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REVIEW

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Assessing the nanotechnology on the grounds of costs, benefits, and risks

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Abstract

Background: The technical innovations are based on the principles of science with the assurance of outweighing their cost and risk factors with the benefits to society. But sometimes, the innovation either itself becomes a risk or brings in some risk factors along with it. For most of the alleyway of an innovation from its emergence to its road to societal acceptance and adoption, the focus remains on the benefits majorly. Only when we are at the neck of the hour we think about some of the apparent cost and risk issues. The understanding, proper communication, and address of the basics of risk factors are necessarily required much in advance to deal with this issue.

Main body: Nanoparticles with very small size and huge surface area are being derived from various plants, microbes, chemical compounds, metals, and metal alloys. Without our realizations, nanotechnology has become a vital part of our day-to-day life, and nanoparticles are proving their worth in almost every field ranging from food, water, medicine, agriculture, construction, fashion, electronics, and computers to eco-remediation, but what about the costs involved and the risks associated? We strongly need to recognize these concerns and challenges, and it requires collaborative efforts from academicians, researchers, industries, government, and non-government organizations to involve people in dialogs to deal with them.

Conclusion: Through reviewing various studies and articles on nanotechnology, this review has shown that nanotechnology can productively be used to produce consumer goods for pharma, electronics, food, agriculture, aviation, construction, security, and remediation sectors which are advantages in their characteristics. Regarding the future of nanotechnology, we need to focus on assessment and management of risks associated for its promising market growth.

1 Background

The growth of nanotechnology has paved the way for new innovations in various areas, including agriculture, food, medicine, textile, and electronics. Some of these are already been established and marketed while several others are still under their laboratory stage [1–3]. Various applications of nanotechnology and designed nanostructures may bring desirable advances to mankind and environment, but they may have health and ecological implications resulting into extensive risks to society. Owing to their adjustable physicochemical properties like thermal–electrical properties, melting point, catalytic behavior, and photo activity, nanomaterials have garnered prominent attention from the researchers worldwide [4, 5]. As per the definition given by ISO, nanomaterials are defined as "Material with any external nanoscale dimension or having internal nanoscale structure" [6, 7]. Based on the above definition, various structures of nanoscale dimensions are named as nanowires, quantum dots, nanoplates, etc. Based on the nature of base material used for the production, nanomaterials can be broadly categorized into 4 categories (Table 1).

All these types of nanoparticles possess various advantageous characteristics which makes them highly useful for a range of applications Table 2 [8–11].

Along with these positive attributes, nanotechnology might bring-in some significant negative implications on

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Table 1 Categories of nanomaterials

SN	Base material	Example
i.	Bio-organic	Dendrimers, micelles, liposomes
ii.	Carbon	Carbon nanotubes, fullerenes, carbon nanofibers, carbon black
iii.	Metal and metal oxide based	Ag, Au, Ti, Fe, Pt, Pd, Sn, Cu nanomaterials
iv.	Composite based	Polymer, composite combinations of carbon-based, metal-based, or organic-based NMs with any form of metal, ceramic, or polymer bulk materials.

society, economy, and environment Table 3 [11–13]. These effects can be summed up in the following ways.

Therefore, it is call of the hour to focus on finding new provisions of increasing the transparency and traceability of nanomaterials through precise assessments and management of all the risk factors associated [14–16]. This article aims to present a summary of existing applications, risks, and legislations as well as some further developments related to nanotechnology and nanostructures.

2 Main text

2.1 Applications, benefits, and services of nanotechnology

Nanotechnology is all about designing, characterization, application, production, and marketing of structures on nanoscale dimensions. The interdisciplinary field of nanotechnology is accepted as a window of new opportunities for providing solutions not only in the core technical areas but also promisingly addressing developmental issues like water treatment, eco-remediation, and sustainable energy [17–20]. The broad relevance of nanotechnology accentuates the manipulation, categorization, and creation of nanoscale materials [21, 22]. Nanotechnology has proven its relevance in almost every area of life, be it agriculture, medical, electronics, fashion, environment, or construction [23–25]. Nanomaterials are the natural or engineered substances with dimensions between 1 and 100 nm. Playing with matter on nanoscale is a revolutionary technology as nanosize exposes a unique world of physiochemical, biological, and toxicological properties. At nanoscale, it is the surface behavior along with quantum behavior that brings about remarkable changes in the properties of matter [16, 26, 27]. The quantum effect gives nanomaterials very diverse physical, chemical, thermal, electrical, optical, and magnetic properties. Materials gain strength and resistance at the nanoscale, their color and light reflecting characteristics get altered, and reduction of size increases the surface area which results in alteration of physiochemical properties of the particle which leads to increased mobility, reactivity, and better aggregation and dissolution properties [28]. The various applications of nanotechnology are summarized in Table 4.

