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SCIENCE & TECHNOLOGY

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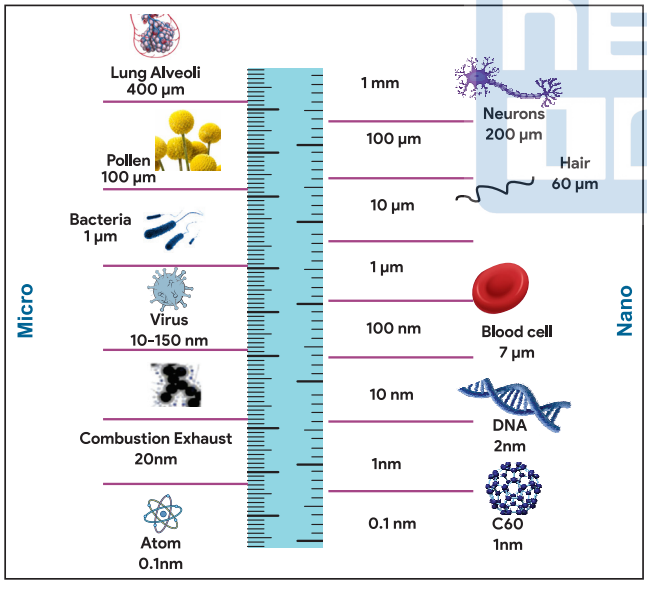
8

NANOTECHNOLOGY AND ITS APPLICATIONS

8.1 Nanotechnology

Nanotechnology deals with the understanding and control of materials with dimensions of about 1-100 nanometers. It involves imaging, modelling, measuring, designing, manufacturing, and applications of nanomaterials. ISO defines nanomaterials as a 'material with any external dimension in the nanoscale (size range from approximately 1 – 100 nm) or having internal structure or surface structure in the nanoscale'.

Nano is mathematically defined by International System of Units (ISU), meaning one-billionth, or 10^{-9}. Therefore one nanometer is one-billionth of a meter. To put it in perspective, one nanometer is equivalent to 1/100,000 of thickness of a sheet of paper; a human hair is approximately 80,000- 100,000 nanometers wide.



8.2 Working at the Nanoscale

Nanotechnology requires the ability to understand and manipulate materials at nanoscale to take advantage of their special properties. However, it is not simple to work at nanoscale. To work on the nanoscale, you need to understand the different types and dimensions of nanoscale materials. Different types of nanomaterials are named according to their individual shape and dimensions. They can be imagined as particles, tubes, wires, films, flakes, or shells with at least one dimensions of nanometer scale. For example, carbon nanotubes have nano-range diameters, but can be hundreds of nanometers in length. Nanofilms, or nanoplates, are nanoscale in thickness, but the other two dimensions can be much larger.

The key is able to both observe and manipulate nanomaterials in order to take advantage of their special properties. Scientists use special microscopes to see, study and work upon nanomaterials. One of the earliest discoveries is the ***scanning tunnel microscope***, which measures tiny objects such as carbon nanotubes.

8.3 Manufacturing at the Nanoscale

Manufacturing at the nanoscale is called nanomanufacturing. Nanofabrication involves the high-end, reliable, and inexpensive manufacturing of nanoscale materials, structures, devices, and systems. There are two basic approaches to nanomanufacturing, top-down or bottom-up.

- **Top-down fabrication** reduces large pieces of materials all the way down to the nanoscale, like someone carving a model car out of a block of wood. This approach requires larger amounts of materials and can lead to waste if excess material is discarded.
- **The bottom-up approach** creates products by building them up from atomic and molecular scale components, which can be time-consuming. Scientists are exploring the concept of spontaneous and autonomous self-assembly by placing certain molecular-scale components together.

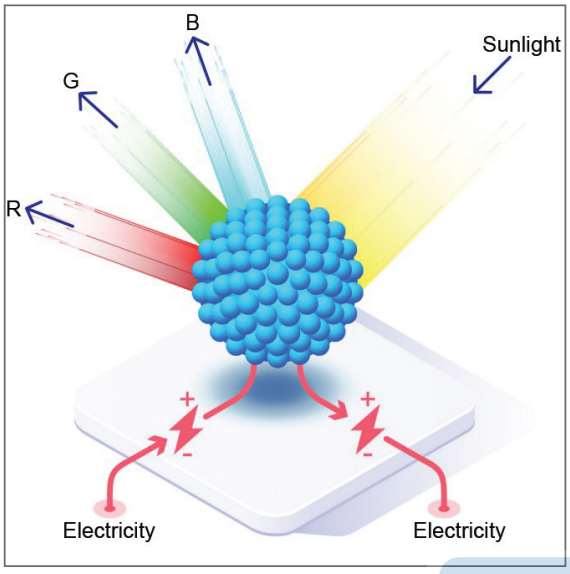
Today, **researchers at** universities and companies around the world are **developing** new products and applications, from medical devices and **medicines used** to treat **illnesses** to **durable**, lightweight materials that reduce fuel costs for cars and planes.

