Nanotechnology Applications in Medicine and Environment: A Multidisciplinary Perspective

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Abstract

Nanotechnology involves the manipulation of materials at an extremely small scale—1 to 100 nm. It thus enables the design of structures, devices, and systems with fundamentally new properties, functionalities, and performance because of their size and structure. A nanoparticle (NP) is a microscopic particle whose size is measured in nanometers. It has a very high surface-to-volume ratio and different properties compared to the same material at a larger scale. NPs are the principal component of nanotechnology and have had, in the last few years, an ever-increasing role in different fields such as environmental protection, development of new clinical instruments, and energy production. Both chemically and physically, NPs have unique size-dependent optoelectronic properties and high chemical stability, diffusing along the human body more than the bulk material. Thus, a deep understanding of their toxicity and interaction with biological tissues and organs is essential.

Although the youngest discipline between genetics, chemistry, and physics, nanotechnology already plays the same role as the first two have had for other scientific fields. Owing to the wide variety of applications and disciplines, the belongings of nanotechnology range from photonic crystals to release and protection of drugs, from microbiology to computation, placing itself as a challenging viewpoint of scientific and technological research with still numerous uncovered aspects.

Chapter - 1

Introduction to Nanotechnology

Nanotechnology was first introduced to the scientific community in the notable year of 1959 by the renowned and highly respected physicist Richard P. Feynman, who provided a visionary and illuminating description of the profound ability to manipulate and exert precise control over matter at the atomic and molecular scale. Over the decades that have followed, the term has become widely embraced and extensively utilized by researchers and industries alike, especially since it coincided with the remarkable emergence of advanced technologies that facilitate direct control and detailed characterization of a diverse array of nanoscale materials. Nanomaterials, which are specifically defined as materials having at least one dimension that is smaller than 100 nanometers, fall within a particular size domain that is notable for enabling a myriad of unique physical and chemical phenomena. These astonishing phenomena create a plethora of innovative applications that were previously deemed unattainable or impossible.

Nanostructures, as a result, are generally classified into distinct and recognizable categories based on their dimensional characteristics. They can be categorized as zero-dimensional structures, such as nanoparticles that are entirely enclosed in all three spatial dimensions; one-dimensional structures like nanorods and nanowires that are confined in only two spatial dimensions; two-dimensional structures, which include various forms of nanofilms and nanocoatings that are limited to one dimension; and finally, three-dimensional structures, exemplified by nanocomposites and bulk materials that contain nano-sized grains. This intricate classification system is fundamentally based on the significant and often transformative effects that nanoscale dimensions exert on their inherent physical and chemical properties.

The expansive and multifaceted field of nanotechnology encompasses a vast range of topics and disciplines, including the essential fundamental physics, chemistry, and biology of various types of nanostructures. This is in addition to the ongoing and dynamic development of novel synthesis methods along with advanced characterization tools and innovative techniques that aid in the thorough exploration of these remarkable materials. Recent significant and impactful advancements in this field encompass an even broader spectrum of nanomaterials, ranging from the well-known carbon nanotubes and quantum dots to innovative two-dimensional nanomaterials that have recently captured considerable attention. Each of these diverse and fascinating materials comes equipped with its own set of corresponding preparation technologies and specialized characterization tools, as well as intricate and nuanced theoretical studies that delve deeply into their unique behavior and wide-ranging applications. These groundbreaking developments empower a seamless and efficient transition from rigorous fundamental research studies into a diverse variety of promising applications that hold immense potential for the future across multiple sectors and fields [1, 2, 3, 4, 5, 6, 7, 8, 9].

