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NANOTECHNOLOGY: A REVOLUTION IN PHARMACEUTICAL INDUSTRY

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Abstract

The ability of nanotechnology to alter materials at extremely small scales to achieve specific properties that would greatly enhance the toolbox of materials science is the basis for many of its benefits. Nowadays, businesses all over the world are attempting to use nanotechnology to make their ideas more productive and efficient in terms of vision, design, and working methods. Nanotechnology has made it possible to modernise practically every industrial sector on a global scale, from small-scale manufacturing and processing facilities like those in the food, medicine, and agriculture sectors to larger-scale production facilities like those in the automotive, civil engineering, and environmental management sectors. Many academics throughout the world have hailed nanotechnology as a revolutionary technology. As an enabling technology, it has the potential to expand research and development across a wide range of disciplines and have a broad range of sectoral applications, from electronics, textiles, healthcare and medicine, construction, water treatment, food processing, and cosmetics. For a developing nation like India, many of these applications are quite relevant. The more sustainable growth of nano-based enterprises can be anticipated in the future with strong collaboration between researchers, industry, scientists, technologists, environmentalists, and educators. The most notable advancements in the field of nanotechnology, including drug delivery systems, applications, and future perspectives, are presented in this review article.

INTRODUCTION

The entire process of turning a novel chemical entity into a recognised treatment that is secure and efficient in curing or preventing illness is known as pharmaceutics. A variety of scientific, medical, legal, commercial, and regulatory skills are needed for this intricate procedure. On average, it typically takes at least ten years for a new drug to complete the process from initial discovery to the retail marketplace, with clinical trials alone taking six to seven years on average [1].

Pharmaceutical formulation is a multi-step procedure that creates a final, useful medicinal product by combining the active medication with all other ingredients while taking pH, solubility, polymorphism, and particle size into account. The four fundamental elements of a good pharmaceutical formulation are the advantages and disadvantages of the active pharmaceutical ingredients (APIs), valuable excipients, related interactions, and manufacturing process. Frequently, the formulation works in a way that incorporates various dose forms. The pharmaceutical drug product as marketed for use with a particular combination of active and inactive ingredients is known as the dosage form. It has to be a particular configuration (capsule shell, for example) and distributed into a particular dose [1, 2].

Figure 1: Types of drug formulations

Particle characterisation of powder materials has emerged as a critical component of therapeutic product development and solid oral dosage form quality control in the pharmaceutical industry. The final performance of the drug product (e.g., dissolution, bioavailability, content homogeneity, stability, etc.) may be significantly impacted by the drug substance's particle size distribution (PSD). Additionally, the PSDs of the drug ingredient and excipients might influence the

Manufacturability of the drug product (e.g., flowability, blend homogeneity, compactibility, etc.), which can ultimately affect the drug product's quality, safety, and efficacy [3].

Nanosizing is a technique used in the pharmaceutical industry to reduce the size of a medicine to the sub-micron range to improve its solubility and bioavailability. The term "nano sizing" refers to a procedure used in the pharmaceutical industry to reduce the particle size of the active medicinal component to the nanometer range. This is defined as a particle size of less than one micrometer. Nanosizing methods have gained popularity because they may be used with a wide variety of chemicals, including those with low solubility. Improving the bioavailability of poorly soluble medications using these methods [2-4].

Nanotechnology has slowly yet deeply taken over different industries worldwide. This rapid pace of technological revolution can especially be seen in the developed world, where nano-scale markets have taken over rapidly in the past decade. Nanotechnology is not a new concept since it has now become a general-purpose technology. Four generations of nanomaterials have emerged on the surface and are used in interdisciplinary scientific fields; these are active and passive nanoassemblies, general nanosystems, and small-scale molecular nanosystems [5, 6].

The 21st Century saw the development of nanotechnology as a scientific triumph. This topic is interdisciplinary and encompasses the synthesis, management, and application of materials smaller than 100 nm. Nanoparticles (NPs) are used extensively in a variety of fields, including the environment, agriculture, food, biotechnology, biomedical, and pharmaceuticals. These include waste water treatment, environmental monitoring, functional food additives, and antibacterial agents.Cutting-edge properties of NPs such as; nature, biocompatibility, anti-inflammatory and antibacterial activity, effective drug delivery, bioactivity, bioavailability, tumor targeting, and bio-absorption have led to a growth in the biotechnological, and applied microbiological applications of NPs [6-8].

