving metamaterials and plasmonics is also transforming displays and optical technologies [173]. In this context, brain-inspired neuromorphic computing systems have emerged as an attractive approach for integrating computation and data storage within compact chips. Such systems can potentially reproduce some of the efficiency and functionality of biological brains, including logical computation [174], self-learning [175], speech and pattern recognition [176, 177], and commercially important applications such as artificial intelligence and deep learning through the use of nanomaterials (refer to Fig.5). On demand manufacturing using nanomaterials such as carbon nanotubes and quantum dots also enables flexible displays, narrow-band light emission suitable for LCD backlighting, and improved screen resolution in smartphones, televisions, and virtual reality headsets [178].

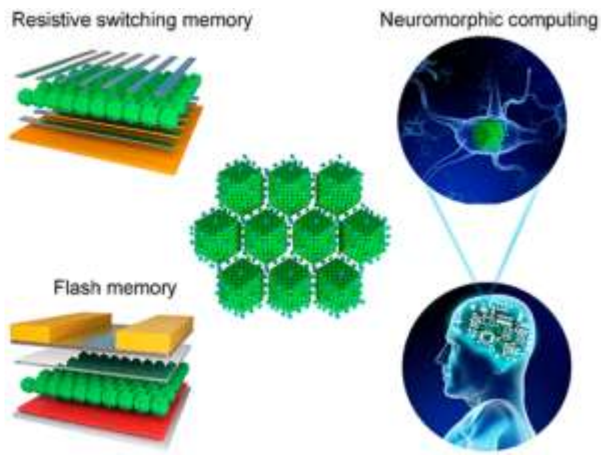

Figure 5. Nanomaterials in electronics and computing [173]

ii. Energy

Over the years, combustion has historically served as an important means of energy conversion; however, it has also produced significant adverse environmental effects. Studies indicate that primary energy consumption increased by 86% by the middle of 2010. In addition, the nonrenewable nature of fossil fuels has raised concerns regarding their future availability and limitations [25]. Consequently, researchers have increasingly focused on producing renewable energy from readily available resources at lower costs, with nanoparticles emerging as promising materials for these applications. According to Lux Research, the market for nanotechnology in energy storage was projected to reach US$3.7 billion by 2011 [179]. Nanomaterials are particularly important for improving the efficiency of energy generation, storage, and transmission. Quantum dot, perovskite, and nanoparticle ink-based solar cells offer prospects for producing photovoltaic systems with low cost and high efficiency [180].

Nanoparticles and carbon nanomaterials (CNMs) are also widely investigated for applications such as photoelectrochemical (PEC) and electrochemical water splitting, piezoelectric energy generation, and the reduction of compounds into fuel precursors [181, 182]. More recently, nanogenerators have been developed to convert mechanical energy into electricity through piezoelectric mechanisms, providing an unconventional approach to energy generation [183]. Fig.6 illustrates several nanomaterial-based energy generation devices. Graphene and carbon nanotube anodes can accommodate more lithium, improving battery performance, while nanogrids and aerogels can provide insulation that enhances the energy efficiency of heating, ventilation, and air conditioning systems and buildings. These developments emphasize the importance of high-performance infrastructure for reducing energy consumption and potentially saving substantial amounts on annual electricity costs.

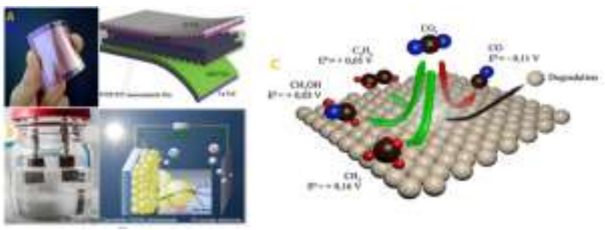

Figure 6. Energy generation approaches from (a) Piezoelectric actuators (b) Water splitting (c) CO2 reduction [25]

D. Automobile industry

The application of nanotechnology in the automotive sector can enable the production of lighter vehicle bodies without sacrificing stiffness or crashworthiness. This reduces the quantity of material required and can consequently lower fuel consumption. Nanocomposites based on different metal or polymer matrices, reinforced with metal or ceramic nanoparticles or nanoplatelets, can increase mechanical strength by up to 100%. Carbon bucky fibers have been reported to possess tensile strengths of approximately 150 GPa, which is around 50 times that of steel while having only one fifth of its weight. Polymer nanofibers can likewise produce thinner, stiffer, and lighter automotive components, creating considerable opportunities for future research and development [184].