8.4 Nanotechnology Related Concepts

Quantum Dots

These are semiconducting nano-crystals that can transport electrons. They can emit light of various colour

when UV light hits them. These artificial semiconductor nanoparticles that have found applications in composites, solar cells and fluorescent biological labels.



Graphene

Graphene is the name given to a monolayer sheet of carbon atoms that are linked together in a hexagonal repeating pattern. The stacked monolayers of graphene form graphite. Graphene has evolved into one of the most promising nanomaterials due to its unique combination of *extraordinary properties*. It is not only the thinnest, but also one of the most powerful materials. It conducts heat better than any other material. It is an excellent electrical conductor. Although it is optically transparent, it is so dense that it does not allow gas to pass through. Even the smallest gas atom, helium, cannot penetrate.

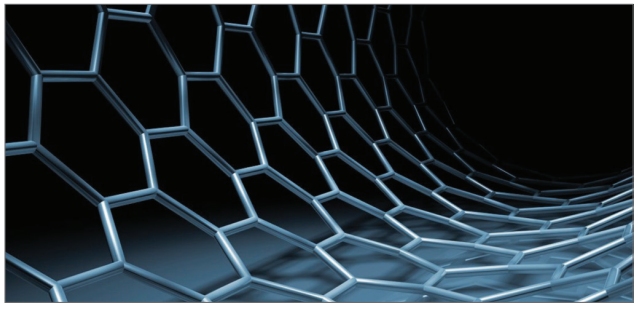


Figure: Structure of Graphene

Nanobot

Nanobot is nanoproduct with a unique property that enables them to be programmed for specific task. For example they can be used in drug delivery or killing cancer cells. A large amount of research is going on make nanoshapes and nanomachines from nucleic acid. DNA assembly is being one of the most actively researched areas of nanorobotics today. Nanobots also helped in vaccine and drug delivery during covid times.

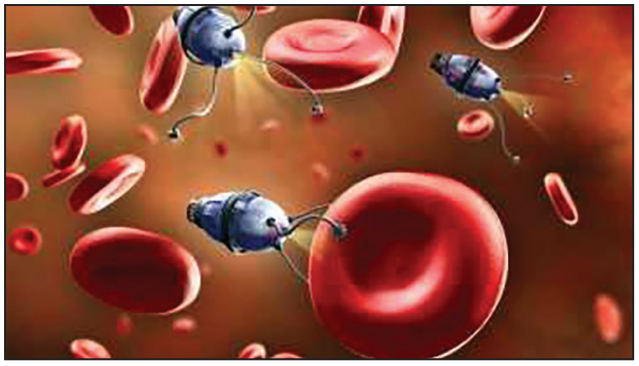


Figure: Computer Model of Nanobots

MXenes

MXenes are the *carbides, carbonitrides*, and *nitrides of 2D transition metals*. MXenes not only possess the standard features of 2D nanomaterials, but also exhibit excellent optical, electronic and magnetic properties.

There applications include lithium-ion and sodium-ion energy storage systems, electromagnetic interference (EMI) shielding, and water purification. MXenes are also promising antibacterial agents, with higher efficiency than graphene oxide in diminishing bacterial cell viability.

Carbon Nanotubes

Carbon nanotubes (CNTs) are cylindrical molecules that consist of rolled-up sheets of single-layer carbon atoms (graphene). They can be single-walled (SWCNT) with a diameter of less than 1 nanometer (nm) or multi-walled (MWCNT), consisting of several concentrically interlinked nanotubes, with diameters reaching more than 100 nm. Their length can reach several micrometers or even millimetres.

