

Nanotechnology in Energy and Environmental Conservation

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Nanotechnology has shown immense promise for energy and environmental applications by engineering materials at the molecular scale. Unique **optical**, **electrical**, and **mechanical** properties of nanomaterials like **carbon nanotubes**, **graphene**, **nano-catalysts**, etc. allow their use in renewable energy production, energy storage, and removing pollutants. The rapid growth of the global population has significantly increased energy consumption and pressure on the environment.

India's energy demand is projected to grow faster than all major economies over the next 25 years. The country needs to expand its energy infrastructure sustainably to support its development needs while also reducing environmental impacts. This is where nanomaterials can play a transformative role if harnessed responsibly.

Nanotechnology for Energy Applications

Nanotechnology is driving key innovations across the energy sector including energy generation, storage, transmission and efficient utilization. Nanomaterials with their unique properties are useful in these applications.

Energy Generation

- **Solar cells:** Nanomaterials like **quantum dots** and **nanowires** are used to improve solar cell efficiency and permeability.
 - The smaller the nanomaterials, the higher will be the **band gap** (due to quantum confinement), facilitating the absorption of a wider solar spectrum.
 - For example, **quantum dot solar cells** can absorb **solar energy from the UV to the IR region** of the solar spectrum, as the quantum dot band gap can be tuned by changing the dot size.
 - **Cells made of** nanomaterials **offer higher charge** carrier mobility over bulkier materials like **silicon**.
 - These materials allow better **photon absorption** and **charge extraction**.
- **Wind Energy:** Nanomaterials help increase the efficiency of wind energy in many ways.
 - **Nanocoatings**, applied to wind turbine equipment, can protect against **wear** and **abrasion**.
 - Nanomaterials like **carbon nanotubes** allow the making of **lighter** and **stronger wind blades**.
 - **Nano-engineered surfaces** can reduce **drag** and **increase turbine efficiency**.
- **Fuel Cells:** Nanomaterials like **carbon nanotubes** and **nanostructured metal oxides** can substantially improve the performance of fuel cell electrodes.
 - Nanoparticles provide **higher catalyst surface area** (due to their smaller size) and, thereby, a **higher efficiency** of the cells.
 - Nanoparticles of **platinum** support better electrochemical reactivity in conventional fuel cell electrodes.
 - Nanomaterials also increase the **durability of the catalysts** in the fuel cells.
- **Nuclear Energy:** Nanotechnology is being used to develop Nanoparticle-enriched nuclear fuels (Uranium).
 - These fuels can withstand **higher burnups** and **temperatures**.
 - They enable efficient use of nuclear fuel reserves by recovering the fuel.
 - They also assist in **nuclear waste management**.

Energy Storage

- **Li-ion Batteries:** Nanostructured electrodes made of materials like **silicon**, **iron oxide**, and **titanium oxide** increase charge storage capacity and battery life significantly.
 - **Aerogel-based separator plates** (for example, Silicon-Nanographite aerogel anodes) can be used to improve the performance of Lithium-ion batteries.
 - Nanoparticles and nanowires of lithium cobalt oxide (**LiCoO₂**) enhance lithium **ion mobility** and **storage**. **Graphene** nanosheets as electrodes provide a large surface area for **charge transfer**.
 - Nanocoatings prevent electrode degradation, leading to **higher power density**, **faster charging**, longer lifespan, and **improved safety**.
- **Nickel-metal hydride (NI-MH) batteries:** They are widely used in hybrid EVs due to their high energy density (but less than Li-ion batteries), low cost, safety and fast charging/discharging. However, there is a problem of high volume change of its positive electrode, Ni(OH)₂, during the charging-discharging process, which hampers its efficiency.

