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Nanotechnology: Exploring the Unseen Science with Emerging Applications in Drug Delivery, Dentistry, and Immunology

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Abstract: Nanotechnology represents an emerging frontier that enables scientific exploration at the molecular and atomic levels, offering transformative possibilities in human health care. This review explores the unseen science of nanotechnology and highlights recent developments in its biomedical applications, particularly in drug delivery, dentistry, and immunology. In drug delivery, nanoscale carriers such as liposomes, dendrimers, and polymeric nanoparticles have demonstrated enhanced bioavailability, targeted release, and reduced systemic toxicity. In dentistry, nanomaterials including nano-hydroxyapatite, nano-composites, and antimicrobial nanoparticles show improved mechanical strength, remineralization potential, and superior oral disease management. Additionally, nanoparticle-based immunotherapies, nano-adjuvants, and vaccine delivery platforms have shown promising results in boosting immune responses and improving therapeutic outcomes. While these advances underline the significant potential of nanotechnology in modern healthcare, challenges such as safety evaluation, regulatory limitations, and long-term biocompatibility must be addressed. Overall, this review presents a concise overview of the scientific foundation and clinical potential of nanotechnology, emphasizing its critical role in shaping the future of medical science.

Keywords: Nanotechnology, drug delivery, dental nanomaterials, nano-immunology, human health Care

1. Introduction

Nanotechnology is an emerging and rapidly progressive scientific field that deals with materials and devices at the nanoscale, where unique physicochemical properties enable applications beyond the limits of conventional technologies [1–3]. The concept of manipulating matter at the atomic level was first introduced by Richard Feynman in 1959 in his visionary lecture “There’s Plenty of Room at the Bottom,” and the term *nanotechnology* was later defined by Norio Taniguchi in 1974 [4,5]. Since then, nanotechnology has evolved into a multidisciplinary domain, particularly transforming biomedical research and clinical sciences. In recent years, nanotechnology has demonstrated substantial potential in human health care by enabling precision diagnostics, targeted therapies, and enhanced treatment efficacy [2,6]. Among these advancements, nanoscale drug delivery systems have emerged as a leading application due to their ability to improve bioavailability, achieve site-specific targeting, and minimize systemic side effects [6–8]. Nanocarriers such as liposomes, dendrimers, and polymeric nanoparticles have shown promising results in the controlled and sustained release of therapeutic agents, addressing limitations associated with conventional drug delivery methods [7–9].

Similarly, nanotechnology has contributed significantly to advancements in dentistry through the development of nano-hydroxyapatite, nano-composite restorative materials, and antimicrobial nanoparticles, which exhibit superior mechanical strength, enhanced remineralization, and improved biocompatibility [10–12]. In addition, the integration of nanotechnology into immunotherapy has led to the development of nanoparticle-based vaccine carriers and nano-adjuvants that enhance immune response and therapeutic efficiency in disease treatment [13–15]. These innovations highlight the growing relevance of nanotechnology in advancing medical science and improving patient outcomes. Despite significant progress, challenges such as toxicity evaluation, biocompatibility, long-term safety, regulatory compliance, and scalability remain major barriers to clinical translation [8,14,16]. Addressing these limitations is essential to enable safe and widespread adoption of nanotechnology-driven health solutions. Therefore, this review aims to explore the foundations of nanotechnology as the unseen science and provide an overview of its major biomedical applications, with emphasis on drug delivery, dentistry, and immunology. By outlining recent advancements and key challenges, this work intends to support ongoing research efforts and contribute to future developments in nanomedicine [17-20].

2. Nanotechnology: Exploring the Unseen Science

The study of matter produced at the atomic, molecular, and supramolecular scales is known as nanotechnology. The initial and widely accepted definition of nanotechnology focused on the specific technological objective of accurately modifying atoms and molecules to create large-scale products; this field is currently known as molecular nanotechnology. Nanotechnology is the science, engineering, and application of materials and devices with a functional organisation with at least one-nanometer range dimension (1–100 nm). At the nanoscale, the properties of materials differ significantly from those at a larger scale. These differences include altered optical, magnetic, and electrical properties [21]. As we explore this unseen science, we uncover a realm where materials can be engineered with extraordinary precision, leading to breakthroughs that can fundamentally transform technology and industry. The size and number of dimensions that surpass the nanoscale range can also be used to categorise nanomaterials (those less than 100 nm). Table 1 illustrates nanomaterials with varying dimensions. Nanotubes and nanowires have two dimensions under 100 nm, whereas thin films have one dimension under 100 nm. There are various kinds of nanomaterials, illustrated in Fig. 1. Among these, nanoparticles are the most frequently utilised, particularly in the healthcare sector. In the natural world, nanoparticles can be found in things like proteins, viruses, and volcanic eruptions and can also be generated through human activities [22].

Table 1: Characterization of Nanomaterials

Dimensions of Nanomaterials	Measurement	Electron Movement	Key Term	Illustrations	Ref.
Zero	All dimensions confined to nanoscale range	Restricted in every direction.	The quantum dots*	Molecular entities include fullerenes, metal carbides, powders, rings, clusters, grains, and structures.	[23]
One	One-Dimension is restricted to the nanoscale range.	Move exclusively along the X-axis	Wires with quantum properties	Microscopic dimensions, threads, coils, pillars, fine hairs, twists, strands, bands, pins, and so on.	[24]
Two	Only Two-Dimensions is restricted to the nanoscale range.	Travel along the X-Y plane.	Thin Films	Different strata, graphene, and its derivative, graphene oxide (GO), among other things.	[25]
Three	Zero-Dimension is confined to the nanoscale range.	Move in every direction.	Nanostructured material, comprised of nanoparticles	Tiny nano-sized clusters, impermeable membranes, and similar structures of a small scale.	[23]

*Quantum dots are nanoscale semiconductor particles characterized by distinctive optical and electronic features resulting from quantum confinement. Their fluorescence varies with size, making them essential in fields such as bioimaging, solar energy, and quantum computing. With adjustable mission, exceptional brightness, and stability, they drive advancements in nanotechnology by enabling precise atomic and molecular-level control.