Nanocomposite plastic components can provide an average weight reduction of approximately 25% compared with highly filled plastics and up to 80% compared with steel. General Motors (GM), for example, developed the electric Chevy Volt using 45.4 kg of thermoplastics, including composites in the hood and doors, together with unreinforced polymeric materials in the rear deck lid, roof, and fenders [185]. Among the materials incorporated into the Volt was a continuous glass fiber reinforced sandwich composite used for lightweight horizontal body panels. Tesla sports cars have also incorporated lightweight carbon fiber/epoxy composites to achieve high power to weight ratios. Similarly, the British automaker Lotus developed the Evora sports model using a predominantly aluminum chassis together with a composite roof and stressed composite body panels, contributing to its high structural stiffness.

Vehicle mass is one of the most important design parameters influencing fuel consumption. According to the study conducted by Fontaras and Samaras [186], an approximate 13% reduction in CO_2 emissions could be achieved through a combination of factors, including a 10% reduction in average vehicle weight combined with 10% aerodynamic optimization, a 20% reduction in tire rolling resistance, and a 7.5% improvement in average powertrain efficiency. Therefore, nanotechnology can provide important advantages for the fabrication of automotive components, supporting vehicle optimization and contributing to reductions in transportation related emissions. A 5% and 10% reduction in vehicle weight can result in CO_2 emission reductions of approximately 1.3–1.8% and 2.7–3.6%, respectively [186]. These findings demonstrate that reducing vehicle mass can decrease the required engine power, reduce rolling resistance, and consequently lower fuel consumption.

Advanced nanotechnology applications are enabling the development of lightweight automotive components and, consequently, reductions in overall vehicle mass. The approximately 900 kg of steel and other metals commonly used in vehicles can potentially be reduced by as much as 300 kg through the incorporation of composite and hybrid solutions. Thermoplastic compounds are increasingly being adopted in the automotive industry, creating opportunities for new material designs. Volkswagen, for instance, uses long fiber reinforced thermoplastic (LFRT) Celstran®+ in the dashboard of the Golf Plus. This approach eliminates certain metal components and processing steps, resulting in a weight reduction of approximately 8 kg as well as lower production costs. RTP Company has also commercialized polypropylene LFRT materials designed to meet automotive requirements.

This impregnated concentrate contains approximately 60% by weight of very long glass fiber reinforcement and additives in a single pellet, allowing processors to blend it readily with polypropylene resin during molding. When diluted to long glass fiber concentrations of 20–40% in the final products, the concentrate can improve the stiffness, impact resistance, and long-term durability of polyolefin materials [185]. These advanced thermoplastics provide increased stiffness, impact resistance, and long-term durability and can therefore reduce vehicle weight without compromising safety. Their application can also improve fuel economy. Compared with metals, LFRT materials provide higher strength-to-weight ratios, improved impact resistance, greater design flexibility, and enhanced corrosion resistance.

Glass mat thermoplastics (GMT) also offer shorter molding cycle times, longer shelf life, and improved resistance across a broad temperature range. These properties make GMT materials attractive for future applications in automotive exterior panels. Ford Motor Company estimated that achieving a 40% improvement in fuel economy by 2010 would require approximately 340 kg of vehicle weight reduction without compromising safety. To meet this challenge, the company proposed the development of paints, plastics, lightweight metals, and catalysts incorporating nanomaterials [185]. Since approximately 90% of the total energy consumed by an automobile throughout its life cycle is associated with fuel use, reducing vehicle weight can provide substantial energy savings for both the automotive industry and vehicle users [187].

Nanoscale reinforcement is expected to facilitate the design of polymer composites that can compete economically with conventional polymers and eventually replace metals and glass. Such developments could support the production of more fuel-efficient, high-quality, and durable vehicles [185, 187]. Nanocomposites are also being investigated for hybrid vehicle components. Recent studies indicate that the use of low-density structural composites produced through one-piece molding for trunk compartments can reduce mass by up to 50%. In addition, green resins containing approximately 30% recycled and renewable materials are being developed for automotive applications.