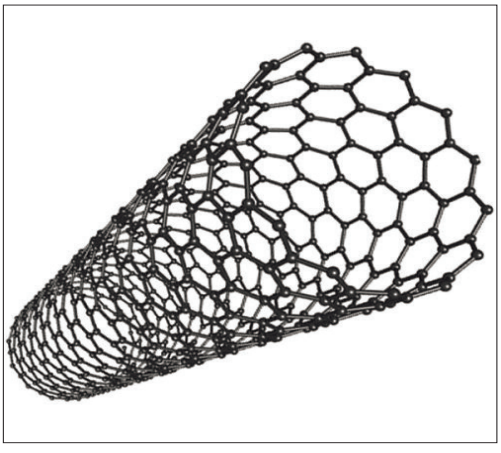


Figure: Carbon Nanotubes

8.5 Applications of Nanotechnology

Daily Use Applications

- **Nanoscale Additives** in polymer composite are used to make baseball bats, tennis rackets, bicycles, motorcycle helmets, automobile parts, luggage, and power tool housings. These additives enhances physical property of these products by making them lightweight, stiff, durable, and resilient.
- **Smart Fabrics** are those fabrics which are equipped with flexible nanoscale sensors and electronics with capabilities for health monitoring, energy harvesting through movement, posture maintenance, etc.
- **Nanoscale Films** are very fine films on eyeglasses, laptop and mobile screen displays, facades, and other surfaces can make them water and residue repellent, anti-reflective, self-cleaning, resistant to ultraviolet or infrared light, anti-fog, antimicrobial, scratch-resistant, energy capture, etc.
- **Nanostructured Ceramic Coatings** exhibit much greater toughness than conventional wear-resistant coatings for machine parts
- **Nanomaterials in Automotive Products** include high-performance rechargeable battery systems, thermoelectric material for temperature control, vehicle tires with low rolling resistance, fuel additive for cleaner exhaust and extended range.
- **Personal Care Products** such as nanoscale titanium dioxide and zinc oxide have been used in sunscreens for years to provide protection from the sun while appearing invisible on the skin.

Electronics and IT

Nanotechnology has greatly contributed to major advances in computing and electronics, leading to faster, smaller, and more portable systems that can manage and store larger and larger amounts of information. These continuously evolving applications include:

- **Transistors:** Nanotechnology researchers in the microprocessor industry have made improvements in nanolithography and changes in the nanoscale structure of the transistors that are increasing the density of transistors in microprocessors.
- **Ultra-HD TV Screens:** Nano crystal or quantum dot technology is a new TV technology that uses nanoscopically small crystals (5 to 20 nanometers in size) as both a light and color source
- **Electronics:** Flexible, bendable, foldable, rollable, and stretchable electronics like e-reader and smartphone displays, photovoltaic clothing, electronic papers etc.
- **Ultra-responsive** hearing aids.
- **Nanoparticle copper** suspensions have been developed as a safer, cheaper, and more reliable alternative to lead-based solder and other hazardous materials commonly used to fuse electronics in the assembly process.

Medical and Healthcare

- **DNA Nanotechnology:** The appeal of DNA to nano-scientists is threefold: first, it is a natural nanoscale material; second, a large number of techniques for studying DNA are already available; and third, its ability to carry information can be exploited in the self-assembly process.
- **Nano Medicine:** Nanomedicine ranges from the medical applications of nanomaterials and biological devices, to nanoelectronic biosensors, and even possible future applications of molecular nanotechnology such as biological machines. For example in Drug delivery the focus is on maximizing bioavailability both at specific places in the body and over a period of time. This can potentially be achieved by molecular targeting by nanoengineered devices.
- **Diagnostics:** Better imaging and diagnostic tools enabled by nanotechnology are paving the way for earlier diagnosis, more individualized treatment options, and better therapeutic success rates. For example: gold nanoparticles are used as probes for the detection of targeted sequences of nucleic acids
- **Medical Devices:** Many new medical devices (embedded or non-embedded) contain nanomaterials either by surface coating with nanoparticles, by direct nanostructuring of the surface or by manufacturing nanobots. Devices such as Nanorobots can be introduced in body to repair or detect damage and infections. Some other devices include orthopedic and dental implants, in-vitro diagnostic devices, wound dressings, bone void fillers, stents, vascular grafts, and more.

HEALTH

- Nanotech detectors for heart attack
- Nanochips to check plaque in arteries
- Nanocarriers for eye surgery, chemotherapy, etc.
- Diabetic pads for regulating blood sugar levels
- Nanoparticles for drug delivery to the brain – for therapeutic treatment of neurological disorders
- Nanosponges – are polymer nanoparticles coated with a red blood cell membrane, can be used for absorbing toxins and removing them from the bloodstream
- NanoFlares – used for detection of cancer cells in the bloodstream
- Nanopores – use in making DNA sequencing more efficient.

