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Review Article

A Comprehensive Review of Nanotechnology And its Medicinal Applications

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ABSTRACT

Nanotechnology is the exploitation of the unique properties of materials at the nanoscale. Nanotechnology has gained popularity in several industries, as it offers better built and smarter products. The application of nanotechnology in medicine and healthcare is referred to as nanomedicine, and it has been used to combat some of the most common diseases, including cardiovascular diseases and cancer. The present review provides an overview of the recent advances of nanotechnology in the aspects of imaging and drug delivery.

INTRODUCTION

About:

Nanotechnology refers to the branch of science and engineering devoted to designing, producing, and using structures, devices, and systems by manipulating atoms and molecules at nanoscale, i.e. having one or more dimensions of the order of 100 nanometres (100 millionth of a millimeter) or less.

Molecular simulation is crucial for advancing nanotechnology, enabling scientists to simulate atomic, molecular, and nanostructure behaviour under various conditions using computer models. Nanomaterials:

Nanomaterials are majorly classified by their origin, dimensionality, and composition. Origin: Can be classified into natural and artificial based on their origin**.**

Natural: Nanomaterials that occur naturally, such as those found in the Earth's crust or in biological systems**.**

Artificial: Nanomaterials that are manufactured by humans to have specific properties. **Dimensionality:** Nanomaterials can be classified

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as Zero-Dimensional Nanomaterials (0D), One-Dimensional Nanomaterials (1D), Two-Dimensional Nanomaterials (2D), and Three-Dimensional Nanomaterials (3D). As the dimensionality decreases, the surface-to-volume ratio increases.

0D: All dimensions (x, y, z) are less than 100 nm, e.g. nanospheres and nanoclusters. 1D: Two dimensions (x, y) are nanoscale, while the third dimension (z) is larger, e.g. nanofibres, nanotubes, and nanowires. 2D: One dimension (x) is nanoscale, and the other two are larger, e.g. nanofilms, nanolayers, and nanocoatings. 3D: None of the dimensions are confined to the nanoscale, but they contain nanoscale elements, e.g. bundles of nanowires and multi-nanolayered structures.

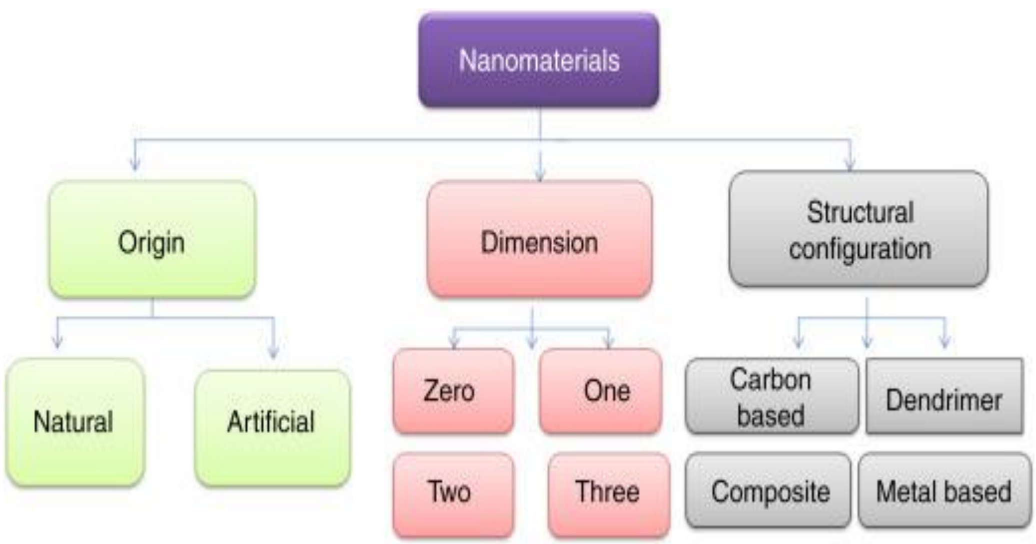
Composition: Based on composition of materials nanomaterials can be classified as organic/dendrimers, inorganic, carbon-based, and composite.