IV. SOCIETAL IMPACTS AND RISKS

A. Job creation

The commercialization of nanotechnology is significantly influencing employment and job trends across different sectors. Policymakers are particularly interested in the implications of emerging technologies, including green nanotechnology, for economic development, employment opportunities, and wages [179]. Although it is difficult to predict the exact number of new occupations that will emerge, approximately 6 million jobs are estimated to be developing in areas such as nanoscience research, applied nanoengineering, and the integration of nanomaterials into industrial processes, related sectors, and services. Importantly, as conventional products are gradually replaced, existing workers may transition into green nanotechnology-related activities [188]. For instance, sectors ranging from healthcare to energy are already experiencing changes in skill requirements, and these demands are expected to continue increasing. By 2015, estimates of nanotechnology-related occupations in the United States ranged from tens of thousands to nearly one million positions [188].

Depending on how green occupations are defined, green nanotechnology could employ a substantial proportion of the nanotechnology workforce as well as some workers in other green sectors [179, 189]. The costs and benefits associated with emerging technologies generally occur at different stages and times. Research and development (R&D) costs, for example, are often concentrated during the early stages of a technology's life cycle, although continued R&D expenditure may be required as the technology is further developed and adapted. Nanotechnology R&D began expanding considerably during the mid-1990s, followed by substantial increases in public R&D investment during the 2000s [190].

As Tassey [191] explains, the benefits of technological development can also emerge over different time scales. Early participants in academia and industry are already experiencing increased demand for workers in R&D and specialized manufacturing. Intermediate outcomes include patents, prototypes, and increased venture capital investment associated with new products, processes, and company expansion, whereas broader industrial, economic, and societal benefits tend to emerge over longer periods [179]. In addition, universities specializing in nanoscience and nanoengineering are expanding their degree programs in response to anticipated shortages of skilled personnel. According to Nanowerk, more than 162 academic institutions worldwide currently provide a combined total of 271 degree programs related to nanotechnology [192].

As nanotechnology becomes increasingly integrated into products and services, IT consultants are expected to play a greater role in system integration. In specialized fields such as medicine, new therapeutic programs may also emerge, increasing the demand for diagnostic expertise. Oncologists trained in AI-assisted biopsy analysis may have an advantage over general practitioners, as targeted nanoparticle drug delivery can support more personalized treatment approaches [193]. Such developments, together with effective immigration policies that attract highly skilled workers and entrepreneurs, can strengthen national innovation capacity while promoting economic growth.

B. Societal acceptance and security

Societal acceptance of nanotechnology is a key consideration in its responsible development and commercialization, as the way nanotechnology is presented and communicated can shape public responses to its research, development, and efforts to prevent and manage potential risks associated with nanomaterials [194]. One of the major challenges to public acceptance is the uncertainty and ambiguity associated with emerging technologies. Historically, public opposition to new technologies has created obstacles to their commercialization [195]. This issue has become increasingly significant as nanotechnology-enabled products, including nutritional supplements, cosmetics, pharmaceuticals, and pesticides, become commercially available and raise concerns about their possible health, environmental, and safety effects. For instance, a product recall in Germany linked to health concerns involving nanoparticles illustrates how perceived or potential risks can influence public confidence and affect the commercialization of nanotechnology [196].

Existing research examining public attitudes toward nanotechnology and the adoption of nanotechnology applications has generally focused on factors operating at the individual and contextual levels [197]. As nanotechnology becomes increasingly incorporated into everyday products such as sunscreens, stain resistant clothing, pharmaceuticals, and food related applications, public awareness, perception, and education become increasingly important [198]. Nevertheless, general knowledge of nanotechnology remains relatively low. Scheufele and Lewenstein [199] found that only 16% of respondents considered themselves at least "somewhat informed" about nanotechnology, while Cobb and Macoubrie [200] reported that 80% of respondents had heard little or nothing about it.

Despite this limited knowledge, respondents generally believed that the benefits of nanotechnology would outweigh its concerns and expressed greater optimism than apprehension. The most preferred potential benefit was "new and better ways to detect and treat human diseases," whereas "losing personal privacy to tiny new surveillance devices" was identified as the most important potential risk to avoid. A study conducted by Macoubrie [201] two years later reported even lower levels of awareness, with 56% of respondents indicating that they had heard nothing about nanotechnology and 39% reporting that they had heard only a little. Similarly, Hart Research Associates found that most Americans had heard either little (27%) or nothing (42%) about nanotechnology. Their findings also showed limited understanding even among demographic groups that were most likely to use products containing nanoparticles.