Nanosilver is used as an antimicrobial agent in cleaning sprays and for disinfecting the chopping boards, food containers, and refrigerator boxes. Nanoclay and nanocomposites are employed to decrease the costs and to increase the strength and shelf life of carbonated and noncarbonated drinks [71, 72]. Nanosensor-based packaging films are utilized for safe and hygienic packing and delivery of food items and improving their shelf life [73, 74]. Cost-effective nanopurification systems for water treatment can resolve the global problem of drinkable water. It is expected that by the year 2030, the world will observe an increase of 60% in the water demand globally [26, 27]. Silver- and chitosan-based nanofilters can play a substantial part in producing drinking water from sea water, thus providing solution to the increasing global demand of fresh water. Nano-based technologies will create enormous ecological paybacks in the area of water treatment through improving the analysis, monitoring, disinfection, desalination, water conservation, recycling, and sewerage systems [75–78]. After water and food resources, energy is proved to be the fundamental resource for mankind, and the ever rising demand for energy

Table 2 Characteristic properties of nanomaterials

SN	Properties	Examples
1.	Catalytic property	Enhanced surface-volume ratio Better catalytic efficiency
2.	Electrical property	Improved electrical resistance Enhanced electric conductance
3.	Mechanical property	Improved magnetism Super-paramagnetic performance
4.	Optical property	Better toughness and hardness Enhanced plasticity and ductility of ceramics
5.	Sterical property	Positive shift in optical absorption and fluorescence Improved quantum efficiency of semiconductors
6.	Biological property	Improved selectivity of chemicals Controlled release and improved drug transformations

Table 3 Negative effects of nanotechnology on society

1.	Ethical influence	Social divides, technology abuse
2.	Social influence	Environmental hazards, health risks, economic effects, educational avenues
3.	Legal influence	Privacy breach, regulations, property rights

resources is expected to climb by 50% by the year 2025. Currently the major sources are the natural energy resources from fossil fuels which are expected to bear double the current burden by 2025 [79, 80]. Nanotechnology has the potential to provide solutions to the global energy demands through cost-effective nanofuel cells, hydrogen storage nanosystems, nanocoated solar cells, and reinventing the energy storage and energy distribution. Nanodevices can track alterations in the glucose level, cholesterol level, and carbon dioxide level of the body without extracting blood; nanobots can help repair or replace the damaged body tissues in injured body; nanosolutions can restore youth and health of aging skin. In the medical field, nanotechnology aids drug delivery methods, tissue engineering, treatment systems, regenerative medicines, cell repair, cancer detecting and treating cancerous patients, gene-therapy, etc. [81–83].

2.2 Market needs of nanomaterials

The growing acceptance of nanotechnology by the society is creating the demand for nano-inspired goods. This is also highlighting the necessity of understanding the potential effects these products would be having on environment, eco-balance, animals, and human beings. In the year 2019, the global market of nanomaterials was estimated to be 8.5 billion US dollars and is anticipated to grow with an annual rate of 13.1% from the year 2020 to the year 2027 [84–87]. This rise in market share of nanotechnology is attributed to the rapid acceptance and adoption of nanostructures in aerospace applications, medical and health sectors, food and packaging industry, agriculture and farming, sports, cosmetics, constructions, paints and coatings, electronics, environmental remediation power and energy sectors, etc. The key factor for this growing market of nanomaterials is the characteristic physical, chemical, and biological properties of metal nanoparticles. Copper, silver, platinum, gold, aluminum, palladium, zinc, tellurium, titanium metals, and their oxide-based nanoparticles along