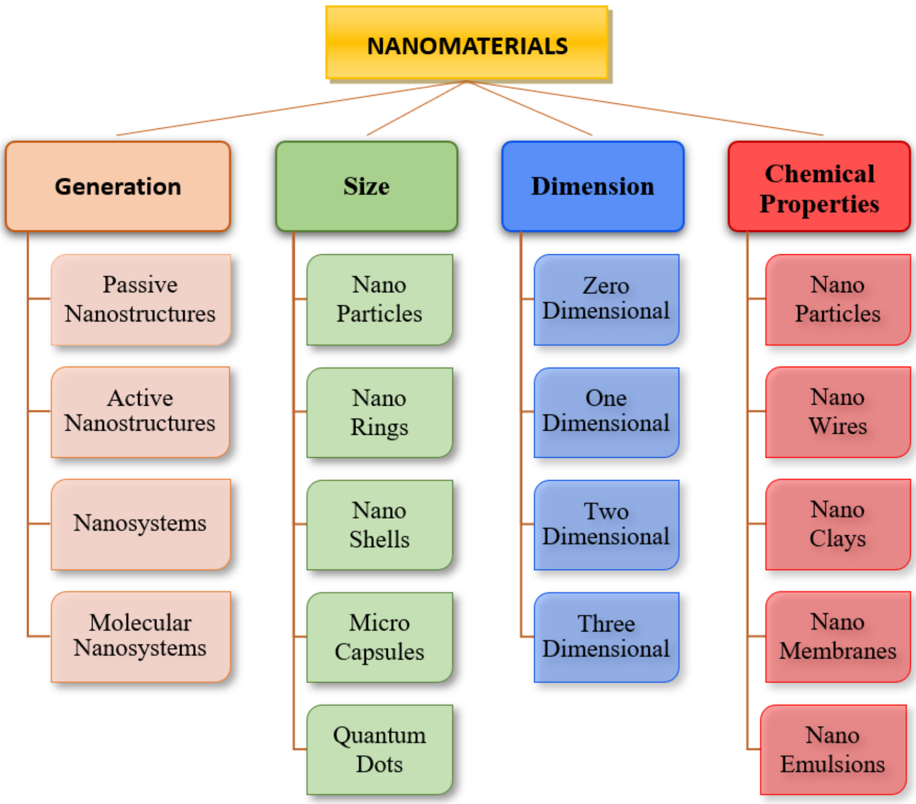

Fig. 1: Categorization of nanomaterials

Furthermore, Mahmoud Nasrollahzadeh et al. [26] illustrated in 2019 that nanotechnology has witnessed remarkable advancements in recent decades [27]. In essence, it involves measuring, predicting, and constructing substances at the level of atoms and molecules. There is optimism that atomic-scale nanotechnology will revolutionize future approaches to manufacturing, design, and production. Nanotechnology represents an atomic or molecular methodology for constructing structurally stable entities, whether physical, chemical, or biological, at the most fundamental level. Thus far, investigators can individually control and manipulate atoms or molecules with exceptional precision [26]. While the contributions of nanotechnology to society may seem modest presently, there is optimism that with ongoing support in manpower and funding, it will yield significant results and innovations in the future. If nanotechnology maintains its current growth trajectory, it is poised to impact the lives of nearly every individual on the planet in the coming years. Advances and discoveries in nanotechnology are affecting many facets of our lives, including materials science, environmental science, medicine, aerospace, energy, defence, and agriculture [28]. Nanotechnology is advancing quickly, and scientists, physicians, government agencies, venture capitalists, and politicians are all becoming more interested in learning more about it. Key research areas include molecular manufacturing, nanotechnology, nanoporous materials, nanostructured catalysts, nanolithography, nanorobotics, nanodevices, nano powders, nanocomputers, nanobiology (including disease prediction, prevention, and treatment), and organic nanostructures [29]. Biomedical and clinical scientists around the world are committed to early detection of illness and disease prevention. The fact that a large number of current technologies depend on processes occurring at the nanoscale has long been recognised by researchers. Lithography, ion exchange, adsorption, drug design, catalysis, composites, and plastics are a few of these technologies. Fullerene C_{60}, also known as buckyballs or buckminsterfullerene, is a nanostructured carbon allotrope (Fig. 2) that has attracted considerable interest across multiple scientific and engineering disciplines. Due to their distinctive physical and chemical characteristics, fullerene and its derivatives hold great promise in materials science.

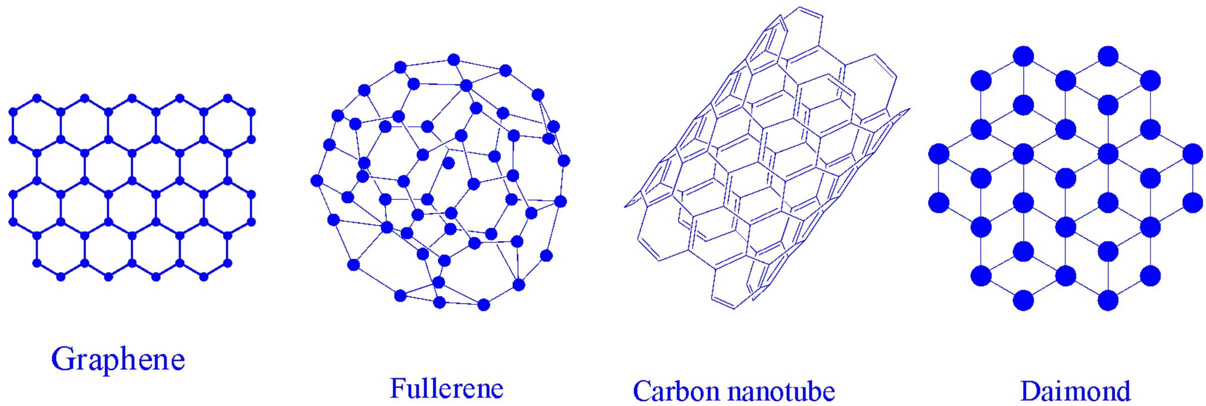

Fig 2: Nanostructured carbon allotropes

Also, Sneha Mohan Bhagyaraj et al. [30] rationalised in 2018 that nanotechnology's influence on diverse aspects of human life is extensive. As one of the 21st century's most important technologies, its importance lies in both its economic potential for developing new or enhanced products and its anticipated role in mitigating ecological strain and resource consumption. While silicon technology remains pivotal in the evolution of micro/nano-electronics, there are instances where non-silicon devices and component technologies offer superior performance. State-of-the-art material growth techniques facilitate the manufacturing and assembly of multi-layered nanostructures and devices consisting of diverse materials with nanoscale thickness. Additionally, sensors empowered by nanotechnology are introducing novel solutions in physical, chemical, and biological sensing. These developments augment detection sensitivity, microsystem integration capability, and portability, thereby providing significant applications in health, safety, and environmental assessments [31]. Ongoing debates concern the potential risks, concerns, and arguments surrounding nanotechnology. However, its appropriate application promises remarkable advancements in medicine, industry, electronics, and various everyday necessities. Numerous technologies have been investigated for creating nanostructures and nanomaterials. These methods can be categorized in various ways, as illustrated in Table 2. Semiconductors and numerous metals exhibit significant variations in their optical properties depending on particle size. An easy illustration of this is the differing colours of various nanoparticle solutions, as shown in Table 3.

Table 2: Diverse Methods for Creating Nanomaterials

Derived from Growth Media		**According to Products**		**Ref.**
Methods	Illustration	**Nanomaterials**	**Illustration**	
Liquid phase growth	Monolayer self-organization	Nanowires	Solution-liquid-solid growth	[32]
Vapor phase growth	Laser pyrolysis	Nanoparticles	Sol-gel	[33]
Solid phase creation	Dual-proton polymerization creates 3D crystals.	Thin films	Molecular beam epitaxy	[34]
Hybrid growth	Nanowire growth via VLS method.	Bulk nanostructured material	Self-assembly	[35]

Table 3: Correlation Between Nanoparticle Dimension and Colour

Nanoparticles	Dimension and Shape	Colour	Ref.
Gold	Yellow	2-5 nm	[36]
	Red	10-20nm	[37]
	Purple	>20nm	[38]
Silver	Blue	40nm	[39]
	Yellow	100nm	[40]
	Red	Prism shape	[41]

Moreover, in 2019 Samer Bayda et al. [42] illuminated the advancement of nanoscience and nanotechnology across various scientific disciplines has branched out in diverse directions. It encompasses the examination of phenomena spanning from micro to nano scales, employing various microscopes in physics, transitioning from the bulk matter at the micro-scale to chemically speaking, tiny carbon dots, evolving from room-sized computers to compact, portable laptops in computer science, and exploring the intricacies of cellular nuclei to study Nanoscale complex biomolecules in biological science. All these advancements across various scientific fields are broadly reviewed and summarized in Fig. 3. Over the course of a few decades, drug delivery systems, imaging probes, diagnostic biosensors, and other medical devices have relied heavily on nanotechnology and nanoscience. In the food industry, nanomaterials have been employed to notably enhance various aspects. For example, ZnO nanostructures demonstrate antimicrobial properties against food-borne bacteria [43], while several nanomaterials are utilised as food sensors for diagnostic purposes to evaluate food quality and safety. Furthermore, nanomaterials are being employed in the advancement of next-generation solar cells, hydrogen fuel cells [44,45], and novel hydrogen storage systems. The goal of these initiatives is to provide nations that still depend on conventional, non-renewable, and dirty fuels with clean energy alternatives. But the most notable developments in nanotechnology are found in the broad field of biomedicine, specifically in the area of cancer therapies [46,47]. This is attributed to its vast potential to offer innovative solutions for overcoming the limitations associated with traditional chemotherapy and radiotherapy approaches. Recent breakthroughs in physics, chemistry, and materials science have resulted in numerous nanomaterials with exceptional properties. These nanomaterials show promise in improving the treatment of various tumors that may be resistant to current therapies. This will be feasible due to their inherent cytotoxic effects and/or their capacity to act as nanocarriers for transporting therapeutic molecules, such as drugs, proteins, nucleic acids, or immune agents. These pioneering biomedical applications are presently undergoing evaluation in various clinical trials and hold the potential to drive substantial progress in cancer therapy in the near future.