These findings have led scientists, regulators, industry stakeholders, and science communicators to conclude that much of the public remains unfamiliar with nanotechnology and is therefore not adequately prepared to participate in discussions concerning research priorities or regulatory issues. As Miller [202] put it, there remains limited knowledge regarding which aspects of nanotechnology concern the public and what actions people would like to see taken in response. Those who question public participation in science frequently invoke a "deficit in public understanding," arguing that insufficient knowledge limits the ability of public engagement to capture collective opinion or the "wisdom of the crowd." However, Gehrke [198] argued that statistical data alone may not fully capture the behaviors and perceptions of members of society. Therefore, a study was conducted in which 59% of respondents demonstrated at least a general awareness of the scalar definition of nanotechnology, recognizing it as something extremely small but potentially highly significant. However, only 9% of respondents showed a high level of expertise, including knowledge of its various applications, particularly in information technology, while 32% exhibited little to no understanding.

To provide a balanced perspective, museums, the internet, television, and newspapers could communicate developments, challenges, and realities associated with nanotechnology. Such communication, however, should avoid excessive simplification and clearly distinguish between hypothetical possibilities and currently available capabilities. Advancing nanotechnology through informed consent and societal consensus offers greater potential for ethical progress and broader social benefits. Clear and accurate public information can enable communities to carefully evaluate potential risks and benefits rather than supporting blanket opposition to technological advancement.

However, societal acceptance of nanotechnology is also strongly connected to concerns about privacy, security, and individual autonomy. As nanotechnology becomes more deeply integrated into healthcare, consumer products, and information systems, its capacity for continuous sensing, data collection, and communication creates new security challenges that require proactive attention. The growing ability to engineer materials at microscopic scales introduces potential risks to privacy, security, and individual control, which could challenge established concepts of consent and autonomy if appropriate safeguards are not implemented [194, 203].

For some individuals, privacy risks associated with nanotechnology are viewed as extensions of those already associated with conventional communication technologies, requiring continued vigilance because of the possibility of personal data theft and misuse. Others argue that the widespread deployment of invisible sensors could eventually make effective privacy protection obsolete [204]. A major privacy concern associated with nanotechnology is its capacity to greatly expand monitoring through extremely small devices that may be invisible or difficult for individuals to perceive. Michael Mehta [205] examines these societal consequences of microsensor development in his work titled "On Nano-Panopticism: A Sociological Perspective." Researchers at Hiroshima University and Nippon Hoso Kyokai (NHK) have demonstrated that silicon nanocrystal films exhibit photoconductive properties. With improved control over crystal grain size, these films could potentially be incorporated into charge coupled devices to produce highly sensitive and compact video cameras.

More broadly, implantable medical diagnostic devices could support continuous self-monitoring of physiological health and abnormalities. Nanodevices controlled by microchips and implanted in the human body [206], could potentially deliver drugs directly to the heart, support Alzheimer's patients through assisted cognition devices, continuously monitor physiological parameters, and communicate with external devices to report health information, including early indications of tumor development, heart damage, or infection [207]. In one study, gold nanoparticles were exposed to light at an appropriate wavelength, producing an LSPR based photothermal response that selectively targeted tumor tissue through localized heating and destroyed cancer cells [153, 154]. Similarly, Yezdani et al. [155] highlighted research by Professor Jennifer at Rice University in which 120 nm gold nanoparticle-coated nanoshells were used to eliminate cancerous tumors in mice.

Antibodies or peptides were attached to the nanoshell surfaces to interact with malignant cells, after which an infrared laser was directed toward the tumor. The resulting heating of the gold nanoshells was sufficient to destroy the cancer cells. Nanotechnology can therefore contribute to surveillance at several levels, including through Radio Frequency Identity Chips (RFIDs) [206, 208], invisible tags, and nanosensors capable of recording and tracking individual movements [204]. Consequently, the combination of nanotechnology, digital technology, and biotechnology, often described as digital convergence, could make extensive tracking of individuals' movements and physiological characteristics possible for healthcare and security purposes. Another important security concern associated with the Internet of Nano Things (IoNT) is the possibility that malicious actors could gain access to and manipulate nanodevices [203, 209].

Since these devices are often embedded within or connected to larger systems, compromising a single device could produce broader consequences for the security and privacy of those systems. Such capabilities could have significant implications for privacy and civil liberties, particularly if governments or other powerful institutions deploy these technologies. As a result, increased activity in nanotechnology has encouraged improvements in encryption and authentication procedures designed to prevent unauthorized access to nanodevices. For example, Germany's Medizinproduktegesetz (Medical Devices Act), which implements European directives 90/385/EWG concerning active implantable medical devices, refers to secure identification and authentication mechanisms, including public key infrastructure (PKI) and multi factor authentication facilities for nanodevices [210].