Organic/Dendrimers: Composed of organic molecules like polymers, lipids, or proteins, with dendrimers being a specific type of highly branched organic structure.

Inorganic/ Metal based: Nanomaterials made from non-carbon elements like metals, metal oxides, or other inorganic compounds.

Carbon-based: Primarily composed of carbon atoms, such as carbon nanotubes, graphene, or fullerenes, fall under this category.

Composite: Made by combining different types of nanomaterials, like embedding inorganic nanoparticles within an organic polymer matrix, creating a composite structure with unique properties.



Properties:

Mechanical Properties: The small grain size of nanomaterials results in higher mechanical strength. They are used in applications where strong, lightweight materials are needed, such as in aerospace and automotive industries.

Quantum Confinement:

As the grain size reduces, quantum mechanical effects become more prominent. This property is essential in semiconductors, optoelectronics, and nonlinear optics. Quantum dots, for instance, can emit and absorb specific wavelengths of light by altering particle size, making them invaluable in display technologies and solar cells.

Catalytic Activity:

Nanomaterials with increased surface area show enhanced catalytic properties, making them ideal for chemical reactions and environmental remediation.

Magnetic Properties:

Nanoparticles often form a single magnetic domain, leading to superparamagnetism. This feature is useful in applications like magnetic recording and information storage.

Nanodevices:

Nanodevices are highly organized chemical systems, built at the nanoscale, that perform various functions such as processing electrons, ions, photons, or mechanical properties.

Applications of Nanodevices

Quantum Electronics:

Nanodevices allow for precise control over quantum mechanical effects, essential in quantum computers and nonlinear optics.

Chemoselective Sensing:

Sensors built with nanomaterials can detect specific chemical reactions, enabling advancements in environmental monitoring and medical diagnostics.

Catalysis and Adsorbents:

Nanodevices enhance catalytic reactions, useful in energy generation and pollution control.

Information Storage and Processing:

Nanomaterials are increasingly used in magnetic recording devices, improving storage capacities.

What are the Applications of Nanotechnology?

Computer Industry:

Originates from microengineering; nanotubes are increasingly replacing silicon chips. Nanomaterials enhance sensor performance, making them more robust and sensitive. Fourth Industrial Revolution integrates Artificial Intelligence (AI), Internet of Things (IoT), 3D printing, and blockchain, with nanotechnology as a core element. Key Technologies based on nanotech are Smart sensors, nanochips, optoelectronics, quantum computing, lab-on-a-chip technologies.

Medicine: Nanotechnology can be used for genome editing, Medical Imaging Iron oxide nanoparticles for Magnetic Resonance Imaging, quantum dots for **fluorescence imaging,** gold nanoparticles for CT scans. **Nanowire, nanotube, and quantum dot-based biosensors** are used for sensitive biomarker detection. Targeted chemotherapy, and magnetic hyperthermia can be done using nanoparticles. Biodegradable nanoparticles are used for controlled antigen(substance that causes your immune system to produce antibodies) release and stable adjuvants. Nanoparticle-loaded hydrogel dressings and silver nanoparticle bandages for infection control. Nanorobots for targeted drug delivery, microsurgeries, and internal diagnostics.

Bioprocessing Industries:

Enhances food safety, quality monitoring, and sustainable practices through nanotechnology. Uses nanodevices for better monitoring across production, storage, and distribution. Nanocomposite films enhance the mechanical strength, barrier properties, heat resistance, and biodegradability of packaging materials.

Agri-Industries:

Nano-Fertilisers enhance nutrient delivery to plants, resulting in improved growth rates and higher productivity. Nanotechnology aids in the processing of agricultural products, enhancing methods that refine and preserve food. Nano Polymeric Coatings promote germination under favourable environmental conditions. This innovation helps ensure better survival rates and productivity of crops. Nano Pesticides improve solubility, dispersion, and target-specific delivery. Nanocapsules and nanogels allow for slow release of active ingredients, reducing the required dosage and toxicity.