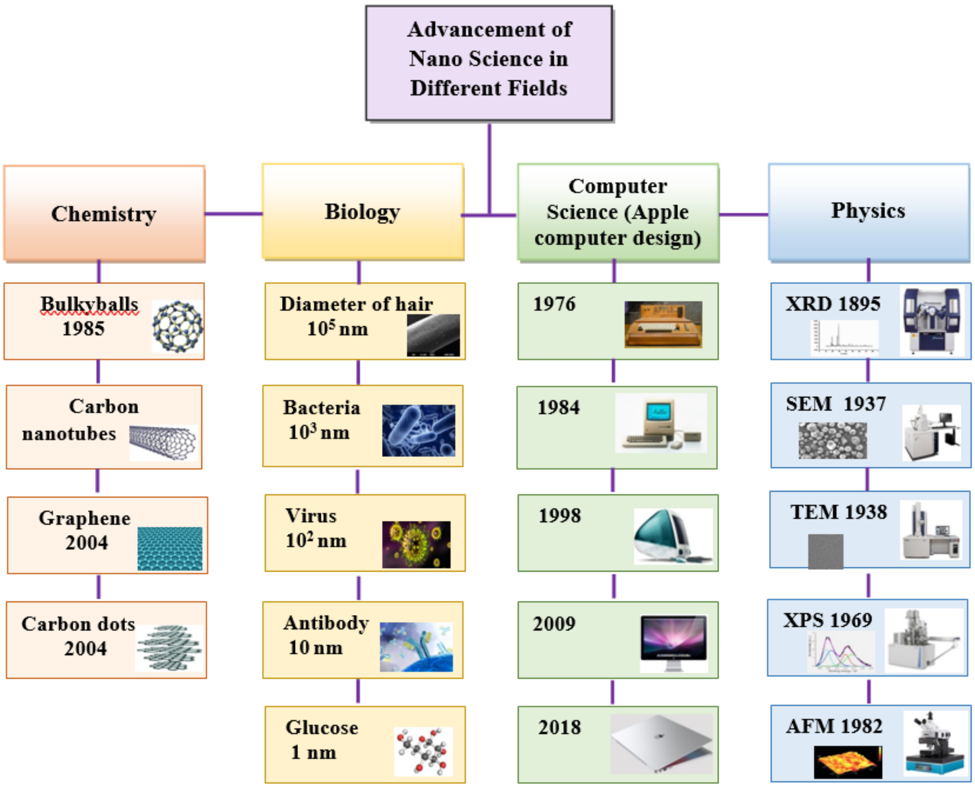

Fig. 3: Advancements in nanotechnology and science across various disciplines.

Recently, Shiza Malik et al. [48] elucidated that nanotechnology, despite its misleading title, has sparked a profound transformation across global industries. This paper predominantly centres on data concerning the utilisation of nanotechnology to modernise various sectors. An extensive research methodology is employed to integrate the most recent data collected from prominent scientific platforms. As a result, a comprehensive overview is provided, encompassing the varied applications of nanotechnology in contemporary industries. This research demonstrates that nanotechnology extends beyond research laboratories or small-scale production facilities focused on nanomedicine, instead playing a significant role across diverse industries [49]. Companies worldwide are actively striving to enhance the efficiency of their innovations in terms of structure, functionality, design, and productivity through the utilisation of nanotechnology. Nanotechnology has impacted the modernization of nearly every industrial sector worldwide, spanning from small-scale operations in food, medicine, and agriculture to more extensive production facilities in fields such as automotive manufacturing, civil engineering, and environmental management. By promoting collaboration among researchers, industrialists, scientists, technologists, environmentalists, and educators, a future of increased sustainability in development for industries built on nanotechnology is conceivable. Nanotechnology, manipulating matter at the nanoscale (1–100 nm), revolutionises diverse fields, from medicine to energy. At this scale, materials exhibit unique optical, electrical, and mechanical properties, enabling drug delivery, diagnostics, and renewable energy breakthroughs. Advances in nanosensors and nanomaterials enhance environmental monitoring and targeted therapies. Cutting-edge techniques like atomic force microscopy (AFM) and scanning electron microscopy (SEM) enable visualisation and manipulation of nanostructures. Ethical considerations and safety regulations are critical as nanotechnology's applications expand. This interdisciplinary field bridges physics, chemistry, biology, and engineering, offering innovative solutions to global challenges while driving the development of next-generation technologies.

Section 2 introduces the fundamental principles of nanotechnology, emphasizing material manipulation at the atomic and molecular levels. It does not cover advanced theoretical frameworks or the historical development of nanotechnology, as these are beyond the scope of this review.

3. Utilizing Nanotechnology: Exploring its Diverse Applications

Nanotechnology's versatility enables its application across a multitude of sectors, each benefiting from the enhanced performance and novel capabilities of nanoscale materials and devices. This section explores the diverse applications of nanotechnology, highlighting its transformative impact on various industries and societal challenges.

3.1 Nanotechnology in Human Health Care

Nanotechnology has emerged as a transformative field in healthcare, offering novel solutions for diagnosing, treating, and preventing diseases. By manipulating materials at the nanoscale, researchers can enhance drug delivery, improve diagnostic precision, and develop advanced therapeutic techniques. The interdisciplinary nature of nanotechnology integrates engineering, physics, chemistry, and biology, facilitating the development of nanoscale tools tailored for medical applications.

The field of nanomedicine leverages nanoscale materials for medical applications, ranging from targeted drug delivery to advanced imaging techniques. In 2017, S.K. Sahoo et al. [50] highlighted the interdisciplinary nature of nanotechnology, emphasizing its convergence with fields such as engineering, physics, chemistry, and biology. With rapid scientific and technological progress, this emerging field is unlocking numerous possibilities for advancing medical research and improving disease treatment. The application of nanotechnology in medicine and physiology involves designing materials and tools that interact with biological systems at the molecular and subcellular levels with remarkable precision. This approach facilitates targeted therapies, enhancing treatment efficacy while minimising adverse effects. As research advances, nanotechnology is transforming theoretical concepts into practical solutions, influencing various scientific and technological disciplines. The impact of these innovations is expected to be profound, extending across multiple sectors. In the coming years, continued advancements in nanotechnology will drive significant progress in medical sciences, particularly in diagnostics, drug delivery, and patient care, further solidifying its role as a transformative force in healthcare.

A cutting-edge innovation in healthcare is the Internet of Nano-Things (IoNT), which integrates nanosensors and nanodevices into a connected network for real-time health monitoring and predictive diagnostics. In 2020, P.K. Dutta Pramanik et al. [51] emphasized that nanotechnology, particularly in the form of nanomedicine, nano-implants, nano-biosensors, and the Internet of Nano-Things (IoNT), holds immense potential to revolutionise medicine and healthcare services (Fig. 4). The development of the IoNT enables seamless communication and coordination between nanodevices and internet-connected devices, expanding its healthcare applications. The integration of nano-communication capabilities into nanodevices promises to overcome current technological challenges and enhance healthcare delivery to unprecedented levels. While nanotechnology offers exciting future possibilities, there are several challenges that must be addressed, including the characteristics of nanodevices, communication protocols, and potential impacts on the human body. Toxicity and health concerns related to nanoscale materials are significant hurdles to the widespread adoption of this technology. Additionally, the IoNT faces challenges in data storage, efficient routing, and integration with existing healthcare systems and IoT networks. Overcoming these issues could lead to major advancements in healthcare, including early disease diagnosis, precise drug delivery, and reduced side effects (Fig. 5), making healthcare more accessible and cost-effective. The development of a persistent computing environment could ensure that these advancements benefit humanity at a global scale, making healthcare more efficient and widespread [52].