Energy Applications

Nanotechnology is finding application to develop clean, affordable, and renewable energy sources, along with means to reduce energy consumption:

- *Nanotechnology* can be incorporated into solar panels to convert sunlight to electricity more efficiently, promising inexpensive solar power in the future.
- *Nanotechnology* is already being used to develop many new kinds of batteries that are quicker-charging, more efficient, lighter weight, have a higher power density, and hold electrical charge longer.
- An epoxy containing *Carbon Nanotubes* is being used to make windmill blades that are longer, stronger, and lighter-weight than other blades to increase the amount of electricity that windmills can generate
- Researchers are investigating carbon nanotube "scrubbers" and membranes to separate carbon dioxide from power plant exhaust.
- Researchers are developing wires containing carbon nanotubes that will have much lower resistance than the high-tension wires currently used in the electric grid, thus reducing transmission power loss.
- Nano-bioengineering of enzymes is aiming to enable conversion of cellulose from wood chips, corn stalks, unfertilized perennial grasses, etc., into ethanol for fuel.

Environmental Applications

Nanotechnology is being used to reduce toxicity burden on environment and for it remediation

- Nanoscience-based options are being pursued to convert waste heat in computers, automobiles, homes, power plants, etc., to usable electrical power.
- Nanotechnology could help meet the need for affordable, clean drinking water through rapid, low-cost detection and treatment of impurities in water.
- Nanoparticles are being developed to clean industrial water pollutants in ground water through chemical reactions that detoxify pollutants.
- Nanotechnology-enabled sensors and solutions are now able to detect and identify chemical or biological substances in the air and soil with much unprecedented sensitivity.
- Researchers are investigating particles such as mesoporous, dendrimers, and carbon nanotubes to see how their unique chemical and physical properties can be used in the cleanup of different types of toxic sites.

Heavy Industries

- **Petrochemical:** Nanomaterials are incorporated into various hydrocarbon extractions, gas separations, solid gas sensors for monitoring air pollution, corrosion inhibitors and more.
- **Aerospace:** Lighter and stronger materials bring immeasurable benefits to aircraft manufacturers, resulting in lower fuel consumption and improved performance.
- **Vehicle Manufacturing:** Similar to the aerospace industry, lighter and stronger materials help to produce faster and safer vehicles. Internal combustion engines also benefit from more wear-resistant and heat-resistant components.

Construction Industry

- **Nano Cement Mortar:** Nano cement mortar refers to the uses of nanomaterials to enhance the structure and properties of mortar. You can effectively use a variety of nanomaterials in mortar, including: NanoSiO2, Nano-Fe2O3, Nano-Al2O3, Nano-TiO2, nanoclay, nanopolymer fabrics, etc.
- **Steel:** The use of nanotechnology in steel improves the properties of steel. It improves the fatigue strength of steel that is repeatedly loaded. The addition of copper nanoparticles reduces the surface roughness of the steel, which limits the number of stress surges and fatigue cracks. The result is increased safety and less need for regular inspections.
- **Glass:** Titanium Dioxide (TiO2) nanoparticles are used for glazing coatings due to their sterilizing and antifouling properties. Particles catalyze a powerful reaction that breaks down organic pollutants, volatile organic compounds, and bacterial membranes. Because TiO2 is hydrophilic, it can attract raindrops. Raindrops wash away dirt particles and create self-cleaning properties. Fire-protective glass is achieved by using an intermediate layer formed of silica nanoparticles (SiO2) sandwiched between glass panels.
- **Paints:** Nanotechnology is applied to the paint to obtain a coating with self-healing properties and corrosion protection under insulation. The nanoparticle-based system protects the metal from saltwater attacks and provides better adhesion and transparency

Application in Food Industry

- The benefits of nanotechnology for the food industry are many and are expected to grow with time. This new, rapidly developing technology impacts every aspect of the food system from cultivation to food production, transportation, shelf life and bioavailability of nutrients.