Manufacturing Industries:

Automotive Industry: Use of nanoparticles in alloys reduces weight and improves fuel efficiency. Nanocoatings enhance surface hardness, corrosion resistance, and aesthetic finishes. Nanoparticle-based catalysts improve combustion efficiency and reduce emissions. Nanosensors monitor vehicle performance and safety in real-time.

Aerospace Industry: Nanotechnology creates lightweight, high-strength materials for aircraft.

Electronics Industry: Enable miniaturisation of components for smaller, more powerful devices. Quantum dots enhance colour vibrancy in Light Emitting Diodes (LED) displays.

Medical Manufacturing: Nanoscale engineering improves integration and functionality of implants.

Construction Industry: Nanomaterials enhance durability and reduce weight in concrete. **Energy Sector:** Nanomaterials boost energy conversion efficiency in Solar Cells, and help to improve storage capabilities for renewable energy applications.

Environmental Remediation:

Pollution Reduction in Manufacturing: Use of silver nanoclusters in producing propylene oxide significantly reduces polluting byproducts, leading to cleaner manufacturing processes for plastics, paints, detergents, and brake fluid.

Efficient Solar Cells: Development of low-cost, high-efficiency solar cells by embedding silicon nanowires in polymers, potentially making solar energy as economically viable as fossil fuels.

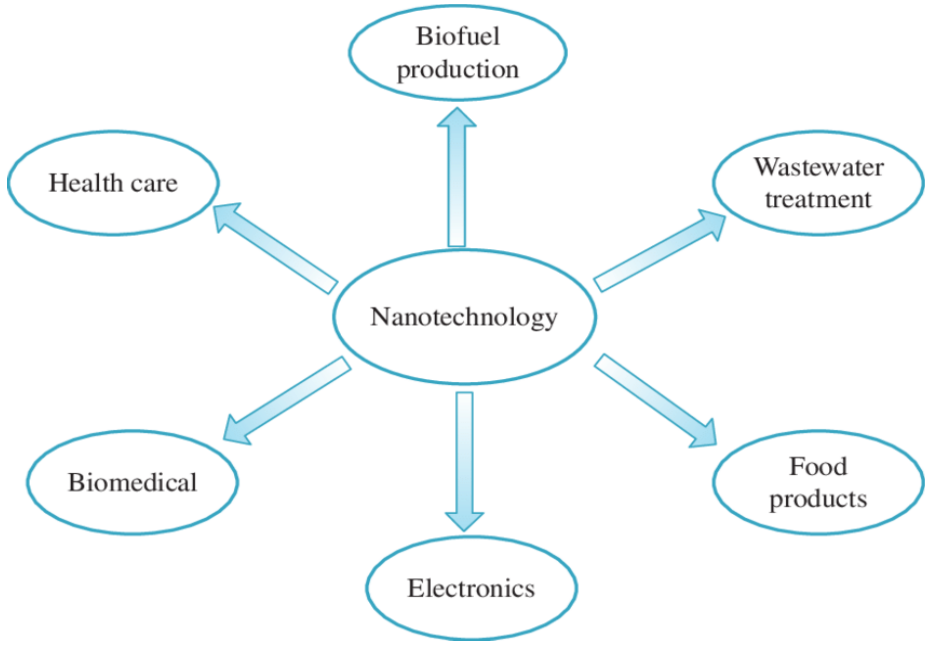
Enhanced Wind Energy Generation: Stronger, lighter blades made from epoxy containing carbon nanotubes increase the electricity output of wind turbines.

Groundwater Remediation: Iron nanoparticles effectively decompose organic solvents in groundwater in situ, offering a cost-effective alternative to traditional extraction methods.

Oil Spill Cleanup: Photocatalytic Copper Tungsten Oxide Nanoparticles break down oil into biodegradable compounds when activated by sunlight, providing an effective solution for oil spill remediation.

Hydrogen Storage for Fuel Cell Vehicles:

Utilising graphene (2D nanomaterial) to increase hydrogen binding energy improves storage capacity in lighter fuel tanks, aiding the development of hydrogen-fueled cars.



