



Nanomaterials: A Review on Modern Applications Across Scientific Frontiers

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ABSTRACT :

The integration of nanomaterials represents a transformative frontier with significant potential for scientific and technological advancement. This review looks at how nanotechnology is being used and what its future holds, trying to find current trends, problems, and possible new uses. We employed a scientometric approach to gather and analyze the existing research and literature within the realm of nanotechnology. By systematically reviewing recent studies and developments, we identified significant trends, challenges, and potential directions for future research and applications. This review's findings demonstrate the significant impact of nanotechnology on the discovery and design of new materials, healthcare, environmental monitoring, energy conversion, and quantum computing. Challenges require careful assessment and mitigation; nevertheless, the opportunities for innovation and progress in diverse domains are unmistakable. This review underscores the importance of nanotechnology in achieving its full potential, thereby impacting the future.

Keywords: Nano, Applications, Trends, Challenges, Nanomaterials.

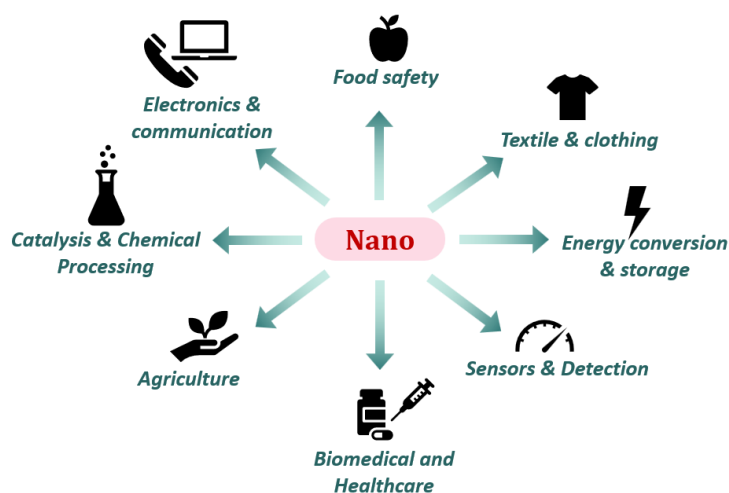


Fig. 1: Graphical Abstract

Introduction

Nanomaterials are now one of the most important types of materials in modern science because they link basic research to advanced technological uses. These materials have physical, chemical, and mechanical properties that are very different from those of bulk materials [1–3]. Their structural characteristics at the nanometer scale (typically 1–100 nm) delineate them. This is due to quantum confinement, changes in the ratio of surface area to volume, and changes in the electronic structures [4, 5]. Nanotechnology has made a lot of progress in the last 20 years. Now, scientists can design and make nanomaterials with full control over their size, shape, and composition. A lot of fields have changed a lot because of this [6].

Nanomaterials are very important in many fields today, such as electronics, energy storage, catalysis, medicine, cleaning up the environment, and sensing. Their adjustable properties have made solar cells work better [7], chemical sensors more selective [8], drugs easier to deliver to specific places [9], and defects [10] and lighter composites [11] easier to make. Nanomaterials can also be used in new areas like artificial intelligence [12], biotechnology [13], and sustainable energy systems [14]. This shows how they could help solve problems in science and society all over the world.

Nanomaterials are important to study because they have unique physical, chemical, and biological properties that bulk materials lack. This opens up

new possibilities for scientific and technological applications. They are very reactive because they have a large surface area compared to their volume. This is why they are great for sensors, catalysis, and cleaning up the environment [15, 16]. Nanomaterials improve the performance of electronics by making devices that are faster and use less energy, and by helping to make progress in energy storage and conversion. In medicine, they enable targeted drug delivery and novel diagnostic instruments [17], transforming healthcare practices and the customization of treatments for individual patients. Nanomaterials research helps us find long-term ways to clean up water, make energy from renewable sources, and cut down on pollution [17–20]. We can guess what dangers nanomaterials might pose to people and work to make them less dangerous if we know about them. Their ability to change encourages new ideas in many fields, such as biotechnology, packaging, and manufacturing. Even though society has a lot of problems to deal with, research on nanomaterials is still an important part of scientific progress in the future.