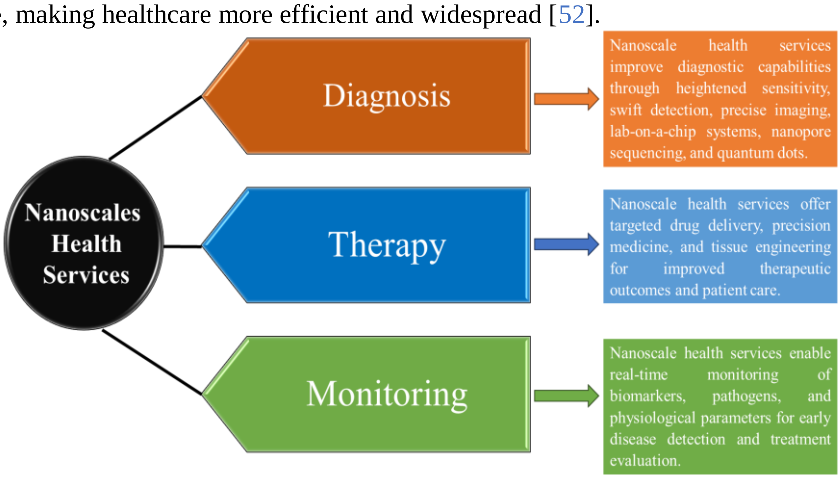

Fig 4: Types of Nanoscale Health Services

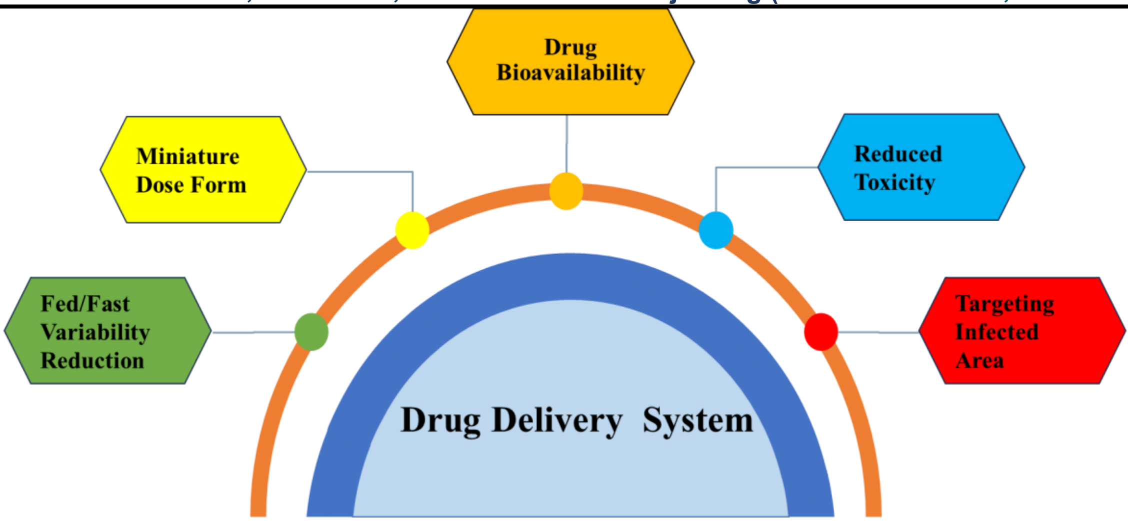

Fig 5: Benefits of using nanoparticles in medication administration

In an extensive study, Shiza Malik et al. [48] underscored the expanding role of nanotechnology beyond conventional medicine into nanobiotechnology, where it integrates with tissue engineering, gene therapy, and regenerative medicine. The advent of nano-based artificial organs and tissue scaffolds is revolutionising organ transplantation and wound healing. Stem-cell-based nano-therapies are also being explored to regenerate damaged tissues, offering potential cures for degenerative diseases. Moreover, personalised medicine, enabled by nanotechnology, is paving the way for patient-specific drug formulations, reducing trial-and-error approaches in treatment. As illustrated in Fig. 6, nanotechnology applications in the medical industry encompass diverse fields, including targeted drug delivery, bioimaging, and diagnostics, further advancing precision medicine. Despite these innovations, several challenges hinder the clinical translation of nanomedicine. These include high production costs, complex regulatory approval processes, long-term toxicity concerns, and scalability issues. While research continues to explore novel nanocarriers, ensuring their safety and effectiveness remains paramount for their widespread clinical adoption.

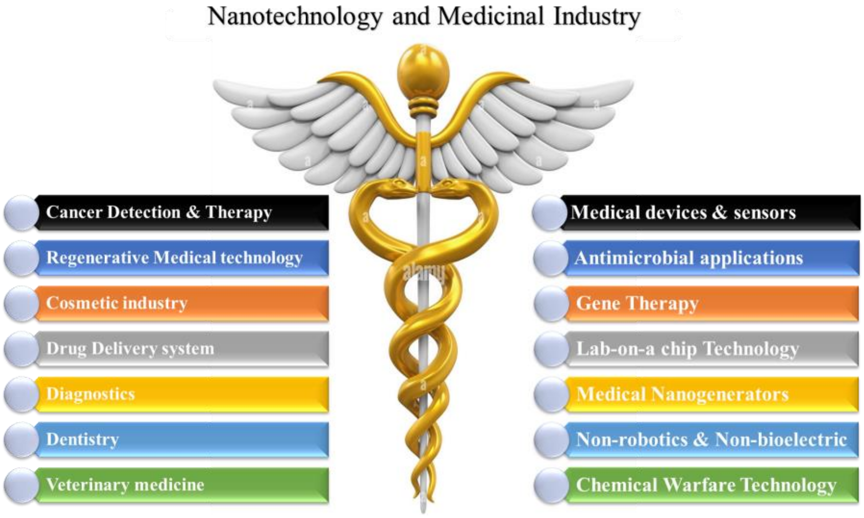

Fig 6: Applications of Nanotechnology in the Medical Industry

Despite the remarkable potential of nanotechnology in healthcare, concerns over nanotoxicology and environmental impact remain significant. The study of nanotechnology environmental health and safety (nano-EHS) focuses on evaluating the potential risks of engineered nanomaterials (ENMs) to human health and ecosystems. In 2015, Andre E. Nel et al. [53] stressed that nanoparticles interact at various biological levels, including molecular, cellular, organ, and systemic scales, raising concerns about their long-term toxicity, bioaccumulation, and unintended side effects. Studies indicate that some nanoparticles can induce oxidative stress, DNA damage, and inflammatory responses, leading to potential cytotoxicity [54,55]. To mitigate these risks, researchers advocate for a safe-by-design approach, where the physicochemical properties of nanomaterials are modified to reduce toxicity while maintaining functionality. Regulatory agencies, such as the FDA, OECD, and EU regulatory bodies, are working to establish standardized safety protocols for nanomedicine (Fig. 7). However, a major challenge lies in the lack of long-term toxicity data, which makes it difficult to predict how these materials will behave over extended periods. While "nanotoxicology" remains a growing subdiscipline, Nel et al. [53] argue that shifting the focus toward "nano-safety" could help guide the development of biocompatible and environmentally sustainable nanomaterials for biomedical and industrial applications.

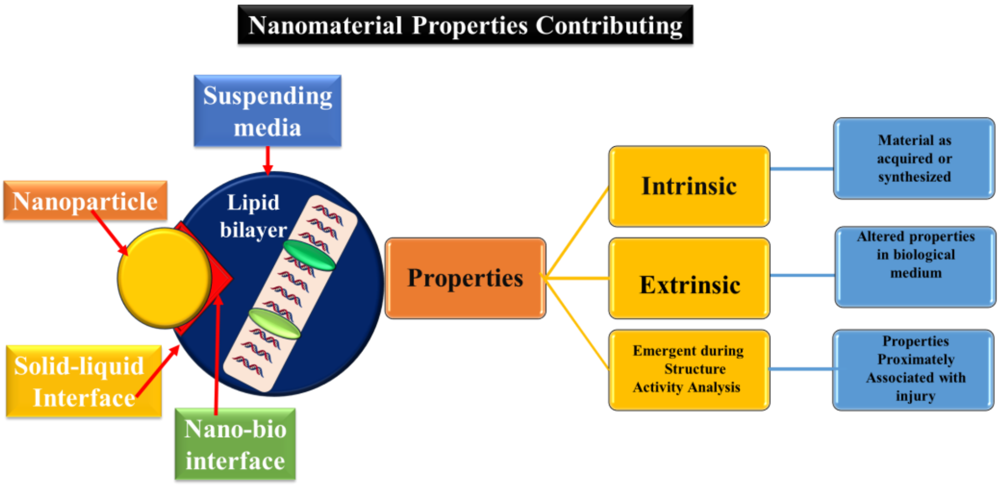

Fig. 7: A visual representation showcasing the interplay between a nanoparticle and a lipid bilayer.