Consumer data collection already raises concerns regarding informed consent, while nanotechnology could greatly expand the amount of information that can be collected about purchasing behavior through embedded sensors. Nevertheless, when implemented responsibly and guided by evolving ethical and social frameworks, nanotechnology could contribute to sustainable abundance and generate benefits across society.

C. Environmental risk and assessment

Nanotechnology is often considered a more environmentally friendly approach to manufacturing. However, although virtually any material can become harmful at sufficiently high concentrations, the more relevant question concerns the toxicity of nanomaterials at realistic exposure levels and quantities [211]. The toxicity of nanomaterials depends on several characteristics, including their constituent material, size, shape, and surface coatings. Proper methodologies and appropriate interpretation of experimental data are therefore necessary to identify and understand the harmful effects of nanomaterials while accounting for the assumptions involved. Nanoparticle toxicity studies can also produce different outcomes because research groups may use different cell lines, culture conditions, and incubation periods.

Patra et al. [212] for example, examined 33nm citrate capped gold nanospheres and found that they were cytotoxic to a human lung carcinoma cell line at different concentrations but did not show the same effects in baby hamster kidney cells or human hepatocellular liver carcinoma cells. Nanotechnology has also raised concerns related to issues such as water filtration and agricultural pollution. Furthermore, some nanotechnology based products can be sufficiently expensive to limit their suitability for industrial applications [6]. Consequently, increasing national and international attention is being directed toward the environmental risks associated with nanomaterials. These concerns have challenged assumptions regarding the overall environmental benefits of nanotechnology and emphasize the need for urgent investigation by environmental and health researchers as well as nanotechnology researchers. One important concern is that nanomaterials may be taken up by organisms at the lower levels of food chains through exposure to different pollutants containing potentially harmful compounds [213, 214].

Research examining nanoparticles within model food chain systems has involved earthworms, semiaquatic organisms, fish, invertebrates, algae, freshwater organisms, amphibians, mammalian cells, and plankton [215, 216]. Organisms such as plankton can absorb nanomaterials, which may subsequently move through the food chain as these organisms are consumed by fish, birds, and other species. Moller et al. [215], for example, investigated the toxicity, bioaccumulation, and contamination of AuNPs in an experimental algal zooplankton food chain, as shown in Fig.7.

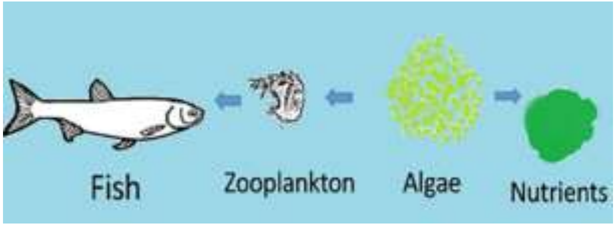

Figure 7. Algae-zooplankton-fish food chain [215]

AuNPs were detected in the zooplankton grazer Daphnia Magna through two pathways: consumption of contaminated phytoplankton (Ankistrodesmus falcatus) and direct exposure through water. Similarly, Bozich et al. [217] examined the short term and whole life cycle effects of negatively and positively charged approximately 4–5 nm AuNPs functionalized with different organic compounds on Daphnia Magna. The positively charged AuNPs were found to be more toxic than their negatively charged counterparts. In addition, the aggregation state of the modified nanoparticles in extracellular and intracellular environments influenced their toxicity. Another concern is the exceptionally large surface area of nanomaterials relative to their volume, which can strongly affect their accumulation and behavior in environmental systems [218].

The surface area of nanoparticles is considered an important factor influencing their toxicity [219, 220]. Their large surface area also allows them to bind to and transport other environmental contaminants, including pesticides and flame retardants, potentially increasing the bioavailability and combined toxic effects of nanomaterials and other pollutants in organisms [221]. Because manufactured nanomaterials are extremely small, airborne particles ranging from several nanometers to several micrometers in diameter can potentially be inhaled [211]. Once released into the atmosphere, some nanomaterials, including titanium dioxide, silicon dioxide, and carbon nanotubes, can remain suspended for extended periods, thereby increasing the potential for inhalation exposure in humans and other organisms [213].