- Many researches are ongoing on **nanoflowers, nanoplates, nanowires, nanorods**, etc., using **graphene**.
- **One-dimensional nanostructured Ni(OH)₂** has been proven to be an ideal positive electrode due to its large surface area and small change in volume during the charging-discharging process.
- **Nanopore battery:** The '**all-in-one**' **nanopore battery array** utilises myriads of nanopores, in parallel. Each of the nanopores acts as a battery.
 - **Pristine V2O5** serves as the cathode, and the **Lithiated V2O5** serves as the anode. Liquid electrolytes such as **aluminium** or **titanium oxide** are used.
 - The high surface area provides sites for **charge storage** and **transfer reactions**.
 - Nanopores also enable better electrolyte penetration.
 - The **high capacitance** allows high energy density comparable to Li-ion batteries, with safety and low costs.
- **Super-capacitors:** Also known as **ultracapacitors** or **electric double-layer** capacitors (EDLCs), they store electric charge at the interface between a **solid electrode** and a **liquid electrolyte**.
 - Nanomaterials like **graphene** increase supercapacitor performance by offering high surface area and conductivity, faster charging, and a longer lifespan.
- **Hydrogen Storage:** Nanomaterials provide safe and compact storage solutions for Hydrogen.
 - For example, Carbon nanotubes (**CNTs**) used as **hydrogen sponges** allow reversible storage.
- **Thermal Energy Storage:** Nano-structured thermo-electric materials improve the conversion of heat into electricity.
 - It allows a **stable operating range** close to working temperatures.
 - It improves **thermal conductivity** and **heat transfer**.

Energy Transmission

- **Power Lines:** Nanosensors enable **real-time monitoring** of transmission lines.
 - It detects issues like **short circuits, overheating** etc.
 - **Nanocoatings** on cables **minimise power losses** during transmission.
 - **Nano-dielectrics** are used in cables to prevent insulation breakdown.
- **Transformers:** **Nanofluid coolants** are used for cooling transformers.
 - It improves **heat dissipation** and the **lifespan** of transformers.
 - It offers **higher dielectric strength** compared to conventional oils.

Increased Energy Efficiency

Area	Key features
Insulation	- Nanomaterial coatings minimise heat loss improving insulation ability. - Aerogel nanoparticles are used for the thermal insulation of buildings. - Doped plastics, nanocellulose, and nanoporous foams enable advanced insulation.

Lighting	- Nanomaterials improve the efficiency of lighting systems. - Quantum dots, nanorods, and nano phosphors enable high-efficiency LEDs. - Offer the ability to tune emissive wavelengths.
Windows	- Nano-engineered smart windows help regulate light and heat. - Electrochromic nanoparticles allow dynamic solar control. - Provide energy savings compared to conventional static glasses.
Vehicles	- Nanocoatings reduce friction enhancing fuel efficiency. - Protect engine components from wear and corrosion. - Used in automotive paints to resist scratches.
Fuels	- Nanocatalysts are used to refine crude oil into fuel more efficiently. - Improve product selectivity and process optimisation. - Minimise waste generation.
Lubricants	- Anti-wear, extreme pressure nanolubricant additives developed. - Improve the durability of moving parts like bearings, and gears. - Provide thermal stability.
Electronics	- Nanomaterials like graphene and CNTs allow faster, more efficient electronics. - Facilitate miniaturisation and feature densification. - Lower power consumption.

Nanotechnology for Environmental Applications

Nanotechnology is enabling innovations across various aspects of environmental protection and remediation.

Environment Remediation

- **Water filtration and remediation:** Nano-materials like nano-particles of **iron oxide**, **carbon nanotubes** and **nano-porous** membranes can effectively remove contaminants like **arsenic**, **lead** and **organic pollutants** from water through adsorption and size exclusion.
- **Air pollution control:** Nanocatalysts and adsorbents can degrade or trap harmful gases like **SOx**, **NOx** and **volatile organic compounds** from industrial emissions to improve air quality.

- **Soil remediation:** Nanoscale **zero-valent iron particles** and **nano-remediation** solutions containing nano-scale minerals/microbes can degrade organic/inorganic contaminants in soil and groundwater and restore soil health.
- **Wastewater treatment:** Nano-adsorbents, nano-catalysts and **nano-membranes** can effectively treat **domestic** and **industrial wastewater**, enable water reuse and prevent environmental pollution.

