



Nanotechnology

For Prelims: [Nanotechnology](#), [Earth's crust](#), Nanodevices, [Polymers](#), [Graphene](#), [Semiconductors](#), [Quantum computers](#), [Silicon chips](#), [Artificial Intelligence \(AI\)](#), [Internet of Things \(IoT\)](#), [3D printing](#), [Biomarker](#), [Chemotherapy](#), [Hydrogel](#), [Nanorobots](#), [Fossil fuels](#), [Light Emitting Diodes](#)

For Mains: National Mission on Nano Science and Technology, Science and Technology Developments and their Applications and Effects in Everyday Life.

[Nanotechnology](#) is revolutionising industries by unlocking new possibilities at the **molecular level**, driving innovation in fields like medicine but it also raises important questions about safety, ethics, and regulation.

What is Nanotechnology?

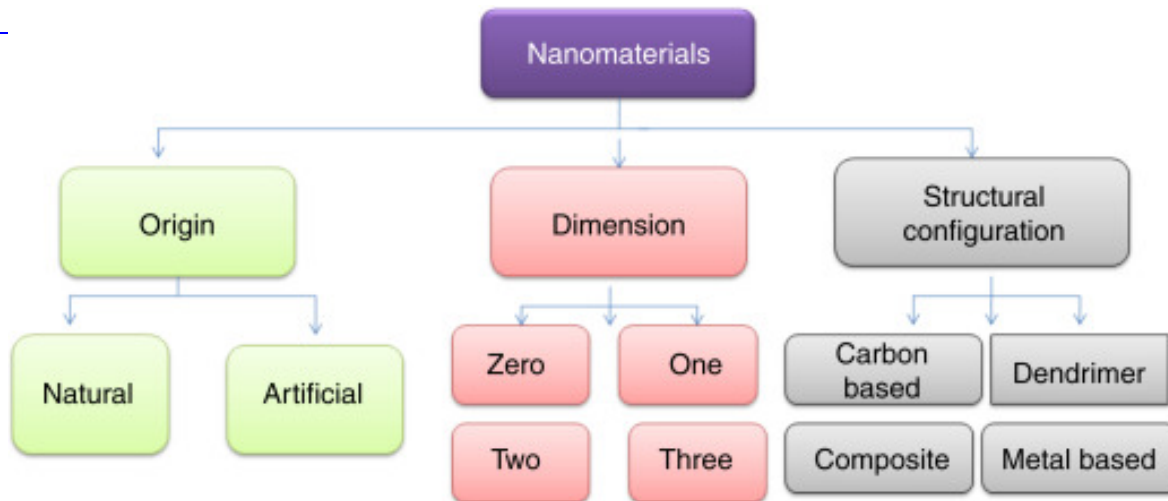
About: Nanotechnology refers to the branch of science and engineering devoted to designing, producing, and using structures, devices, and systems by manipulating atoms and molecules at **nanoscale**, i.e. having one or more dimensions of the order of 100 nanometres (100 millionth of a millimeter) or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

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▪ **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.

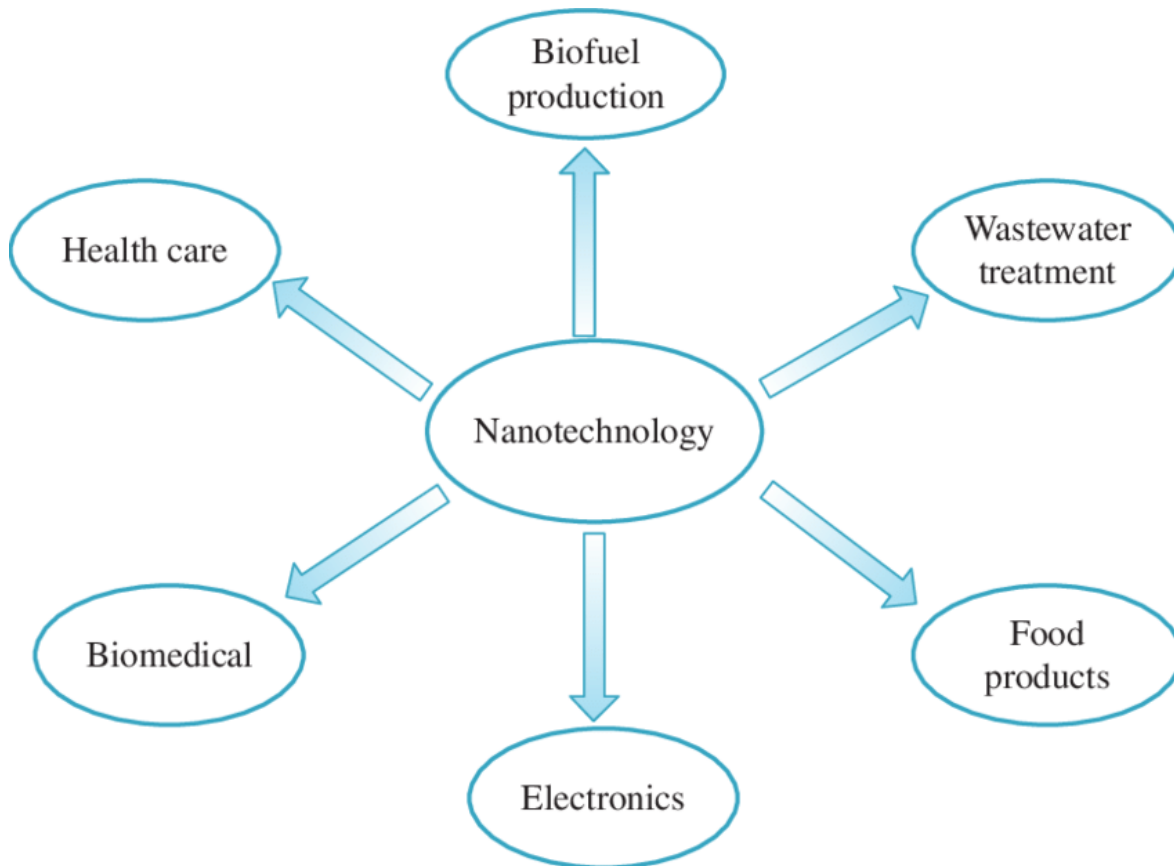
What are the Applications of Nanotechnology?

- **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 long-term 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 mission-mode 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 cost-effective 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 nano-sensors 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.

UPSC Civil Services Examination, Previous Year Question (PYQ)

Prelims:

Q: There is some concern regarding the nanoparticles of some chemical elements that are used by the industry in the manufacture of various products. Why? (2014)

1. They can accumulate in the environment, and contaminate water and soil.
2. They can enter the food chains.
3. They can trigger the production of free radicals.

Select the correct answer using the code given below.

- (a) 1 and 2 only
- (b) 3 only
- (c) 1 and 3 only
- (d) 1, 2 and 3

Ans: (d)

Q: Consider the following statements: (2022)

1. Other than those made by humans, nanoparticles do not exist in nature.

2. Nanoparticles of some metallic oxides are used in the manufacture of some cosmetics.
3. Nanoparticles of some commercial products which enter the environment are unsafe for humans.

Which of the statements given above is/are correct?

- (a) 1 only
- (b) 3 only
- (c) 1 and 2 only
- (d) 2 and 3 only

Answer: (d)

Mains

Q. What do you understand by nanotechnology and how is it helping in the health sector? **(2020)**

Q. Why is nanotechnology one of the key technologies of the 21st century? Describe the salient features of Indian Government's Mission on Nanoscience and Technology and the scope of its application in the development process of the country. **(2016)**

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