How did Nanotechnology Evolve in India?

Early Stages: 9th Five-Year Plan (1998-2002):

Marked the first mention of nanomaterials within India's strategic science and technology goals. Core research groups were established for frontier areas such as superconductivity, robotics, neurosciences, and nanomaterials. In 2001, the Department of Science and Technology(DST) established an Expert Group on "Nanomaterials: Science and Devices" to develop a longterm strategy.

Tenth Five-Year Plan (2002-2007):

Led to the formal introduction of nanoscience, envisioning the National Nanoscience and Nanotechnology Initiative (NSTI) launched in 2001. NSTI aimed to create research infrastructure and foster basic research, particularly in fields like drug delivery, gene targeting, and nanomedicine. The 10th Five-Year Plan paved the way for creating the Nano Science and Technology Mission (NSTM) in 2007 to push nanotechnology into missionmode R&D efforts. Twelfth Five-Year Plan (2012-2017): The government continued to support nanotechnology through Phase II of the NSTM. The emphasis shifted towards application-oriented R&D, where the mission aimed to bring tangible products, processes, and technologies from research laboratories to industry. Institute of Nano Science and Technology (INST), Mohali, is an autonomous institution of the DST, established under the NSTM to emphasise nano research in India.

Institutional Support and Initiatives:

DST Programs: Intensification of Research in High Priority Areas (IRHPAS) and National Programme on Smart Materials (NPSM) laid the groundwork for nanotechnology research. Nano Functional Materials Technology Centre (NFMTC): Focused on costeffective production of nanomaterials and applications in sectors like ceramics and pharmaceuticals. Department of Biotechnology (DBT): Active in nano-biotechnology R&D, focusing on healthcare, agriculture, and environmental management. Promotes development in areas like tissue-specific drug delivery and nanosensors for food safety. Department of Electronics and Information Technology (DeITy): Established the Centre for Materials for Electronics Technology (C-MET) to develop nanomaterials for electronics. Special Incentive Package Scheme (SIPS) encouraged the establishment of micro and nanotechnology industries, particularly focusing on the semiconductor sector. International Collaborations: The International Conference on NanoScience and NanoTechnology (ICONSAT). Indo-US Nanotechnology Conclave: It brings together all stakeholders to work together and provide cost-effective quality products using nanotechnology to the global society at the right time.

Recent Innovations in Nanotechnology in India:

C.N.R. Rao: Dr. Chintamani Nagesa Ramachandra Rao is considered as the "Father of Indian Nanotechnology". His work on inorganic nanotubes and carbon nanotubes is an excellent contribution to nanochemistry, making him a great exponent of nanoscience. Water Purification: Carbon Nanotube Filters developed by scientists at Banaras Hindu University, these filters effectively remove micro-to-nano scale contaminants from water. Made from carbon nanotubes, they are strong, reusable, and heat resistant, able to filter out polio viruses and bacteria like E. coli. Healthcare Solutions: The Defence Research & Development Establishment (DRDE), Gwalior has created a rapid detection kit for typhoid using nanotechnology. The kit detects Salmonella typhi antigens in patient serum within 1-3 minutes, a significant improvement over traditional methods. Energy Generation: Research by Indian Institute of Science, Bangalore showed that liquid flow in carbon nanotubes can generate electric current, leading to the development of a self-powering heart pacemaker (send electrical pulses to help heart beat at a normal rate). This innovation has the potential to reduce reliance on batteries, thereby improving the quality of life for patients with heart issues. Drug Delivery Systems: A team from the University of Delhi has developed several nanoparticle-based technologies for improved drug delivery. Innovations include the encapsulation of non-steroidal drugs in nanoparticles to enhance efficacy while minimising side effects.

What are the Key Challenges for Nanotechnology?

Safety and Toxicity: The health and environmental impacts of nanomaterials are not fully understood. Research is needed to assess potential toxicity and safe handling practices for nanomaterials.

Scalability: While many nanotechnology applications show promise at the lab scale, scaling up production for commercial use poses challenges in terms of cost, efficiency, and quality control.