Sensing and Monitoring

- **Pollution sensing:** Nano-sensors incorporated in **mobile devices** and **wireless sensor networks** can detect **toxic gases**, **water pollutants** and **environmental radiation** in real-time. This allows quick response and remediation.
- **Lab on a chip: Portable nano-chip devices** can rapidly detect and analyse environmental samples **onsite**, eliminating the need for transporting samples to centralised laboratories.
- **Nano-satellites & remote sensing:** Small and micro nano-satellites can monitor **forests**, **agriculture**, and **coastal regions** and provide early warning for **natural disasters** and **anthropogenic changes** with high resolution.

Energy Conservation

- **Nano-coatings:** Nano-structured coatings of surfaces can retard **heat flow** and **improve thermal insulation**.
 - This helps conserve energy in buildings, piping, storage systems etc.
- **Smart glass:** Nano-particle **dispersed fluid between glass panes** can modulate light transmission. This conserves heating/cooling energy while maintaining natural lighting.
- **Efficient lighting:** White LEDs using **nano-structured phosphors** increase lighting efficiency and lifetime and reduce electricity consumption.

Key Challenges of Nanotechnology in Energy and Environmental Conservation

While nanotechnology in Energy and Environmental Conservation represents exciting opportunities in sustainability, there are some challenges and risks:

- **High costs:** Nanomaterials and nanomanufacturing currently have very high costs. This limits the widespread commercial adoption of nanotechnology solutions for **energy and the environment**.
 - Bringing down **fabrication costs** through better manufacturing techniques is necessary.
- **Durability and reliability:** Nanomaterials can degrade during operation due to factors like **sintering**, **corrosion** etc.
 - This affects the durability and reliability of nanotech-enabled products for long-term use in energy systems and other applications.
 - Enhancing stability through **surface modifications** is an area of further research.
- **Health and safety risks:** The toxicity and potential environmental impacts of engineered nanomaterials are not fully characterised.

- Understanding health and environmental hazards and appropriate safety guidelines for nanomaterial design, use and disposal are still evolving.
- **Multifunctionality:** Designing nanomaterials that provide multiple functionalities relevant to energy systems reliably still poses engineering challenges.
 - For example, nano catalysts for solar fuel conversion need **high activity, selectivity** and **stability**.

Key Initiatives in India

Realising the potential of nanotechnology, India has established dedicated nanotechnology programs and research centres:

- **Nano Mission:** The Government has established research centres like the **Center for Nano Science and Engineering (CeNSE)** at IISc Bangalore which developed **zinc oxide nanowires** for **dye-sensitized solar cells**.
 - Also supported pilot projects on **graphene-based water filters** at IIT Bombay.
- **Other Government Initiatives:** The Ministry of New and Renewable Energy has supported projects leveraging nanomaterials for renewable energy solutions.
- **International Collaboration:**
 - **Indo-US Joint Clean Energy Research and Development** Center has joint R and D projects using nanomaterials for **solar energy harvesting, storage, and conversion**.
 - India has also partnered with **Israel** on **nanotech-based solutions for water treatment**.

Way forward

The future outlook for nanotechnology contributing positively to sustainability is promising. Several enabling developments are on the horizon:

- **Expanding market:** Strong growth is forecasted in nanomaterial use for renewable energy technologies like solar panels and lithium-ion batteries.
- **New capabilities:** Advances in nanofabrication, and directed self-assembly to enable precise, low-cost manufacturing at scale.
- **Multifunctionality:** Combining capabilities from different nanomaterials in hybrid nanocomposites for improved performance.
- **Commercialisation:** More pilot studies are underway. Commercially viable products are expected soon for areas like nano-enabled batteries, and water purification devices.
- **Policies and regulation:** Governments establishing guidance frameworks for responsible development and use of nanotechnology.

Nanotechnology is essential for the development of advanced and sustainable manufacturing globally. It can enhance efficiency across industrial processes and enable next-generation products. However, potential risks to health and the environment need to be addressed through safety research and responsible development. With prudent policies and collective efforts, nanotechnology can hugely benefit industries worldwide and enable inclusive economic growth.

Nanotechnology in Energy and Environmental Conservation UPSC PYQs

Question 1: Consider the following statements: (UPSC Prelims 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?

1. 1 only
2. 3 only
3. 1 and 2 only
4. 2 and 3 only

Answer: (d)

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