Beyond healthcare, nanotechnology plays a crucial role in environmental sustainability, particularly in addressing the global clean water crisis. In 2020, Ankit Nagar et al. [56] examined how sustainable nanotechnology has enabled the development of advanced water purification systems, particularly for communities with limited access to clean water. Innovations such as graphene-based filters, nanomembranes, and nano-enabled adsorbents have significantly improved the removal of pathogens, heavy metals, and toxic chemicals from water sources (Table 4). For instance, rural communities have benefited from rolling water purification drums, which allow individuals to collect and purify water simultaneously while transporting it from distant sources (Table 5). Despite these advancements, challenges persist. Large-scale implementation of nanotechnology-based water purification faces economic constraints, environmental concerns related to nanoparticle disposal, and the need for sustainable manufacturing processes. As noted by recent studies [57- 63], green nanotechnology, focusing on minimizing resource consumption and waste production, offers a promising approach to balancing technological advancements with environmental responsibility.

Table 4. Utilization of Nanotechnology for Purifying Water: Current Implementation Status

Substance	Technological canopy	Issue tackled	Organization	Current situation	Price per gallon / cents	Ref.
Nano alumina fibers	Adsorption	Tiny particles smaller than a micron, colloidal particles, microbes like bacteria and viruses, dissolved salts, endotoxins, and pharmaceuticals	Argonide	Industrial	0.03	[64]
Iron(III) hydroxide	Adsorption	arsenic	IIT, Madras	Industrial	0.14	[65]
nanocellulose	Sorption	Metal ions	UPM-Kymmene Oy	Industrial	-	[66]
zeolite	Adsorption and physical separation	Ammonia with a substantial metal content	KMI -zeolite	Industrial	-	[67]
CNT-based membranes	Forward osmosis	Brines and various types of industrial salts	Porifera	Industrial	-	[68]
CNT-based membranes	Reverse osmosis	dissolved salts	NanOsis	Industrial	-	[69]
Aquaporin water channels	Forward osmosis and Reverse osmosis	micropollutant, xenobiotics, organics	Aquaporin	pilot	-	[70]
High surface area carbon electrodes	Capacitive Deionization	dissolved salts and metals	InnoDI an IIT Madras	Industrial	0.5	[71]
Hollow fibre membrane	Nanofiltration	Salt, dense metals, and harmful substances.	De Mem Ltd. And NTU Singapore	pilot	-	[72]
Iron nanoparticles	Abiotic chemical reduction or anaerobic biodegradation	heavy metal, nitrates, phosphates	NANOIRON	Industrial	-	[73]

Table 5. Instances of developing nanomaterials with the ability to be utilised, or already being utilised, in the realm of nanotechnologies aimed at purifying water

Matter	Usage	Institute	Ref.
A silver nanoparticle-infused non-metallic oxyhydroxide with an organic template.	Water purification	IIT Madras, India	[74]
Metal-organic framework	Atmospheric water harvesting	MIT, United States	[75]
Metal oxide nanocomposite hetero-structured powder	Sensing of hydrogen sulphide	Honeywell Romania, SRL Romania	[76]
Cationic and anionic membranes	Capacitive deionization	IDDS, Italy	[77]
Creating a membrane by assembling graphene oxide layer by layer with aromatic diamide chromophores.	Water purification	University of Maryland, US	[78]
Aromatic diamide chromophores	Sensing of volatile organic compounds	JNCASR, Indian	[79]
Graphene oxide	Dehydration through vapor phase separation or via evaporation.	The University of Manchester, United Kingdom	[80]
Doped carbonaceous material	Elimination of chemical and biological pollutants as well as micropollutants through photocatalysis	University of Arakanese, United states	[81]

Nanotechnology is revolutionizing multiple sectors, particularly healthcare, smart diagnostics, environmental sustainability, and clean water management. The integration of nanomedicine, IoNT, and nanosensors is redefining medical science, offering more precise, efficient, and personalized treatments. However, to fully realize the potential of nanotechnology, several key challenges must be addressed. First, ensuring biocompatibility and safety requires the development of standardized toxicity assessments and regulatory frameworks. Second, scalability and cost efficiency must be improved by reducing production costs to enable widespread clinical applications. Third, ethical and privacy concerns should be mitigated by implementing robust data security measures in Internet of Nano-Things (IoNT) healthcare systems. Finally, sustainability must be prioritized by promoting green nanotechnology to minimize environmental impact.

Section 3.1 *explores nanotechnology's transformative role in healthcare, particularly in diagnostics, drug delivery, and personalized medicine. It highlights the interdisciplinary nature of nanomedicine, the integration of nanosensors and IoNT for real-time monitoring, and emerging innovations like nanoimplants. Despite its potential, challenges such as toxicity concerns, regulatory hurdles, and scalability issues persist. Addressing these will enhance nanotechnology's impact, driving advancements in healthcare, environmental sustainability, and beyond.*

3.1.1 Nanotechnology for Drug Delivery

Nanotechnology has transformed drug delivery systems by enabling targeted delivery of therapeutic agents to specific cells, reducing side effects, and improving treatment efficacy. This is particularly beneficial in cancer therapy, where chemotherapeutic agents can be directly delivered to tumor cells, sparing healthy tissue. In 2013, Kinam Park et al. [82] noted that nanoparticles possess unique properties for tumor targeting in both laboratory (in vitro) and living organisms (in vivo). However, translating these results from animal models to clinical success has been challenging. Effective translation requires reevaluating the role of nanotechnology in drug delivery, addressing nanoparticle limitations, and dispelling misconceptions. Nanoparticles improve drug delivery by increasing drug loading capacity, enhancing targeting affinity, and controlling drug release location and timing. For instance, drug concentrations around tumors can increase by 100–400% with nanoparticle formulations compared to solution formulations (Fig. 8), though over 95% of nanoparticles may end up outside the target area.

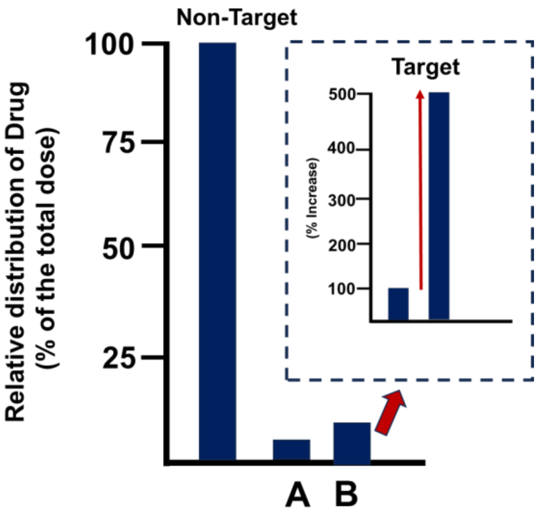

Fig 8: Comparative distribution of a drug at a target tumor site using (A) traditional solution formulation and (B) nanoparticle-based formulation.

Nanomedicine, an extension of nanotechnology, involves engineering nanodevices for monitoring, repairing, and regulating biological systems at the molecular level. A major focus is on ensuring efficient distribution of drugs throughout the body. Over the past two decades, researchers have developed various drug delivery systems to improve stability, absorption, and therapeutic concentration, and to enable sustained release at the target site. These systems also enhance the pharmacokinetics of proteins and peptides, which have short half-lives in vivo, and reduce drug administration frequency, improving patient comfort. In the pharmaceutical sector, innovative delivery technologies provide a competitive edge and extend the market life of drugs once patents expire, with drug delivery systems currently comprising 13% of the global pharmaceutical market. Despite their promise, some drug delivery systems face significant challenges. For example, the oral route, though preferred for its non-invasiveness, is ineffective for peptide or protein drugs due to the stomach's acidic environment, the liver's first-pass effect, and the intestine's resistance, which reduce drug bioavailability. This contributes to the need for daily insulin injections for diabetics, leading to non-adherence to treatment [83]. Nanotechnology holds great promise in medical applications, including molecular imaging, targeted drug delivery, and disease diagnosis, with several products undergoing clinical trials. While the full extent of its impact on healthcare is still unfolding, advancements suggest it will play a major role in disease prevention, diagnosis, and treatment [52]. Systemic distribution of drugs faces challenges, such as maintaining therapeutic drug concentrations and managing toxicity, metabolism, and excretion. Nanotechnology-based delivery systems may help address these issues by integrating organ-specific targeting with therapeutic effects. The most significant medical applications of nanotechnology are expected to be in pharmaceutical development, with emerging applications focusing on controlled release, drug targeting, and enhancing the bioavailability of poorly soluble drugs [84, 85]. Research is also underway to develop new polymers and explore drug-polymer combinations [86].