- In agriculture, Nanoformulations of agrochemicals are used as pesticides and fertilizers for crop improvement. Nanosensors/nanobiosensors can be used in crop protection for the identification of diseases and residues of agrochemicals.
- In biotechnology, Nano devices are employed for the genetic manipulation of plants, for plant disease diagnostics, etc.
- Food processing industries use nanomaterial as an ingredients and additives in nutrient and health supplement for enhanced absorption and bioavailability. Nanocapsules infusion of a plant based steroids are used to replace meat's cholesterol content.
- Food technologists are working hard to improve food safety of our food supply and nanotechnology opens door to a whole new array of products. Some nanomaterials like ZnO and MgO have anti-microbial properties that can be used in packaging for increasing life of food.

Figure: Nanotechnology in Agriculture and Food processing Industry

8.6 Nanotoxicology and Nano Pollution

Nanotoxicology is the study of the toxicity of nanomaterials. Effect of nanomaterial on biological systems, human health and environment are yet to be fully understood. Due to the small size and large surface area to volume ratio, nanomaterials have unique properties that affect toxicity. Of the potential risks, inhalation exposure appears to be the number one concern. Animal studies have shown the effects of some nanomaterials on the lungs, including inflammation, fibrosis, and carcinogenicity. Skin deterioration and ingestion are some other concern

Nanopollution refers to all the waste matter or byproducts that occur during the manufacture or use of nanoscopic devices or material.

There are three main ways that nanoparticle waste enter the environment. The first is emission during processes like mining and refining. The second is emission due to washed away cosmetics such as sunscreens into the

environment. The third is from disposal of nanoparticle products or use during waste treatment, like nanoparticles in sewage and wastewater streams.

Measuring Nanomaterials in the Environment

Significant progress has been made in the last decade in understanding the sources, fate, and effects of nanoparticles. Predictions of environmental concentrations based on the modeling approach can be confirmed by the concentrations measured in the field. Analytical techniques are still being developed to more efficiently and reliably characterize and quantify nanoparticles. In addition, the impact of nanoparticles on aquatic and terrestrial systems is receiving increasing attention.

A new cost-effective invention called Microwave Heating is being explored to measure carbon nanotube concentration where they are being used. IT reveals not only the presence but also the concentration.

Preventing Nanopollution

Although the fight against nano pollution has begun, there is a long way to go. One research showed that not all nanoparticles are toxic, as most of them have a stable protective coating rendering them nontoxic to living cells. What this means is that surface chemistry of nanoparticles play a big role in classifying them as toxic or not.

Most commentators agree that the best way to work towards a solution to the problems posed by nano pollution is initially through increased levels of communication and discussion. Collaboration between experts from a variety of scientific disciplines, such as materials science, toxicology, chemical engineering and environmental sciences is essential for the development of new concepts and technologies to deal with this new environmental threat.

It seems almost certain that strict regulations will be necessary on the nanomaterials which can be released into the environment from manufacturing facilities. Regulators are hesitant to act, however, because of the unclear consensus from the research to date about the health implications of exposure to nanopollution. They are therefore reluctant to place undue limits on a growing industry without concrete evidence.

In the coming years hopefully, we will see nano-based companies competing against each other to implement the most effective new practices to prevent nanopollution.

Nanopollution is a growing issue - we are already releasing a large amount of nanomaterials into the environment, and we do not have a strong idea how many of them will impact human health.

Research is progressing rapidly, and hopefully we will build a picture of which materials need particular care and attention, and develop methods of dealing with them, before too much damage is done.

Regulators have been reluctant to place any heavy restrictions on nano pollutants, as that could place a serious block on the growth of industries outside of nanotechnology, as well as the booming nano sector itself. This may be sensible in the short term, but could create issues later on if we cannot develop methods to treat or remediate nanopollution.

8.7 India and Nanotechnology

The Ministry of Electronics and Information Technology (MeitY) has taken several important initiatives to promote research and innovation in nanoelectronics in the country. Important nanoelectronic centers with international standards are set up at major institutions in the country. The Indian Nanoelectronics User Program (INUP), launched by MeitY, and is being implemented at the Center of Excellence in Nanoelectronics (CEN) at IISc and IIT Bombay. This is helping the R & D community across the country to access the state-of-art nanofabrication facility for nanoelectronics. Approximately 400 researchers receive nanofabrication training at these centers each year. Research activities to date have resulted in numerous research publications and a significant number of patent application

Mission on Nano Science and Technology (Nano Mission)

Building upon the promotional activities carried out as part of the Nano Science and Technology Initiative (NSTI) in the highly promising and competitive area of Nano Science and Technology, the Government of India launched a

Mission on Nano Science and Technology (Nano Mission) in May 2007. It was a five year program with funding of $ 250 million. The funding spanned multiple areas like basic research in nanotechnology, human resources development, infrastructure development and international collaboration. The Department of Science and Technology was the nodal agency for implementing the Nano Mission.