For example, as the agricultural and metallurgical sectors expand, inappropriate waste disposal and the use of fertilizers and pesticides classified as inorganic pollutants can result in their release into waterways, soil, and the surrounding environment [218]. Some nanoparticles can induce inflammation, tissue damage, and asbestos-like pathogenic effects following inhalation. Health conditions associated with exposure to such substances include chronic obstructive pulmonary disease (COPD), asthma, bronchiolitis, malignancies, cardiovascular problems, central nervous system (CNS) dysfunction, and skin disorders [222]. Anthropogenic carbon nanotubes (CNTs) have recently been detected in bronchoalveolar lavage fluids obtained from asthmatic children in Paris following routine human exposure to CNTs [223].

Importantly, the extremely small size of nanomaterials makes environmental contamination difficult to identify and remediate because analytical techniques capable of accurately quantifying nanomaterial concentrations within complex environmental matrices remain limited. Therefore, despite the scientific and technological benefits offered by nanomaterials, their release into the environment, whether through accidental spills during production and transportation or through disposal at the end of their life cycle, requires careful management because of their high mobility and reactivity.

V. CHALLENGES AND OPPORTUNITIES OF NANOTECHNOLOGY

Despite its wide range of applications and considerable transformative potential, the continued development and large-scale commercialization of nanotechnology remain accompanied by scientific, technological, environmental, economic, ethical, and societal challenges. The same nanoscale features that give nanomaterials enhanced reactivity, surface area, optical, electrical, mechanical, and biological properties can also create uncertainties concerning their interactions with biological systems and the environment. Therefore, achieving the full potential of nanotechnology requires these challenges to be addressed alongside technological progress.

One of the primary challenges involves evaluating and managing the potential health and environmental risks associated with nanomaterials. Their toxicity can differ substantially depending on factors such as composition, particle size, morphology, surface chemistry, surface charge, and surface coatings. Their small dimensions and high surface area can affect their mobility, reactivity, biological uptake, and interactions with other environmental contaminants. Consequently, nanomaterials released into environmental systems may undergo transport, transformation, bioaccumulation, and transfer through food chains. Airborne nanomaterials may also create inhalation exposure pathways, while their small dimensions can make environmental monitoring and remediation particularly difficult. These concerns emphasize the importance of reliable toxicity evaluation, standardized characterization procedures, long term exposure studies, and a better understanding of nanomaterial behavior throughout their complete life cycle.

Another significant challenge is the transition from laboratory scale nanotechnology to economically feasible and industrially scalable technologies. Although many nanomaterials exhibit exceptional properties under controlled laboratory conditions, their large-scale synthesis, processing, stabilization, integration, and quality control can present substantial technical and economic difficulties. In some cases, nanotechnology enabled products may remain too expensive for widespread industrial applications, thereby limiting their accessibility and commercialization. Future research should therefore consider not only the achievement of superior nanoscale properties but also the development of reproducible, cost effective, scalable, and environmentally sustainable manufacturing methods. In particular, synthesis strategies that minimize energy consumption, hazardous reagents, waste production, and manufacturing costs will be essential for sustainable commercialization.

Standardization and regulatory development are also essential for the responsible advancement of nanotechnology. Variations in nanomaterial composition, size, morphology, surface modification, and physicochemical characteristics can produce different biological and environmental responses. As a result, conventional methods developed for bulk materials may not always provide an adequate assessment of nanoscale materials. Harmonized characterization procedures, exposure assessment techniques, toxicity testing protocols, and regulatory frameworks are therefore required to improve the consistency and reliability of nanotechnology risk evaluation. These approaches should account for the complete nanomaterial life cycle, including production, application, transportation, environmental release, and end of life disposal.
Public acceptance is another important factor influencing the development of nanotechnology.

As demonstrated in this review, uncertainty and limited public knowledge can shape attitudes toward nanotechnology and influence its commercialization. With nanotechnology becoming increasingly incorporated into pharmaceuticals, food related products, cosmetics, clothing, sensors, and other everyday applications, transparent communication regarding both its benefits and potential risks is becoming increasingly important. Public engagement should clearly distinguish established applications from hypothetical or future capabilities and provide accessible information that enables society to evaluate technological benefits and risks objectively. Effective communication and meaningful public participation can consequently strengthen public trust and support informed decision making.