In 2014, Nicolas Bertrand et al. [87] highlighted the rapid progress in cancer nanotherapeutics, particularly since the early 2000s. Despite the challenges in bringing oncology drugs to market, nanoparticle technologies are seen as crucial for advancing cancer drug development. Pharmaceutical companies are increasingly collaborating to leverage proprietary nanoparticle technologies. Nanotechnology has the potential to improve the effectiveness and acceptability of novel therapeutic candidates, thereby enhancing clinical outcomes. This study reviews the progress since the introduction of first-generation nanotherapeutics like DOXIL® and Abraxane® and examines the development stages of targeted and non-targeted nanoparticles, including MM-398 and BIND-014 [88]. It also addresses the prospects and challenges nanomedicines face in oncology, particularly with the rise of personalized medicine. The review covers the enhanced permeability and retention (EPR) effect and explores strategies to improve selective retention within tumors, such as actively targeting nanoparticles, attaching drugs to tumor-specific targets, or engaging tumor-associated macrophages. The effectiveness of actively targeted nanoparticles relies on selecting appropriate ligands [89]. Initially, antibodies were the primary targeting moieties, but recent studies have introduced proteins, peptides, nucleic acid-based ligands, and small molecules (Table 6).

Table 6: Different instances of targeting ligands employed in preclinical investigations. EpCAM, which stands for epithelial cell adhesion molecule, and EDB, an abbreviation for extra-domain B, are among them

Delivery Systems	Kinds of Ligands	Targets	Applications	Ref.
Fragments and Antibodies(Ab)				[90]
Quantum dots	Full antibody	Prostate-Specific Membrane Antigen	Cancer (imaging)	
Liposome	Hypervariable region	Gastric Adenocarcinoma Homing	Gastric cancer	
Liposome	Fragment antigen-binding.	Human Epidermal Growth Factor Receptor 2	Breast cancer	
Liposome	single-chain variable fragment	Human Epidermal Growth Factor Receptor 2	Breast cancer	
Proteins				[91]
Polymeric NPs	Transferrin	Transferrin receptor	Cancer	
SiRNA complexes	Ankyrin repeat protein	Epithelial Cell Adhesion Molecule	Cancer	
Polymeric NPs	Affibodies	Human Epidermal Growth Factor Receptor 2	Breast Cancer	
Peptides				[92]
Protein NPs	CGNKRTRGC (LyP-1)	gC2qr(p32)	Cancer	
Iron oxide NPs	F3 peptide	Nucleolin	Cancer (imaging)	
Iron oxide NPs	iRGD	αβv3/5	Cancer (imaging)	
Polymeric NPs	iRGD	αβv3/5	Cancer	
Polymeric NPs	KLWVLPKGGGC	Collagen IV	Inflammation	
Polymeric NPs	KLWVLPK	Collagen IV	Vascular wall	
Liposomes	Aptides	Fibronectin	Cancer	
Ligands derived from nucleic acids				[93]
Polymeric NPs	A10-aptamer	Prostate-specific membrane antigen	Prostate Cancer	
Gold NPs	A9 CGA aptamer	Prostate-specific membrane antigen	Prostate Cancer	
Tiny particles				[90]
Gold nanorods	Folic acid	Folic acid receptors	Cancer	
Polymeric NPs	Folic acid	Folic acid receptors	Cancer	

Polymeric NPs	Triphenylphosphonium	Mitochondria	Various	
Polymeric NPs	S,S-2-[3-[5-amino-1-carboxypentyl]- ureido]-pentanedioic acid	Prostate-specific membrane antigen	Cancer	

Also, Remião et al. [94] highlighted that reproductive medicine focuses on methods to help couples achieve pregnancy, preserve fertility, and treat conditions affecting the reproductive system. Assisted reproductive technology (ART) is commonly used for infertility, but it presents challenges that require continuous attention. Nanotechnology has become a valuable tool in reproductive medicine, improving diagnostic capabilities and enhancing specificity and sensitivity [11]. Recent advancements in nanotechnology have aimed to address issues in ART, such as ovarian stimulation, multiple pregnancies, and genetic disorders. Despite progress in ART, challenges remain, particularly in pregnancy rates, multiple births, and genetic disorders [95,96]. Nanotechnology offers potential solutions to these problems, providing opportunities for more effective diagnostics and treatments for future generations. Besides, Vinay Bhardwaj and his team (2017) studied the biomedical applications of nanotechnology and nanomaterials [97]. The growing clinical acceptance of nanomaterials in medicine, known as "nanomedicine," is transforming global healthcare. This progress requires collaboration among academia, industry, and government, with over 250 nanomedicine products currently available, 50 of which are in use by medical professionals [98]. Notably, some commercial nanomedicines, like Abraxane (130 nm) and Myocet (180 nm), exceed the 100-nanometer threshold, challenging the conventional size limit for nanomaterials.

Inorganic nanomaterials, particularly those based on transition metals, offer unique optical, electrical, and magnetic properties, making them ideal for applications in optical and electrical sensing [99], diagnosis [100], photothermal therapy [101], and optogenetics [102]. These materials, alongside nanotechnology and stem cell biotechnology, hold significant potential for regenerative medicine. Bioactive nanomaterials, including polymers and metals, are being developed to improve therapeutic efficacy. For example, the Polymer Drug approach engineer's polymers that degrade into therapeutically active molecules like PolyAspirin and PolyMorphine, enhancing the effectiveness of conventional drugs for pain and inflammation management [103].A promising strategy involves amphiphilic nanomaterials with core-shell micelles, made from sugar-based structures, which can encapsulate drugs and deliver them precisely, especially in cancer treatment. These materials also block scavenger receptors, potentially inhibiting diseases like atherosclerosis and Parkinson's [104,105]. Nanotechnology enables precise drug delivery to targeted tissues or cells, minimizing off-target effects. Engineered nanoparticles can bind to cancer cells, reducing harm to healthy tissues, and improving drug solubility and stability. Nanocarriers, such as liposomes and polymeric nanoparticles, enable sustained or triggered drug release, enhancing therapeutic efficacy and reducing dosing frequency. Additionally, nano-drug delivery systems integrate diagnostics and therapy (theranostics), offering advantages over traditional methods by concentrating drugs at disease sites and minimizing systemic exposure.

Section 3.1.1 *discusses how nanotechnology has revolutionized drug delivery through nanoparticles designed for targeted therapy, particularly in cancer treatment. While nanoparticles enhance drug loading, improve targeting, and increase tumor drug concentrations by 100–400%, over 95% still fail to reach the intended site. Nanomedicine extends these applications to diagnostics and therapeutics, with advances in sustained drug release, bioavailability, and patient adherence. Despite challenges like systemic toxicity and delivery barriers, nanotechnology holds promise in pharmaceuticals, regenerative medicine, and theranostics. Emerging nanoparticle-based therapies, including DOXIL® and Abraxane®, continue shaping modern oncology and personalized medicine, driving innovation in drug development.*

3.1.2 Nanotechnology for Dentistry and Immunology

In dentistry, nanotechnology offers new materials and techniques for dental restoration, oral hygiene, and the treatment of periodontal diseases. Nanocomposite materials are used for stronger and more durable dental fillings, while nanoparticles in toothpaste and mouthwash enhance antibacterial properties, improving oral health. In 2023, Shiza Malik et al. [48] studied 'Nanotechnology: A Revolution in Modern Industry' and provided an overview of cost-effective and vibrant nanotechnologies in materials and mechanical sciences, offering insights into their applications across various fields. While nanotechnology holds immense potential, its associated risks, especially in nanotoxicology, remain largely undefined, requiring further investigation. Collaborative efforts among researchers, technicians, and industrialists are essential to explore its practical applications and evaluate nanoscale developments. Despite its promising industrial prospects, precautions must be taken to address environmental, health, and sustainability concerns. Integrating sustainability with nanotechnology will ensure its responsible and prosperous future. Nano dentistry, a specialized branch of nanomedicine, employs nanotechnology in dental care, enhancing diagnosis, prevention, treatment, and oral health maintenance [106-108]. Notable applications include the use of nanoparticles in remineralizing enamel to prevent decay and nanostructures for enhancing tooth sensitivity treatment by targeting nerve endings. Advanced enamelling techniques involve nanomaterials that form a protective layer on teeth, providing a durable solution for dental restoration. Denaturalization of dentition refers to the process of using nanomaterials to reverse damage caused by mineral loss. Mechanical dentifrobots, designed to interact with tooth tissues by modulating nerve impulses in real-time, regulate tooth-tissue interactions to restore normal function. These devices work with nanocomputers that adapt to external stimuli and nerve signals. While promising, further research into the feasibility, challenges, and current developmental status of mechanical Denti robots and other nanotechnology applications in dentistry is essential to fully realize their potential [109]. These dental applications of nanotechnology are elaborated further in the accompanying Fig 9.