Chapter - 2

Historical Background of Nanotechnology

Nanotechnology, a swiftly advancing domain of research and technological development, originated with the imaginative conception of revolutionary nanotransformers, pioneering nanomotors, and state-of-the-art nanoactuators. The expansive and richly woven history of this captivating field is sharply centered around Richard P. Feynman's impactful and transformative talk delivered in 1959, entitled "There's Plenty of Room at the Bottom." In this seminal address, Feynman passionately advocated for the manipulation and precise governance of individual atoms and molecules, fostering what was envisioned as an extraordinary generation of miniature, ultraperformance machines that held the power to fundamentally revolutionize technology as we understand it today. It was a forward-thinking Ph.D. student named Norio Taniguchi who first put forth the term "nanotechnology" in 1974, thereby marking an essential and significant milestone in the ongoing evolution of the discipline. Feynman's visionary insights and perspectives now serve as the essential motivation and unwavering driving force behind the expansive field of nanotechnology. In the subsequent year of 1981, pioneering scientists Gerd Binnig and Heinrich Rohrer revealed the revolutionary scanning tunneling microscope, which significantly enhanced the three-dimensional visualization capabilities of individual atoms displayed on surfaces, thus opening a multitude of new avenues for research, discovery, and innovation. A decade later, in 1991, the distinguished researcher Sumio Iiejima made a notable advancement in the field by elucidating the remarkable characteristics and properties of multiwalled carbon nanotubes. This groundbreaking work has had lasting implications for nanotechnology and materials science. In the year 2004, researchers successfully reported the assembly of carboranethiol monolayers on Au (111), dramatically showcasing the extensive potential for advanced materials to be explored and applied within the realm of nanotechnology. By the year 2008, extraordinary progress was accomplished with the synthesis of hollow tubular structures of WS2, which impressively exhibited a high refractive index of 4.2, further extending and pushing the boundaries of what is deemed feasible and achievable in the exciting and intricate world of nanotechnology [10, 11, 12, 13, 14, 15, 16].

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Fundamental Principles of Nanotechnology

Nanotechnology encompasses a vast and intricate array of processes and techniques involved in the meticulous design, detailed characterization, systematic production, and innovative application of a wide variety of structures, devices, and systems. These entities exhibit remarkable and novel physical, chemical, and biological properties, all achieved by exercising precise control over their shape and size at the nanoscale, which is defined as the nanometre scale. The fundamental concepts that serve as the backbone of the expansive field of nanotechnology include several critical phenomena, among them the enhanced surface reactivity of nanoparticles, the intriguing quantum size effect, the significant quantum confinement, and the fascinating quantum tunneling.

The enhanced surface reactivity of nanoparticles arises primarily from the substantial increase in the surface-to-volume ratio that is characteristic of materials at the nanoscale. When particles are reduced to dimensions within the nanoscale range, a considerable and significant fraction of the atoms within these particles are situated at or near their very surface. This unique arrangement leads to a substantial alteration of their chemical reactivity when compared to larger particles. For instance, experimental investigations and measurements of the adsorption characteristics of various molecules on titania substrates revealed a clear and pronounced inverse linear scaling relationship with respect to particle size. This phenomenon demonstrates the critical impact of nanoscale dimensions on surface phenomena, showcasing how size can influence chemical interactions.

Additionally, the quantum size effect represents a remarkable phenomenon that occurs when the physical dimensions of a material—be it a particle, a quantum well, or even a nanowire—become comparable and relevant to the de Broglie wavelength associated with electrons. As a result of this notable size reduction, the previously continuous electron energy bands found in bulk materials undergo a transformation, splitting into discrete and separated electron energy levels. This transition effectively alters the electronic properties of the material in profound ways.

Furthermore, the quantum confinement effect is closely related to this phenomenon and arises from the existence of an energy barrier, such as that established by a potential well. This barrier restricts the motion of electrons or atoms in one or more specific directions, which leads to notable modifications in the local density of electronic states. Specifically, this confinement results in significant alterations in the energy band structure, which can have far-reaching implications for the electronic properties and behavior of nanomaterials.

Lastly, the concept of quantum tunneling delineates the remarkable ability of a particle to traverse an energy barrier, thereby defying the traditional principles of classical mechanics. This intriguing phenomenon of tunneling plays a crucial role in enabling high electrical conductivity in certain nanostructures, such as the extensively studied carbon nanotubes. It underscores the unique and sometimes counterintuitive behaviors that materials can exhibit at the nanoscale. The implications of these phenomena pave the way for groundbreaking advancements and innovative applications across various technological domains. Thus, the exploration and understanding of nanotechnology continue to unlock potential that can significantly influence fields ranging from electronics to medicine [17, 18, 7, 19, 20, 21, 22, 23, 24, 25, 6].