Millions and billions of dollars and euros are being spent on nanotechnology worldwide, especially in the industrialised nations of China, America, and Europe, in order to capitalise on the vast potential of this new science. However, emerging nations continue to fall behind since they are unable to even keep up with the industrial achievements of the last decade. The main cause of this lag is that these countries still have economic difficulties and need some time to make progress in the field of nanotechnology. It's crucial to note, however, that scientists in both the developed and developing worlds agree that nanotechnology will be the next big technological development. This will make further industrial upgrading and investment in the field of nanotechnology crucial in the years to come [4,8,9]. The development of nanotechnology through the use of nanoparticles as carriers for both tiny and large molecules has attracted a lot of research interest in recent decades. Nanoparticles have been created using a variety of polymers. The most notable advancements in the field of nanot echnology are highlighted in this study. The Latin word "Nano," which signifies dwarf, is the source of the English word. A nanometre is one thousand millionth of a metre, or 1n=109m. Nano size is defined as one thousand millionth of a certain unit. For many years, the scientific domains of electronics, physics, and engineering have been the most frequent users of the word nanotechnology. Nonetheless, biomedicine is a multidisciplinary field that combines applied and basic sciences, including biophysics, molecular biology, and bioengineering [10, 11].

A basic unit operation with significant applications in pharmacy is size reduction. One of the main benefits of nanosizing is that it increases surface 2. Improved solubility 3. Boost oral bioavailability and dissolution rate 4. Quick start of action 5. In the world of pharmacy, fewer doses are needed. These materials and technologies can be made to interact with a high degree of functional specificity for use in physiology and medicine, enabling a level of technological and biological system interaction that was previously unattainable. It should be understood that nanotechnology is a combination of established disciplines like chemistry, physics, material science, and biology that brings together the necessary collective skills to produce these new technologies rather than a single developing scientific subject [6, 10-12].

Both interdisciplinary and diverse fields of study and application apply to nanotechnology. Nanotechnology is ubiquitous, as seen by the wide range of applications it currently and in the future will serve. As many academics throughout the world have proposed, nanotechnology finds a role-or rather, a "defining role"-to play in a variety of industries, including agriculture, energy, electronics, medicine, healthcare, textiles, transportation, construction, cosmetics, and water treatment. Long before the term "nanotechnology" was coined, physicist Richard Feynman gave a talk titled "There's Plenty of Room at the Bottom" at an American Physical Society meeting held at the California Institute of Technology on December 29, 1959 (1960). This speech served as the foundation for the ideas and concepts that underpin both nanoscience and nanotechnology. Feynman explained in his address how scientists would be able to control and manipulate individual molecules and atoms. Prof. Norio Taniguchi first used the word "nanotechnology" more than ten years later in his research on ultra-precision machining (1974). Modern nanotechnology didn't start until 1981, when the scanning tunnelling microscope was created to help observe individual atoms. In his work, Eric Drexler popularised nanotechnology and broadened Taniguchi's definition. Engines of Creation: Nanotechnology's Coming Era (1986) [13-15].

HISTORY OF NANOTECHNOLOGY

The term “Nanotechnology” was first used in 1974 by Japanese scientist Professor Norio Taniguchi at an international symposium on industrial production held in Tokyo. Taniguchi coined the phrase to refer to the nanoscale ion beam milling and semiconductor manipulation method. He defined nanotechnology technically by stating that it involves the processing processes of dissociation, merging, and material deformation. The “golden era” of nanotechnology began in 1981 when Gerd Binning and Heinrich Rohrer invented the

Scanning Tunneling Microscope (STM), which made it possible to identify individual atoms ("Scanning the past," 2013). The discovery of Buckminsterfullerene C60 (buckyballs) by Robert Curl, Richard Smalley, and Harry Kroto further accelerated this age. One of the main contributors to the advancement of nanotechnology concepts was Eric Drexler of Massachusetts Institute of Technology (MIT). Drexler gave nanotechnology a commercial definition in his 1986 book "Engines of Creation: The Coming Era of Nanotechnology," where he defined it as engineering on the billionth of a meter scale. To increase public understanding of nanotechnology concepts and ramifications, Drexler established the Foresight Institute after the book's publication. Throughout the late 1980s and early 1990s, significant discoveries and inventions further propelled nanotechnology's development. These advancements led to significant improvements in nanotechnology research, design, and publication output, shaping its trajectory for future growth and innovation [16-19].