The Rationale of the Review

This review aims to satisfy the growing necessity for a comprehensive understanding of nanomaterials and their various applications in scientific and technological domains. This review systematically analyzes the existing research landscape, identifying critical knowledge gaps, clarifying emerging trends, and providing insights into the practical, environmental, and industrial implications of nanomaterials. The reason for this review is that nanomaterials have already changed fields like energy, healthcare, electronics, environmental cleanup, and agriculture because of their unique size-dependent properties. They are better than other materials because they have a unique surface area, quantum effects, and properties that can be changed for light, electricity, and chemicals. Learning about these applications is not just an academic exercise; it is also necessary because nanomaterials can make technology more energy-efficient, improve medical diagnostics and treatments, make sensitive sensors possible, and help create long-lasting technological solutions [21].

The study aims to provide a thorough examination of current applications of nanomaterials within scientific fields, highlighting recent developments and future research directions. It also talks about issues like toxicity, scalability, cost-effectiveness, and rules that must be followed. This review seeks to direct subsequent research trajectories, educate policymakers, and advocate for the ethical advancement and utilization of nanomaterials across scientific domains [22]. It does this by emphasizing how important it is for materials scientists, engineers, and experts in specific fields to work together.

Methodology

We used academic databases like PubMed, IEEE Xplore, Google Scholar, and Scopus to do a thorough review of the literature. Searching for terms like "Nanotechnology," "nanomaterials," and "Nano applications" led us to useful research articles, conference papers, and reviews. We picked articles from 2015 to 2025 to look at recent trends and changes. This time frame was chosen so that the most up-to-date research could be included and deadlines for publication could be met. The review had articles about how to use nanomaterials in real life and new ways to use them. We didn't include papers that only looked at theoretical ideas and didn't have any real-world applications.

Applications of Nanomaterials

4.1 Energy conversion and storage

Nanomaterials are very important for making energy applications better because they have special properties like a large surface area, an electronic structure that can be changed, and better catalytic activity:

- ✓ **Energy Generation:** Nanomaterials are used in photovoltaics (solar cells) to make solar panels work better by helping them absorb light and move charges. Nanomaterials like TiO₂ [23], ZnO [24], SnO₂ [25], NiO [26], Fe₂O₃ [27], CdS [28], PbS [29], and CdSe [30] can make solar cells work better.
- ✓ **Energy Storage:** Nanomaterials improve batteries and supercapacitors by giving the electrodes more surface area, better conductivity, and more room to store charge. Nanostructures like carbon nanotubes, graphene, and metal oxide nanostructures are important for making energy storage devices better [31].
- ✓ **Hydrogen Production:** Nanocatalysts improve the process of splitting water into hydrogen using light or electricity. Nanostructured materials like MgH₂ nanoparticles make it easier to store hydrogen by making storage capacity and speed better. Aluminum, sodium, and zinc [32].
- ✓ **Fuel Cells:** Nanomaterials make fuel cell electrodes better, which makes electrochemical reactions work better and last longer. Carbon, oxygen, and hydrogen [33–35].

We need these improvements in nanomaterials to make energy technologies that are clean, efficient, and last a long time. These technologies will meet the world's energy needs and have less of an impact on the environment.

4.2 Sensors and Detection

Nanomaterials are very important for improving sensors and detection systems because they have a lot of surface area and special electronic properties. They help you find tiny amounts of gases and chemicals. Quantum dots, metal nanoparticles, and carbon-based nanomaterials are common in biosensors, optical sensors, and electrochemical sensors. People have been paying more attention to CuO [36], NiO [37], and ZnO [38] sensors lately.

Biomedical and Healthcare

Nanomaterials can kill cancer cells when they are delivered to the right place. In medicine and health care, nanomaterials are used a lot. They let drugs go straight to sick cells, which lowers the chance of side effects. They improve imaging techniques such as MRI, CT, and fluorescent tagging. You can also use NiO thin films to test for bacteria. Coatings help find diseases and stop infections from spreading. Researchers are still working to make them safer, more stable, and more useful in the clinic. Radiation and chemotherapy are two current cancer treatments that are invasive and have side effects that make people feel bad. These treatments kill both cancer cells and healthy cells [39, 40].