Table 4 Applications of nanotechnology

S N.	Application	Example
1.	Energy storage, production, and conversion	Nanomaterials as catalysts for hydrogen production, carbon nanotubes for hydrogen storage and as composite coatings in solar cells, quantum dot-based light-emitting devices and photo-voltaic cells, grapheme-based ultra-capacitors, hybrid protein-polymer bio-mimetic membranes produced from protein hybrid polymer [29–34]
2.	Agricultural productivity enhancement	Nanocapsules for precision farming; nanoporous zeolites for the precise and sustained release of nutrients, pesticides, herbicides, drugs for livestock and plants, and efficient dosage management of water; nanosensors for monitoring of plants and soil health and pest control; nanomagnets for removing soil contaminants [35–38].
3.	Air and water remediation	Nanomembranes, metal oxide nanoparticles, magnetic nanoparticles, nanosensors, nanoporous zeolites, and grapheme-based treatment structures or detection of pollutants and remediation of air and water [39–43].
4.	Disease diagnosis and drug delivery	Carbon nanotube sensors, quantum dots, conjugates of dendrimer and antibody, as the detection and diagnosis medical tools to act as sensors and in situ examinations of diseases and sustained drug release [44–48]
5.	Food storage and processing	Silver and zinc oxide nanomaterials for antimicrobial actions; nanoemulsions and nanocomposites for food-packaging, storing, and decontamination; silver, silica, selenium, iron, platinum, titanium dioxide, calcium, and magnesium as nanosupplements [49–51].
6.	Constructions	Nanomaterials for cost management, weathering management, and durability of coatings, paints, surfaces, concrete materials, adhesives, and photosensitivity of constructions [52–55]
7.	Social-security	Detection systems based on nanotechnology [56, 57]
8.	Academics	Improved communication systems through better band-width and lower cost [58]
9.	Beauty and cosmetic	Nano-based age-defying creams, ethosome- and liposome-based hair-care products, sunscreen lotions [59–63].
10.	Sports	Nanotechnology-based golf/tennis balls, bow-arrows, helmets for football, bats for baseball, racquets for badminton and tennis, racing bicycles, sticks for hockey, etc. [64, 65].
11.	Electronics	Nanocomputer and nanoprocessors, nanotech detectors, nanomemory devices and nano-based display systems, etc. [66–70]

with carbon-based nanostructures are broadly being used in various consumer products.

Revenues in $ billions	Annual growth rate 2000–2010	Annual growth rate 2010–2013	Estimated growth for year 2020	Estimated growth for year 2030
World	25%	48%	3000	30,000
USA	24%	38%	750	7500

Source: data from Roco et al. and from Lux Research [88, 89]

The area of nanotechnology is continuously attracting investments from all over the world with the USA and China leading the list. This inflow of funds is rendering the process of integration of manufactured nanomaterials into the finished market product. With this interest and funding, it is expected that the market for nanotechnology will expectedly grow with 17% CAG rate in the span of 7 years from the year 2018 to 2025. The optimistic market trend reflects the balanced collaborations between research, industry, and society.

2.3 Sources and synthesis of nanomaterials

As nanomaterials have proven their worth in almost every aspect of societal problems, we need to get them extracted naturally or produced synthetically (Table 5) [96, 97].

Nanoparticles can be synthesized through various physiochemical or biological methods (Fig. 1). The physical methods of synthesizing nanoparticles are enormously expensive whereas chemical routes pose serious environmental risks along with the issues of slow growth rate and inaccuracy in the structure of the designed nanoparticle. Nanomaterials are being synthesized as per the following two approaches [98–101]:

- Bottom-up approach—this approach begins with initial structures at atomic level. It is a cost-effective method for large scale productions.
- Top-down approach—this approach begins with the initial structures at macroscopic level. It is a slow method and not cost-effective for large scale productions. Hydrothermal synthesis

Table 5 Sources of nanomaterials

S.N	Source	Example
1.	Incidental nanomaterials	Nanoparticles from forest fire, dust storm, cosmic evolutions, volcanic eruptions, etc. [90].
2.	Engineered nanomaterials	Nanoparticles synthesized in the laboratory, released from the exhausts of engines, construction, and demolition works, found in health care and biomedical products [91–93].
3.	Naturally produced nanomaterials	Nano-organisms, viruses, nanobacteria, magneto-tactic bacteria, etc. [94, 95].

Synthesizing nanoparticles from chemical solutions can be achieved by the following routes [54, 102, 103]:

- Colloid-based synthesis
- Microemulsion-based synthesis
- Hydrothermal-based synthesis
- Solvothermal synthesis
- Chemical vapor-deposition synthesis
- Thermal-decomposition synthesis
- Pulsed laser-ablation synthesis
- Template-based synthesis
- Combustion
- Gas phase methods
- Microwave synthesis
- Conventional sol-gel method

In order to minimize the environmental risks from physiochemical synthesis, researchers are looking out for sustainable and green synthesis of nanoparticles. The green methods are comparatively faster in terms of reaction rate and are cost effective and less hazardous to the environment. Green synthesis of nanoparticles involves mixing of appropriate amount of metal ions with plant extracts or microorganisms under requisite conditions (Fig. 2) [26, 27].