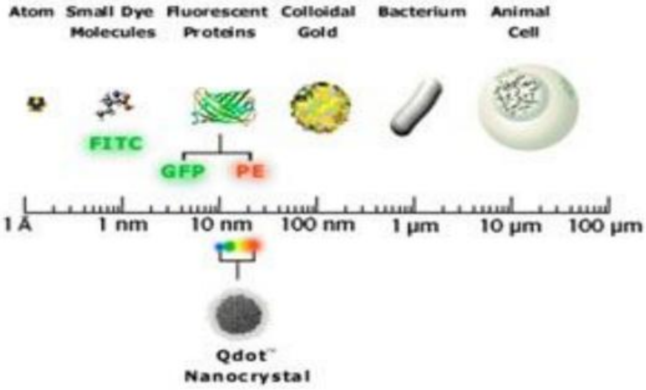

Figure 2: Nano-particles with their approximate sizes

APPLICATIONS

Nanotechnology has huge reach across science, medicine, and industry. Here is a clean, exam- and presentation-friendly overview of the major applications of nanotechnology, with examples you can relate to;

1. Medical & Pharmaceutical Applications

- Targeted drug delivery (nanoparticles, liposomes, dendrimers)
- Cancer therapy (gold nanoparticles, magnetic nanoparticles)
- Improved bioavailability of poorly soluble drugs
- Gene delivery & vaccines
- Imaging and diagnostics (quantum dots, nanosensors)
- Wound healing (nanofibers, nano-silver dressings)

2. Diagnostics & Biosensors

- Early detection of diseases using nanosensors
- Point-of-care diagnostic devices
- Rapid detection of pathogens (COVID, TB, cancer biomarkers)
- Lab-on-a-chip systems

3. Agriculture & Food Technology

- Nano-fertilizers for controlled nutrient release
- Nano-pesticides with reduced toxicity
- Smart food packaging (spoilage indicators)
- Improved food preservation and shelf life
- Detection of contaminants and pathogens in food

4. Electronics & Information Technology

- Nanoelectronics (smaller, faster transistors)
- Quantum dots in LED displays
- High-density data storage devices
- Flexible and wearable electronics

5. Energy Applications

- Solar cells with improved efficiency
- Nanomaterials in batteries and supercapacitors
- Fuel cells and hydrogen storage
- Energy-efficient coatings and insulation

6. Environmental Applications

- Water purification using nanofilters
- Removal of heavy metals and pollutants
- Air purification systems
- Environmental monitoring sensors
- Oil spill cleanup using nanomaterials

7. Cosmetics & Personal Care

- Nano-encapsulated vitamins and antioxidants
- Sunscreens (ZnO, TiO_2 nanoparticles)
- Anti-aging and skin-penetrating formulations
- Improved stability and texture of products

8. Textile Industry

- Stain-resistant and wrinkle-free fabrics
- Antimicrobial clothing
- UV-protective textiles
- Smart fabrics with sensors

9. Industrial & Manufacturing Applications

- Stronger, lighter nanocomposites
- Anti-corrosion and self-cleaning coatings
- Lubricants with reduced friction
- Precision manufacturing tools

10. Defense& Space Technology

- Lightweight armor and protective gear
- Stealth coatings
- Advanced sensors and surveillance
- Spacecraft materials with high strength-to-weight ratio

Nanotechnology enables manipulation of materials at the molecular level, leading to innovative solutions in medicine, energy, electronics, environment, and industry [20-24].

NANOTECHNOLOGY, HEALTHCARE, AND MEDICAL INDUSTRY

When discussing the vast domains of biological sciences, biotechnology, and medicine, it is impossible to overlook the origins of nanomedicine. In the larger context of nanobiotechnology, nanotechnology is already surpassing expectations. Successful uses of nanotechnology in medicine have consistently raised human life quality, leading to the emergence of a whole new field called nanomedicine. This has enabled researchers to develop improved methods for disease prevention, screening, treatment, diagnosis, and proactive healthcare measures. These processes may also encompass drug design, conjugation, manufacturing, and efficient delivery techniques due to advancements in tissue engineering, gene therapy, and nano-based genomics. Given this, it is logical to believe that the next generation of biologists will soon focus their research on nanomedicine, exploring both the potential advantages and risks of this sector.

Scientists are investigating the potential advantages of nanotechnology in a variety of medical operations. Numerous robotic features that originated in nano-scale computers have been used in the realm of medical instruments, including sample purification kits, sensor technologies, and diagnostic surfaces. With the creation of technologies that can function, react, and change inside the human body for the sole goal of early detection and therapy, some changes are also becoming acceptable in the field of diagnostics. Along with tissue engineering and cell treatment, regenerative medicine has paved the way for nanomanufacturing applications.

Similarly, as previously discussed, several new technologies in the form of "lab-on-a-chip" are being developed with significant ramifications in a variety of disciplines, including the cosmetics, diagnostics, dentistry, and nanomedicine industries. Modern nanotechnology applications in the domains of proteomics and genomes have produced molecular understandings of antimicrobial illnesses. Additionally, applications including surgical nanorobotics, nanobioelectrics, and drug delivery techniques are being developed through the fusion of programming, biotechnology, nanoengineering, and medicine. Together, these aid researchers and medical professionals in better understanding the pathophysiology of illnesses and developing more effective treatment options in the road.