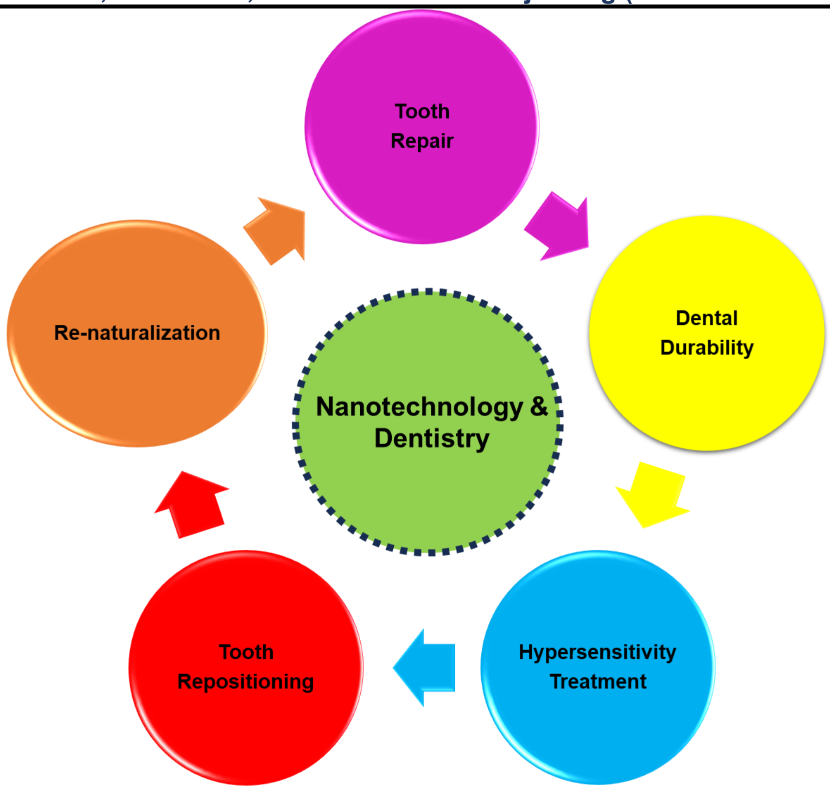

Fig. 9: Nanotechnology applications enabling significant advancements in repairing and treating dental problems.

Nanotechnology in dentistry has gained significant attention due to its potential to revolutionize dental care, particularly in areas such as tooth regeneration, restoration, and infection control. The application of nanoparticles enables improved drug delivery, bioactive materials for tissue regeneration, and enhanced diagnostic techniques. These advancements not only offer more efficient treatments but also promote better patient outcomes by minimizing side effects and improving the precision of therapies. As a result, the incorporation of nanotechnology has transformed the landscape of dental care, offering new solutions for common challenges in oral health. The successful integration of nanotechnology in dentistry has paved the way for exploring its potential in other biomedical fields, notably immunology. The parallels between both fields, especially regarding nanocarriers and the targeted delivery of therapeutic agents, are becoming increasingly evident. In immunology, nanoparticles are being developed to deliver vaccines, regulate immune responses, and treat autoimmune diseases with greater specificity. The ability of nanoparticles to interact at the molecular level, similar to their role in dentistry, enhances their effectiveness in immunological applications. This transition from dental applications to broader immunological uses signifies the growing interdisciplinary potential of nanotechnology, bridging previously distinct domains to address complex healthcare challenges.

Nanotechnology is also advancing the field of immunology. Nanoparticles can be used to develop more effective vaccines and immunotherapies by enhancing the delivery and presentation of antigens to the immune system. This leads to stronger and more precise immune responses, which is crucial for combating infectious diseases and cancer**.** Likewise, Douglas M. Smith et al. [110] studied the applications of nanotechnology for immunology and found that nanotechnology is being leveraged to engineer immune responses for both prophylactic and therapeutic purposes. Future advancements in nanoparticles, with tailored properties like size, shape, charge, and hydrophobicity, will allow for customized immune responses. Rapid activation of innate and adaptive immune systems could improve protection against emerging pathogens and pandemics, potentially within hours or days after vaccination. This may involve nanoparticles delivering antigens, cytokines, or even immunoglobulin genes for immune replacement. Nanotechnology also holds promise in activating cytotoxic T lymphocyte (CTL) responses to target tumors or infected cells by combining nanoparticles with antigens or immunomodulators like cytokines. Co-stimulatory ligands, such as CD40L and GITR, could enhance precision in immune response regulation compared to current methods. Additionally, nanoparticles could induce CTL responses to normally inert antigens or provide preventative treatment for autoimmune diseases. Genetic screening could enable early correction of immune defects through nanoparticle gene delivery. Nanotechnology-based screening techniques, like silicon nanowires combined with siRNA, offer new ways to explore immune response pathways, potentially leading to better therapeutics with fewer side effects. Overall, nanotechnology holds significant potential for advancing immune-related therapies and disease prevention. Nanoparticles influence immune responses through various mechanisms. They enhance antigen delivery via tissue penetration and lymphatic access, create a depot effect for sustained antigen release, and promote repetitive antigen display for B cell activation. Additional pathways include Toll-like receptor signaling, cross-presentation of antigens via cytosolic leakage, and cytokine-mediated immune regulation (Fig. 10). The biological spectrum of materials relevant to the immune system is shown in Table 7, and the immunosuppressive effects of nanotherapeutics are discussed in Table 8.

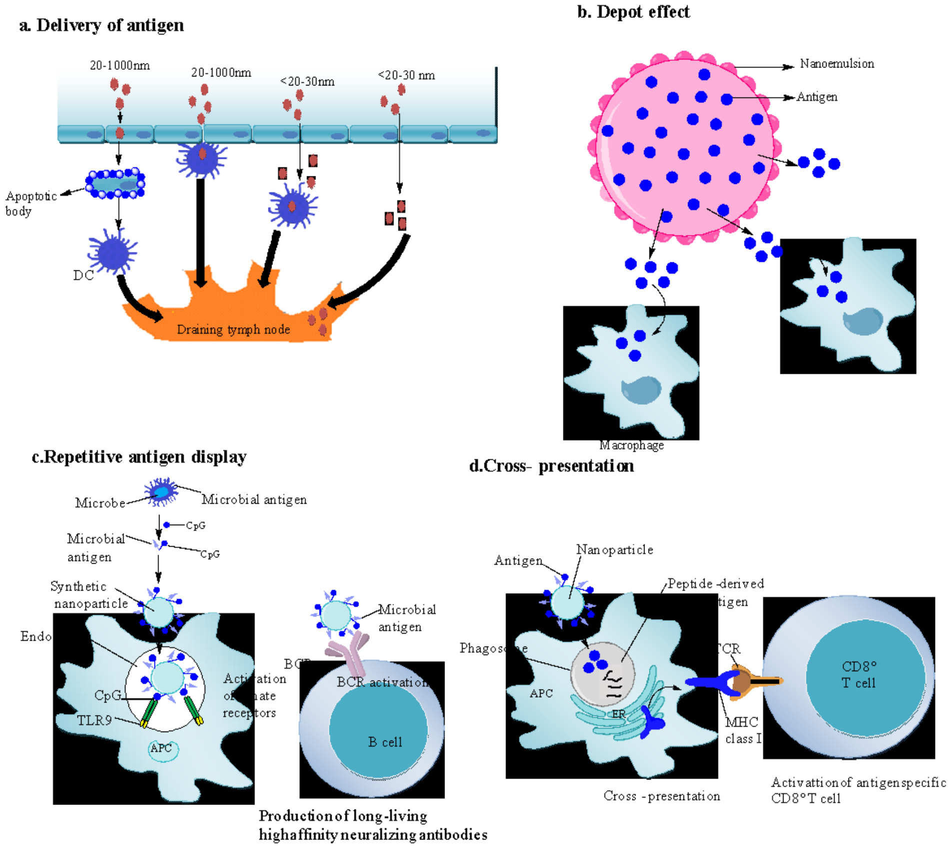

Fig. 10: Mechanisms through which nanoparticles modify the activation of immune responses.