2.4 Risks of nanotechnology

Anticipated benefits of nanotechnology integrate enhanced efficiency, improved bio-accessibility, and sophisticated packaging. These novel products or constituents may pretense a threat to humans and environment. There are global efforts for addressing and regulating the manufacturing and secure management/applications of nanotechnologies either by advices and supervision or by legislations [104, 105]. Presently, there is no law wholly committed to the directives focusing towards nanotechnologies in any of the countries globally [106, 107]. Existing laws are being considered as adequate and precise enough for regulating the uses of nanotechnology [108, 109] though some modifications have been recommended by numerous policy-making bodies like various NGOs and the European parliament [110, 111]. The call for supplementary directions to evaluate the impending hazards and for suggestions to guarantee the secure utilization of nanotechnology is being recognized, and quite a few specialist organizations are working actively in this area, for instance the Organization for Economic Cooperation and Development (OECD), the International Standard Organization (ISO), or the US Food and Drug Administration (FDA) [112, 113]. The recent review article presents a sketch of the assessment of disputes and threat issues related to nanomaterials and indicates that these characteristics are straightly linked to the methods used for their synthesis.

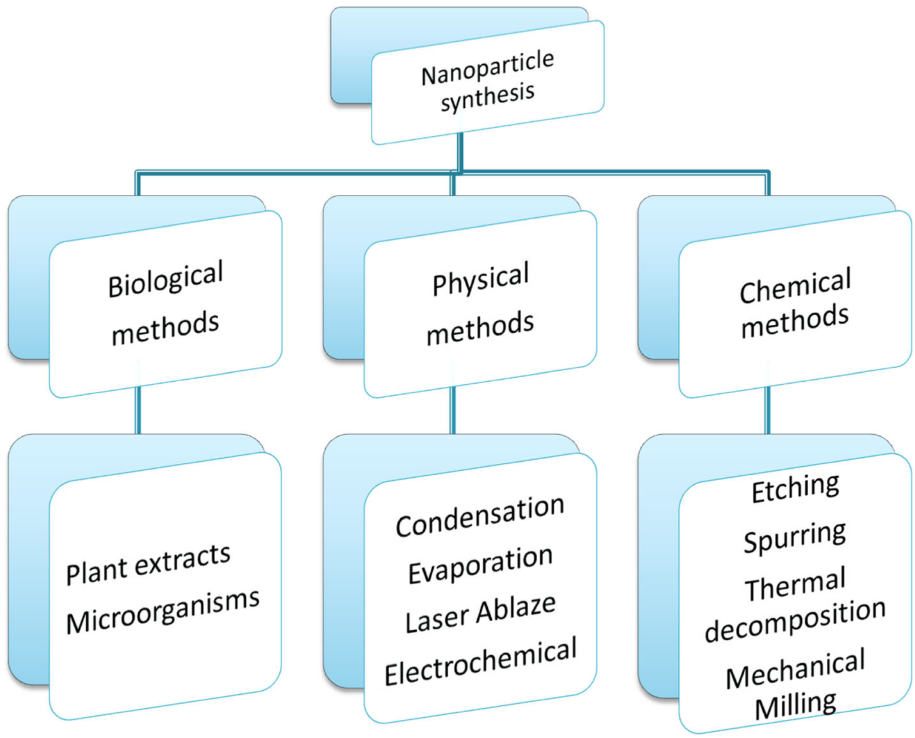

Fig. 1 Nanoparticle synthesis

Important dictatorial concerns are to be analyzed for nanomaterials which comprise of a description of the term "nanomaterial," listing processes, precise information necessities for risk-assessment, management and terms to boost the clearness, and recording of the marketable usages, as cataloging or informing to a record for goods containing [114–116]. The general characteristics of nanoparticles and their effects are summed up in Table 6.

2.5 Nanomaterial toxicity

The environment and an individual get the exposure to nanoparticles either during natural processes [28, 129] or during their manufacture, distribution, usage, clearance, and waste management. Nanoparticles get released in the environment either accidently or gradually during their synthesis, transport, storage, applications, or disposal methods. In some applications, like nanoremediation, significant amount of nanoparticles are deliberately being introduced to detoxify and transform the environment. The nanoscale dimension of these particles aids their movement in various body parts causing different types of cancers, swelling and damage of organs, protein denaturation and asthmatics attacks, etc. The enhanced surface area and great tendency to bind facilitates the adsorption and transportation of pollutants through long distances over a longer period of time.