Nanotechnology is producing amazing applications in a wide range of industries, which have been investigated, reviewed, and chosen to be included in this study after careful and comprehensive analyses. To further explain the extensive uses of nanotechnology across several industries, several subcategories of industrial linkages may be covered under a single category. This article's graphical abstract at the outset lists the several industries where nanotechnology is having amazing effects; specifics are covered in brief under the various topics in the following session [24-30].

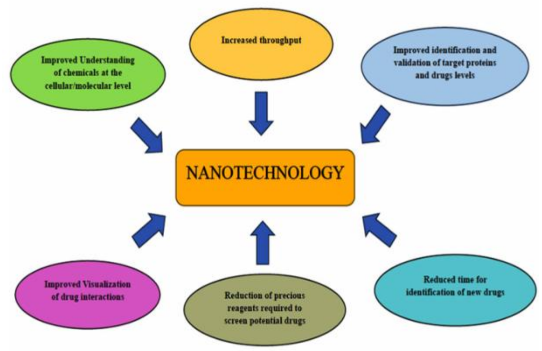

Figure 3: Role of nanotechnology in drug delivery

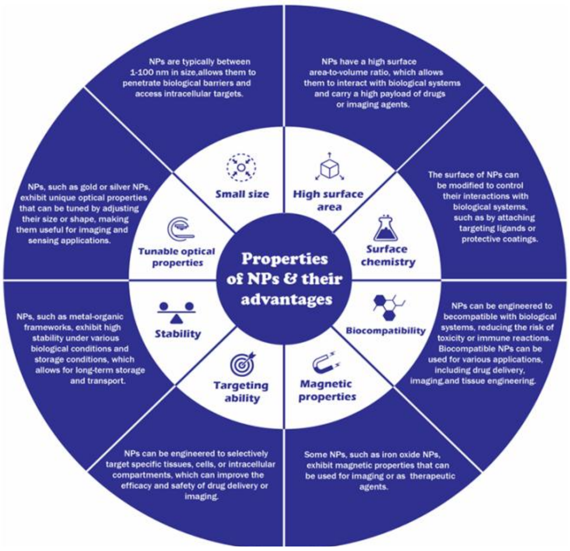

Figure 4: Properties of nanoparticles and their advantages

FUTURE PERSPECTIVES

Applications for metal nanoparticles are possible in a number of domains, such as electronics, energy storage, catalysis, and medicine. However, there are some obstacles that need to be overcome in addition to possible avenues for the advancement and application of metal nanoparticles in the future. Controlling the size and structure of metal nanoparticles during production and processing is a significant challenge. The high temperatures and harsh chemical conditions involved in several metal NP synthesis techniques may make them difficult to scale up for large-scale manufacturing. Furthermore, it is essential to synthesise metal nanoparticles (NPs) with exact control over size and form because these factors might significantly affect the particles' characteristics and their uses.

The environmental effects of metal nanoparticles present another difficulty. Some metal nanoparticles, like silver, might harm aquatic life, but they might also have other impacts on the ecosystem. Both the creation of more ecologically friendly production and processing techniques as well as additional study on the effects of metal nanoparticles on the environment are required. An interesting topic for more research is the application of metal nanoparticles for energy conversion, storage, and environmental protection. Metal nanoparticles, for instance, might be utilised to boost solar cell efficiency or battery performance. Metal nanoparticles can also be employed in catalysis to increase the effectiveness of chemical reactions. Furthermore, research is still being done on metal nanoparticles in medicine, including drug delivery [31-35].

CONCLUSION

The fundamental idea behind the development of nanotechnology in India has been that this new and developing technology has enormous potential to assist the nation in addressing societal issues like the supply of drinking water, healthcare, etc., while also generating economic benefits through the expansion of the industrial sector based on nanotechnology. Pharmaceutical nanotechnology has become a promising field for the delivery of bioactives and diagnostics in both space and time, as well as for the creation of intelligent materials for tissue engineering. The new tools, options, and breadth that its nano-engineered technologies offer are predicted to have a profound impact on many aspects of disease, diagnosis, prognosis, and therapy.

Even though nanotechnology has many uses, its hazards from unchecked use are yet unknown and subtle. To uncover more answers in the subject of nanotoxicology, more work needs to be connected and carefully selected. In order to investigate possibilities and employ nanotechnology in field trials, it is also advised that researchers, technicians, and industrialists collaborate at the field and educational levels. More developments must be made and carefully examined at the nanoscale for a future world if we are to be conscious of this massive technology. It is very possible that nanotechnology will soon be incorporated into every industry due to its incredible applications in business. This is significant since sustainability is a factor that is being considered more globally. Therefore, it is possible to ensure that nanotechnology will have a profitable future by combining it with sustainability.

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The author declares no conflicts of interest.

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