Privacy and security present additional challenges, particularly as nanotechnology increasingly converges with biotechnology, information technology, and the Internet of Nano Things. Nanosensors and connected nanodevices can facilitate continuous monitoring of physiological conditions, environmental characteristics, locations, and other forms of information. Although these capabilities may provide significant benefits for healthcare, diagnostics, and security, they also raise concerns related to unauthorized data collection, privacy, surveillance, authentication, and control of connected devices. Unauthorized access to nanodevices could also introduce vulnerabilities into larger interconnected systems. Consequently, privacy protection, secure communication, authentication, data governance, and ethical considerations should be incorporated into nanotechnology design from the outset rather than being considered only after deployment.

Despite these challenges, nanotechnology offers substantial opportunities for transforming society. Within healthcare, nanoscale platforms can facilitate targeted drug delivery, early disease detection, biosensing, medical imaging, cancer treatment, and regenerative medicine. In agriculture and food systems, nanotechnology can enhance the delivery of nutrients and agricultural inputs while supporting pathogen detection and monitoring. Nanomaterials also provide promising opportunities for water purification, desalination, and environmental remediation because of their large surface areas and enhanced reactivity.

The energy and electronics sectors provide additional opportunities for nanotechnology. Nanomaterials can contribute to improvements in energy generation, storage, and transmission, while quantum dots, graphene, carbon nanotubes, and other nanostructures can support advanced electronic, sensing, photonic, and computing technologies. In transportation, nanocomposites can reduce vehicle weight while retaining mechanical performance, potentially improving fuel efficiency and reducing associated emissions.
Nanotechnology can also contribute to economic development and employment generation. Its commercialization requires expertise across several areas, including nanoscience, materials engineering, manufacturing, characterization, modelling, healthcare, environmental science, and information technology. Continued expansion of the field can therefore create new employment opportunities while increasing the demand for interdisciplinary education and specialized technical skills.

Future development should consequently progress toward a responsible and sustainable nanotechnology framework in which technological performance is considered together with safety, environmental consequences, economic feasibility, societal acceptance, and ethical requirements. Greater incorporation of life cycle assessment, green synthesis, safer by design approaches, standardized testing, digital security, and public engagement could allow nanotechnology to deliver its intended benefits while minimizing unintended consequences. Such an integrated approach could help advance nanotechnology from a promising scientific platform into a mature and socially responsible technology capable of addressing complex global challenges.

VI. CONCLUSION

Nanotechnology has evolved from a scientific concept concerned with manipulating matter at the nanoscale into a multidisciplinary technological platform with far reaching implications for modern society. The distinctive physicochemical properties of nanomaterials provide capabilities that are difficult to achieve with conventional materials and have driven developments across healthcare, agriculture, environmental protection, energy, electronics, transportation, and other sectors. This review has demonstrated how these nanoscale characteristics are being translated into practical applications, including targeted drug delivery, medical diagnostics, water purification, environmental remediation, energy technologies, advanced electronics, and lightweight automotive materials.

The societal significance of nanotechnology extends beyond its technological applications. Its commercialization can promote economic development, stimulate research and innovation, generate employment, and support the emergence of new industries and specialized skills. At the same time, the widespread integration of nanomaterials into consumer products and interconnected technologies introduces important concerns related to public acceptance, privacy, security, human health, and environmental protection. These concerns are particularly important because the nanoscale characteristics that provide nanomaterials with their technological advantages can also influence their biological activity, environmental mobility, persistence, and toxicity.

For this reason, the future development of nanotechnology should not focus exclusively on improving material performance or accelerating commercialization. Greater attention should be given to understanding the long-term consequences associated with nanomaterial production, use, environmental release, and disposal. Robust risk assessment, standardized characterization, life cycle evaluation, sustainable manufacturing practices, and effective regulatory frameworks will be essential for ensuring the safe development and application of emerging nanotechnologies. Similarly, transparent communication and meaningful public engagement will be important for improving societal understanding and building confidence in nanotechnology. Ultimately, nanotechnology offers both significant opportunities and substantial responsibilities.

Its ability to contribute to improved healthcare, environmental sustainability, energy efficiency, advanced manufacturing, and economic development makes it an important component of future technological advancement. However, these benefits can only be fully achieved when innovation is accompanied by careful consideration of health, environmental, ethical, social, and security implications. A balanced approach based on responsible innovation, interdisciplinary collaboration, evidence-based regulation, and sustainable design will therefore be essential. Through such an approach, nanotechnology can extend beyond technological advancement and become an important instrument for sustainable societal transformation.

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