The mission was a success. During the course of five years, India published over 23000 papers in nanoscience. In 2013, India ranked third in the number of papers published, behind only China and USA. There have been 300 patent applications in the Indian Patent Office in 2013, ten times that of 2006.

International Conference on Nano Science and Technology (ICONSAT)

ICONSAT is the series of biennial international conferences held in India under the aegis of Nano Mission, Department of Science and Technology (DST). The last conference was held in 2020 at Biswa Bangla Conventional Centre, Kolkata. Some of the highlights of this conference are:

- There were emphasis on 5Ms – *mechanical, material, machines, manufacturing and manpower*. This would help in finding the solutions for the challenges like sustainable development and new technology (machine learning, artificial intelligence etc.)
- Several emerging areas such as quantum materials, energy materials and nanotechnology for agriculture have been identified as the thrust areas of DST Nano mission.

Impacting Research, Innovation & Technology (IMPRINT)

The IMPRINT program aims to establish a roadmap for India to gain a leadership position in nanotechnology product development. It addresses five problem areas in its Nanotechnology Grand Challenges initiative. These are Security, Healthcare, Agriculture, Pedagogy and Environment (SHAPE).

- The **Center of Excellence in Nanoscience and Nanotechnology** established by DSTNanomission helps research and PG students in various thrust areas.
- **Department of Science and Tech-Nanomission**

  The nano-biotechnology activities through DBT, ICMR, and CoE in Nanoelectronics by MeitY support nanoscience, nanotechnology, nanobiotechnology, and nanoelectronics activities.
- **Thematic Units of Excellence (TUEs)** for various areas of nanoscience and nanotechnology play a major role in product-based research to support nanotechnology.
- **DST-Nanomission** supports more than 20 PG teaching programs to create a baseline for nanoscience and nanotechnology in India, out of about 70 PG programs currently running in India.

8.8 Conclusion

Development in Nanotechnology can make India self-sufficient in sectors like defence and anti-terrorism. Through Nano Mission we have increased our publication significantly, however, the quality of research needs to be enhanced. Further, number of patents should also be increased. This would require increased spending from both private and public sector. Given the enhanced focus of government in sectors like renewable energy, environmental preservation, pollution control, biotechnology, manufacturing, etc., the future of nanotechnology in India seems bright.

■■■■

TRY SOME PRELIMS PREVIOUS YEAR QUESTIONS

1. **Consider the following statements:**

1. Carbon fibres are used in the manufacture of components used in automobiles and aircrafts.
2. Carbon fibres once used cannot be recycled

Which of the statements given above is/are correct?

(a) 1 only (b) 2 only
(c) Both 1 and 2 (d) Neither 1 nor 2

(2023)

Ans. (a)

2. **Consider the following statements for nanotechnology:**

1. It is the technology of creating materials and devices atom by atom
2. Physical properties change at the nanometer scale.
3. Chemical properties change at the nanometer scale.

Which of the above statements are correct?

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

(2022)

Ans. (d)

3. **With reference to carbon nanotubes, consider the following statements:**

1. They can be used as carriers of drugs and antigens in the human body.
2. They can be made into artificial blood capillaries for an injured part of the human body.
3. They can be used in biochemical sensors.
4. Carbon nanotubes are biodegradable.

Which of the statements given above are correct?

(a) Only one (b) Only two
(c) Only three (d) All four

(2020)

Ans. (d)

4. **With reference to the use of Nano-technology in health sector, which of the following statement(s) is/are correct?**

1. Targeted drug delivery is made possible by nanotechnology.
2. Nanotechnology can largely contribute to gene therapy.

Select the correct answer using the codes given below.

(a) 1 only (b) 2 only
(c) Both 1 and 2 (d) Neither 1 nor 2

(2015)

Ans. (c)

5. **There is some concern regarding the nanoparticles of some chemical elements that are used by the industry in the manufacture of various products. Why?**

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 codes given below:

(a) Only one (b) Only two
(c) All three (d) None

(2014)

Ans. (c)

TRY SOME MAINS PREVIOUS YEAR QUESTIONS

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

2. 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)