Agriculture

Today, nanotechnology is changing the way we farm. Nanofertilizers make it easier for plants to get and use nutrients. Nano-pesticides and herbicides work better to get rid of weeds and bugs. Nanosensors watch the soil's quality, moisture level, and pathogens in real time. Research is still going on to make these uses safe, useful, and long-lasting [41].

Catalysis and Chemical Processing

Nanotechnology has enabled the chemical industry to utilize materials with extensive surface areas and nanoscale reactivity to enhance catalysis and optimize processes. Nanocatalysts speed up reactions, make them more selective, and make them work better overall. This means that less energy is needed for processes like making hydrogen, refining fuel, and making petrochemicals. Nanoparticles of metals and metal oxides have a lot of active sites, which makes chemical changes happen quickly. They are also used in environmental settings to break down pollutants and clean up wastewater, and they help with making chemicals in a way that is good for the environment. Even with these benefits, there are still issues like the stability of the catalyst, the cost, the recovery, and the safety of the environment. Researchers are looking for strong, reusable, and eco-friendly nanocatalyst solutions for this reason [42].

Electronics and Communication

New Nanomaterials are improving electronics and communication technology. Some of the materials that make electrical, optical, and thermal properties better are graphene, carbon nanotubes, quantum dots, and silver nanoparticles. They are very useful in sensors, transistors, flexible displays, and high-speed communication devices. Nanoscale materials let signals be processed more quickly, hold more data, and use less power. Research is still making progress on stability, large-scale production, and making new electronic systems work with old ones [43].

Food safety

Nanomaterials are being used to check the safety and quality of food. Ag nanoparticles, TiO₂, and WO₃ keep microbes out of things so that pathogens, toxins, and spoilage can be found right away. Nanocoatings on packaging help keep chemicals from moving and make it last longer. Research focuses on safe, effective, and environmentally friendly techniques for food monitoring and preservation [44].

Textile and clothing

Nanomaterials have shown that there is a lot of room for growth in the textile and clothing industries, which are usually very traditional. It is important to have UV protection, easy cleaning, water and stain resistance, and odor resistance here [45].

Challenges and Limitations

Nanoscience might be useful in everyday life, but there are some issues that need to be fixed before it can be used. The table below shows a more complete picture of the problems, gives a short description of each one, and explains how they affect applications. This will give you a new way to handle the problems we have now.

Table 1: Challenges and limitations of nanomaterials

Challenges	Description	Impact on Applications	Ref.
Synthesis Control	Difficult to produce uniform size & shape of nanomaterials.	Variation affects performance.	46
Stability	High surface energy causes reducing	Low efficiency.	47

	active surface area.		
High Cost	Expensive & high energy requirement for production.	Hinders industrial and commercial use.	48
Integration	Difficulty to tune nanomaterials existing systems.	Limits practical implementation.	49
Lifespan	Nanomaterials may degrade under environmental conditions.	Reduces durability.	50

Emerging Trends and Future Scope

For almost twenty years, the number of patents and technical papers about nanotechnology and nanoproducts has been steadily rising. Nanotechnology is expected to be worth more than \$1 trillion in business use in 10 to 15 years. This technology will have a big effect on science, technology, education, manufacturing, and the way people live all over the world. Nanotechnology is also used in quantum computers. It gives us the tools we need to control these quantum systems at the nanoscale, which helps us build quantum computers and other technologies that use quantum mechanics. .

Conclusion

Nano science is useful in many areas, such as sensors, food science, energy, catalysis, and more. Nanotechnology also gives us new ways to measure, keep track of, and control things. Nanotechnology is a field that is growing and changing at a very fast rate. New generations of nanomaterials will come out, and they will bring with them problems that we may not have thought of. It is the future of advanced development. Nanomaterials have some issues to work out, but we should push for them more for the sake of our future and the betterment of our lives.

Credit authorship contribution statement

Shital: Central theme, Original draft. **Rutuja:** Writing- review & editing. **Abhilasha:** Figure, Investigation. **Shivani:** Literature survey, Methodology.

Pooja: Review on applications. **Nandini:** Analysis of Limitations. **Nageshwari:** references. **Digvijay:** Supervision and Conceptualization.

Conflict of interest

The authors affirm that, there is no conflict of interest that, could have appeared to influence the research work reported in this paper.

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