There is not much information available about the effects of nanoparticles on the environment. Further research is required to mend the knowledge and information gap about the characteristic behavior of nanoparticles in soil, air, and water and their accumulative properties in food-chains.

Since nanotechnology is still in its nascent stage, there are questions about the effect of industrial and commercial use of nanotechnology on environment and organisms. During their production, nanoparticles might get released in the air, water, or soil in turn affecting the environment and organisms [130, 131]. The regular assessment of nanoparticles is very much necessary because every application of them creates a new environmental impact. The eco-toxicological effects and the consequences of accumulation of nanoparticles in organisms need more and more research. The alien matters to the human body are normally trapped by the skin and hairs of the organs, while human gastrointestinal tract and the lungs are most susceptible to the infections [132, 133]. Nanoparticles if inhaled by the organism can readily get to the heart, liver, and blood cells through the bloodstream. The tiny dimensions of nanoparticles can facilitate irreparable oxidative strain, denaturation of protein, internal organ injury, agitation of phagocyte functions and asthmatic and cancerous infections, and production of neo-antigens causing organ magnifications and non-functioning. It is being observed that many of

Fig. 2 Green synthesis method

the nanoparticles are non-hazardous, whereas some have the tendency of having positive health effects. As per the data available, the toxicity of nanomaterials is based on a variety of characteristics [134–136].

i. Their dosage and the time of exposure effect
ii. The concentration and aggregation property effect
iii. The crystal structure, shape, and size effect
iv. The surface fictionalization and area effect

Various policies in the form of rules, laws, and legislations are being taken into practice by some organizations to reduce or evade the risks linked with

Table 6 General characteristics and risks of nanoparticles

1. Nanomaterial properties	Risk description
2. Aggregation	Aggregation of nanoparticles pose considerable threat as it leads to phase changes, reduced resistance towards corrosion, and increase in the solubility causing the weathering of structures [117, 118].
3. Reactivity	The spontaneous degradation reactions of nanoparticles may lead to alterations in the functional group-based properties of compounds [119, 120].
4. Impurity	High reactivity of nanoparticles makes them react with impurities changing their outcomes; therefore, these are encapsulated with non-reactive species [121, 122].
5. Contaminant dissociation	The contaminations in the metal and nonmetal impurities like sulfur, rubidium, and yttrium of nanoparticles are significant risk agents [123, 124].
6. Size	The outstanding size-based properties of nanoparticles are severely affected by their agglomeration nature [125, 126].
7. Disposal and recycling	The disposal policies of nanomaterials are not well defined, and toxicity-related statistics are not much available for nano-materials. Therefore, the ambiguity in the effects of nanomaterials has to be resolved to develop significant disposal policies [127, 128].

nanomaterials. However, there are not distinct legal definitions, regulations, and protocols for creation, management, cataloging, testing, and evaluating the effects of nanoparticles on environment. The toxicity listing of nanomaterials is an extremely stipulated study area in current times [137, 138]. Nanoparticles, if inhaled by the organism can readily get to the heart, liver, and blood cells through the bloodstream. The tiny dimensions of nanoparticles can facilitate irreparable oxidative strain, denaturation of protein, internal organ injury, agitation of phagocyte functions and asthmatic and cancerous infections, and production of neo-antigens causing organ magnifications and non-functioning. It is being observed that many of the nano-particles are non-hazardous, whereas some have the tendency of having positive health effect.

3 Conclusion

Nanotechnology innovations are still in laboratory stage, generally incoherent from the public and areas where these are ultimately being practiced. Consequently, the people interact with technological advances merely as customers, for their commercialization, and when there is a conflict with the social values, the technology faces resistance. For the broad acceptance of nanotechnology, it is very much necessary to have a balance between the production, marketing, usage, risk assessment, and management of nanoparticles. Without proper regulations and legislations, the usages of nanotechnology may lead to serious grievances causing irreparable damage to the environment and mankind. More and more research and progressive work is still needed to find new cost-effective green synthesis routes, legislation bound usages, and risks and hazard assessment and their solutions. Imparting these points will result into the successful nanoinventions.

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Authors' contributions

GP has collected and formatted the article, and PJ did the editing and typing work. All authors have read and approved the manuscript

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