Regulatory Frameworks: Existing regulatory frameworks often do not adequately address the unique properties of nanomaterials. There is a need for specific guidelines and standards to ensure safety without stifling innovation.

Economic Factors: The costs associated with the synthesis and processing of nanomaterials can be prohibitively high, impacting their market competitiveness. There may be reluctance from consumers and industries to adopt nanotechnology due to concerns over safety and efficacy.

Interdisciplinary Collaboration: Effective application of nanotechnology often requires collaboration across multiple disciplines (chemistry, physics, biology, engineering), which can be challenging to achieve. Securing funding for interdisciplinary research initiatives can be difficult, impacting the development of innovative nanotechnology solutions. Intellectual Property Issues: The rapidly evolving nature of nanotechnology raises questions about patenting, ownership, and protection of innovations, leading to potential legal disputes.

Way Forward

» Research and Development:

Prioritise research in areas with high potential for societal and economic benefits. Foster international collaboration among researchers to accelerate progress and share knowledge. Encourage public-private partnerships to bridge the gap between research and commercialization.

» Addressing Safety and Health Concerns:

Conduct rigorous testing of nanomaterials to assess their potential toxicity and environmental impact.

»Ethical and Social Responsibility:

Develop and implement ethical guidelines for the development and application of nanotechnology. Ensure that the benefits of nanotechnology are distributed equitably and do not exacerbate existing social and economic disparities.

» Regulatory and Policy Framework:

Develop comprehensive regulatory frameworks to ensure the safe and responsible use of nanotechnology. Develop international standards and regulations for nanotechnology to ensure consistency and harmonisation.

» Public Awareness and Education:

Develop educational programs for the public, policymakers, and industry professionals to increase understanding of nanotechnology.

CONCLUSION

Nanotechnology holds immense potential across various sectors, offering groundbreaking innovations. However, challenges like safety, scalability, and ethical concerns must be addressed to harness its benefits responsibly. A balanced approach, combining research, regulation, and public awareness, is essential for its sustainable development.

REFERENCES

1. Zelzer M., Ulijn R.V. Next-generation peptide nanomaterials: Molecular networks, interfaces and supramolecular functionality. Chem. Soc. Rev. 2010;39:3351–3357. doi: 10.1039/c0cs00035c. [DOI] [PubMed
2. .Anselmo A.C., Mitragotri S. Nanoparticles in the clinic: An update. Bioeng. Transl. Med. 2019;4:e10143. doi: 10.1002/btm2.10143. [DOI] [PMC free article] [PubMed]
3. Rickerby D., Morrison M. Nanotechnology and the environment: A European perspective. Sci. Technol. Adv. Mater. 2007;8:19. doi: 10.1016/j.stam.2006.10.002.
4. Bhushan B. Handbook of Nanotechnology. Springer Handbook of Nanotechnology; Berlin/Heidelberg, Germany: 2017. Introduction to nanotechnology; pp. 1–19.
5. Kroto HW, Heath O Jr, O'Brien SC, Curl RF and Smalley RE: Buckminsterfullerene. This Week's Citation Classic. Nature. 318:162–163. 1985.
6. Allhoff F, Patrick L and Daniel M: What is Nanotechnology and Why Does it Matter? From Science to Ethics. John Wiley & Sons, pp3-5, 2010.
7. Mashaghi S, Jadidi T, Koenderink G and Mashaghi A: Lipid nanotechnology. Int J Mol Sci. 14:4242–4282. 2013.PubMed/NCBI View Article : Google Scholar
8. Farokhzad OC and Langer R: Nanomedicine: Developing smarter therapeutic and diagnostic modalities. Adv Drug Deliv Rev. 58:1456–1459. 2006.PubMed/NCBI View Article : Google Scholar