Table 7: The biological spectrum of materials pertinent to the immune system

Dimensions	**Category**	**Ref**
Receptors		
2-10nm	Toll-like Receptors	[111]
10-15nm	Antibodies	[112]
10-15nm	T-cell Receptors	[113]
Molecules		
1-3nm	DNA	[114]
200-1000nm	Polysaccharides	[115]
2-10nm	Proteins	[116]
Cells		
10-22µm	Dendritic cells	[117]
10-22µm	Macrophages	[118]
7-10µm	B cells	[119]
7-10µm	T cells	[120]
8-15µm	Neutrophils	[121]
10-12µm	Eosinophils	[122]
Pathogens		
10-200nm	Viruses	[123]
0.1-8µm	Bacteria	[123]
1-100µm	Fungi	[124]
1-100µm	Protozoa	[125]

Table 8: Illustrations of immunosuppressive impacts caused by nanotherapeutics

Compounds	Dimensions	Medical applications	System	Present application	Ref.
Direct Applications					
Single-walled carbon nanotubules	1-4 nm diameter; 1,000-3,000nm length	Inhalation exposure	Suppression of dendritic cell function	In mice	[126]
Multi-walled carbon nanotubules	10-20nm diameter; 5,000-15,000nm length	Inhalation exposure	Suppression of T lymphocyte proliferation and function	In mice	[127]
Spherical fullerenes	1nm diameter	Allergy	Suppression of mast cell and basophil degranulation	In mice and in vitro	[128]
Delivery Applications					
Polyamidoamine dendrimers	1-20 nm	Cerebral palsy, scar formation and gastroenteritis	N-acetyl-cysteine glycosamine	In rabbits	[129]
Nanocrystals	200nm	Transplant rejection	Sirolimus	Licensed in humans	[130]
Poly(lactide-co-glycolide)	1-400nm	Arthritis and autoimmune disease	Betamethasone, bifunctional peptide inhibitors, and leukaemia-inhibitory factor	In mice and rats	[131]
Liposomes	100-160nm	Arthritis, coronary artery stenosis and acute lung injury	Liposomal bisphosphonates	In rats, rabbits and pigs	[129]
Solid lipid nanoparticles	200-400nm	Transplant rejection	Cyclosporin	In humans	[130,132]
Carbon nanotubules	3.5nm diameter and 90nm length	Induction of apoptosis	Cytochrome and phosphatidylserine	In mice and rats	[133]
Sterically stabilized phospholipid micelles	15nm	Rheumatoid arthritis	Camptothecin and vasoactive intestinal peptide	In mice	[130,132, 133]
Liposomes with DC-targeting ligands	50-92nm	Autoimmune disease	small interfering RNA	In mice	[131]
Nano emulsions	3-400nm	Autoimmune thyroiditis	Self-antigen	In mice	[134]

Nanocomposites offer superior mechanical strength, aesthetics, and durability in dental restorations compared to traditional materials. Nanoparticles, such as silver or zinc oxide, demonstrate potent antibacterial properties, preventing infections in dental procedures like fillings and implants: an advantage not provided by conventional methods [107,108]. Nanotechnology also enhances the adhesion of dental materials to enamel and dentin, improving the longevity of treatments. Nanomaterials, such as hydroxyapatite nanoparticles, support tissue regeneration, enabling more effective dental repairs than traditional approaches. Furthermore, nano-dentistry facilitates non-invasive or minimally invasive diagnostics and treatments, such as the early detection of oral cancers using nanosensors, which are significantly more sensitive than conventional diagnostic tools [107]. While nanotechnology has shown remarkable potential in healthcare, its applications extend far beyond medicine, offering innovative solutions in agriculture as well. The same principles and technologies that enable targeted drug delivery and disease detection in healthcare are being leveraged to enhance agricultural practices. For instance, nanosensors used for health monitoring are now being applied to detect soil health and crop diseases. Similarly, the development of nanomaterials for drug delivery systems has inspired the creation of nano pesticides and nano fertilizers that offer more efficient, sustainable solutions for crop protection and nourishment [131]. As nanotechnology continues to bridge these fields, its interdisciplinary applications promise to transform both sectors in complementary ways.

Nanotechnology holds promise in dentistry and immunology, but it also presents significant limitations and challenges. Ethical concerns arise due to the potential unknown long-term effects of nanoparticles on human health and the environment [110,116]. The manipulation of materials at the nanoscale may lead to unforeseen biological interactions, raising questions about patient safety and consent. Cost is another critical limitation. Developing, manufacturing, and deploying nanotechnology-based treatments are often expensive, restricting access to these advanced therapies [130]. This economic barrier can exacerbate disparities in healthcare, making cutting-edge treatments available only to wealthier populations. Accessibility further complicates the widespread adoption of nanotechnology. The need for specialised equipment and trained personnel limits its application in underresourced regions. Consequently, the benefits of nanotechnology may not reach those who need it most, such as populations in developing countries or rural areas. Additionally, potential risks include toxicity and unintended immune responses. Nanoparticles may accumulate in organs, causing adverse effects or chronic conditions [126,127]. In immunology, there is a risk of overstimulating the immune system, leading to autoimmunity or severe allergic reactions [110,116,117]. While nanotechnology offers transformative potential in dentistry and immunology, ethical concerns, high costs, limited accessibility, and potential risks must be carefully managed to ensure its safe and equitable implementation. While nanotechnology has made significant advances in healthcare, offering innovations in drug delivery, diagnostics, and disease prevention, its applications also extend to other vital sectors, such as agriculture. In agriculture, nanotechnology plays a transformative role by enhancing crop protection, improving nutrient delivery, and developing sustainable farming practices [131]. The interdisciplinary nature of nanotechnology allows for the exchange of knowledge and techniques between these sectors, fostering advancements that can improve both human health and food security. Thus, the synergies between healthcare and agriculture highlight nanotechnology's broad potential to address global challenges across various domains.

Section 3.1.2 *explores the diverse applications of nanotechnology in dentistry and immunology, highlighting its transformative potential in both fields. In dentistry, nanotechnology enhances dental materials, including stronger and more durable fillings, antibacterial properties in oral care products, and advanced techniques for tooth regeneration and enamel remineralization. Nanotechnology also facilitates non-invasive diagnostics and treatments. In immunology, nanoparticles improve vaccine delivery, enhance immune responses, and enable targeted therapies for diseases like cancer and autoimmune disorders. Despite its promise, challenges such as ethical concerns, high costs, accessibility, and potential risks like toxicity must be addressed to ensure safe and equitable use across healthcare and other sectors.*

5. Conclusion

Nanotechnology stands at the forefront of modern scientific innovation, offering powerful solutions to many of the critical challenges faced in healthcare. This review emphasized the unseen science of nanotechnology and its significant impact on human health care, particularly through advancements in drug delivery, dentistry, and immunology. Nanoscale drug delivery systems, such as liposomes, dendrimers, solid-lipid nanoparticles, and polymeric carriers, have demonstrated remarkable improvements in targeted therapeutic delivery, controlled drug release, and reduced systemic toxicity, ultimately enhancing treatment efficiency and patient outcomes. Similarly, nanomaterials used in dentistry, including nano-hydroxyapatite, nano-composites, and antimicrobial nanoparticles, have shown superior mechanical properties, enhanced tooth remineralization, and improved resistance to oral infections. Additionally, nanotechnology has advanced immunology through the development of nanoparticle-based vaccines and immune-modulating nano-adjuvants that strengthen immune responses and support emerging therapies for infectious and chronic diseases. Despite these successes, challenges remain regarding biocompatibility, long-term safety, clinical translation, regulatory frameworks, and manufacturing scalability. Overcoming these barriers requires interdisciplinary collaboration, standardised safety protocols, and responsible research practices. With continued progress, nanotechnology is poised to transform the future of healthcare and advance more effective and personalised medical solutions.

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