9. Filipponi L and Nicolau DV: Cell Patterning. Wiley Encyclopedia of Biomedical Engineering. John Wiley & Sons, 2006.
10. Lombardo D, Kiselev MA and Caccamo MT: Smart Nanoparticles for Drug Delivery Application: Development of Versatile Nanocarrier Platforms in Biotechnology and Nanomedicine. J Nanomater. 12:1–26. 2019.
11. Katsuki S, Matoba T, Koga JI, Nakano K and Egashira K: Anti-inflammatory Nanomedicine for Cardiovascular Disease. Front Cardiovasc Med. 4(87)2017.PubMed/NCBI View Article : Google Scholar
12. Morgan MT, Carnahan MA, Finkelstein S, Prata CA, Degoricija L, Lee SJ and Grinstaff MW: Dendritic supramolecular assemblies for drug delivery. Chem Commun (Camb). 97:4309–4311. 2005.PubMed/NCBI View Article : Google Scholar
13. Tiriveedhi V, Kitchens KM, Nevels KJ, Ghandehari H and Butko P: Kinetic analysis of the interaction between poly(amidoamine) dendrimers and model lipid membranes. Biochim Biophys Acta. 1808:209–218. 2011.PubMed/NCBI View Article : Google Scholar
14. Palmerston Mendes L, Pan J and Torchilin VP: Dendrimers as nanocarriers for nucleic acid and drug delivery in cancer therapy. Molecules. 22(1401)2017.PubMed/NCBI View Article : Google Scholar
15. Kukowska-Latallo JF, Bielinska AU, Johnson J, Spindler R, Tomalia DA and Baker JR Jr: Efficient transfer of genetic material into mammalian cells using Starburst polyamidoamine dendrimers. Proc Natl Acad Sci USA. 93:4897–4902. 1996.PubMed/NCBI View Article : Google Scholar
16. Svenson S and Tomalia DA: Dendrimers in biomedical applications - reflections on the field. Adv Drug Deliv Rev. 57:2106–2129. 2005.PubMed/NCBI View Article : Google Scholar
17. Nune SK, Gunda P, Thallapally PK, Lin YY, Forrest ML and Berkland CJ: Nanoparticles for biomedical imaging. Expert Opin Drug Deliv. 6:1175–1194. 2009.PubMed/NCBI View Article : Google Scholar
18. Shi Kam NW, Jessop TC, Wender PA and Dai H: Nanotube molecular transporters: Internalization of carbon nanotube-protein conjugates into Mammalian cells. J Am Chem Soc. 126:6850–6851. 2004.PubMed/NCBI View Article : Google Scholar
19. Pantarotto D, Briand JP, Prato M and Bianco A: Translocation of bioactive peptides across cell membranes by carbon nanotubes. Chem Commun (Camb). 7:16–17. 2004.PubMed/NCBI View Article : Google Scholar
20. Dai HJ, Hafner JH, Rinzler AG, Colbert DT and Smalley RE: Nanotubes as nanoprobes in scanning probe microscopy. Nature. 384:147–150. 1996.
21. Acharya S and Sahoo SK: PLGA nanoparticles containing various anticancer agents and tumour delivery by EPR effect. Adv Drug Deliv Rev. 63:170–183. 2011.PubMed/NCBI View Article : Google Scholar
22. Mulder WJ, Strijkers GJ, van Tilborg GA, Cormode DP, Fayad ZA and Nicolay K: Nanoparticulate assemblies of amphiphiles and diagnostically active materials for multimodality imaging. Acc Chem Res. 42:904–914. 2009.PubMed/NCBI View Article : Google Scholar
23. Probst CE, Zrazhevskiy P, Bagalkot V and Gao X: Quantum dots as a platform for nanoparticle drug delivery vehicle design. Adv Drug Deliv Rev. 65:703–718.

2013.PubMed/NCBI View Article : Google Scholar

24. Medina C, Santos-Martinez MJ, Radomski A, Corrigan OI and Radomski MW: Nanoparticles: Pharmacological and toxicological significance. Br J Pharmacol. 150:552–558. 2007.PubMed/NCBI View Article : Google Scholar
25. Ratner BD and Bryant SJ: Biomaterials: Where we have been and where we are going. Annu Rev Biomed Eng. 6:41–75. 2004.PubMed/NCBI View Article : Google Scholar

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