Chapter - 4

Nanomaterials: Types and Properties

Nanomaterial technology has developed at an astonishingly rapid pace over recent years, primarily because it not only enhances the existing properties of a myriad of materials but also enables the fabrication of entirely new materials that are particularly effective and feasible for specific applications across diverse fields and industries. Nanomaterials are specifically defined as materials that possess a physical size smaller than 100 nm in at least one dimension. It is precisely within this diminutive size range that such materials exhibit truly remarkable and astonishing properties that are seldom observed in bulk materials. These unique and exceptional properties arise due to a combination of factors, including quantum effects and the significantly high surface-to-volume ratio that nanomaterials inherently possess. The study of materials at the nanoscale, which is often referred to as nanostructures, provides a substantial and diverse array of opportunities in terms of tailoring and customizing properties for a wide variety of applications across different domains. The properties of materials, including mechanical, electrical, thermal, and optical characteristics, can be finely tuned and adjusted in nanomaterials by systematically controlling various critical variables such as size, shape, surface morphology, and composition. Moreover, nanomaterials are classified based on several distinct criteria, which include their size, dimensionality, source, chemical composition, and the specific method of synthesis employed in the creation of these materials. This classification can be categorized in a general manner or be based on particular applications that are relevant to different industries and research fields, demonstrating the versatility and adaptability of nanomaterials in numerous cutting-edge applications [26, 2, 1, 27, 4, 5, 7, 28, 8, 9].

4.1 Metallic Nanoparticles

Nanotechnology is playing an increasingly pivotal role in driving significant and transformative advances across multiple fields such as medicine, electronics, energy harvesting, manufacturing processes, and environmental remediation strategies. Engineered nanoparticles, which have already been produced in remarkably large and technologically sophisticated volumes, are now being incorporated into a broad range of both commercial and medical products to improve functionality. This incorporation not only enhances their overall performance but also significantly improves the quality and efficacy of these diverse products. However, alongside these impressive advancements, the potential environmental impacts and health risks associated with nanometals and nanoparticles have generated crucial new insights and discussions within the emerging field of nanotoxicology. This highlights an urgent need for comprehensive further investigation and deeper understanding of these materials and their complex effects on human health and the surrounding environment. As the utilization of nanotechnology expands, addressing these concerns will pave the way for safer and more responsible innovations [29, 30, 31, 32, 33, 34, 35, 36].

Metallic nanoparticles play an incredibly vital role in a remarkably wide range of applications, including catalytic processes, numerous biomedical endeavors, magnetic recording, and several other innovative and groundbreaking uses. The meticulous and precise control over parameters such as particle size, shape, and aggregation is fundamentally crucial across many of these commercial processes, primarily due to the size dependency of numerous associated properties and characteristics. Specifically in the intricate realm of catalysis, it is particularly important to cultivate supported metal nanoparticles (NPs) that can retain their reduced size even under elevated temperatures and challenging conditions. Over the recent years, significant and noteworthy progress has been made in the innovative development and preparation of both metal and magnetic metal-oxide nanoparticles that feature well-defined size and structure, with an increasing focus on utilizing advanced reverse micelle methods. In addition to these impressive advancements, a novel and groundbreaking approach to synthesizing supported metal NPs has emerged, which incorporates the effective dispersion and size regulation of pre-formed colloids that are stabilized by steric surfactants.

By synthesizing these colloids at lower temperatures, this novel method enables the formation of particles with a smaller size compared to those generated at higher thermal conditions and temperatures. However, one of the critical challenges associated with this sophisticated technique arises from the necessity of effectively removing surfactants and other unwanted contaminants during the process of transferring the colloid metal NPs onto the support substrate. Addressing this significant challenge is essential for enhancing the overall effectiveness and efficiency of the nanoparticle integration process in various applications while ensuring the desired performance outcomes [37, 38, 39, 40, 41, 42, 43, 44, 45].

4.2 Carbon-Based Nanomaterials

Nanocarbons, which include a diverse range of fascinating materials such as carbon nanotubes (CNTs), carbon nanohorns (CNHs), and fullerenes, have been the subject of extensive and thorough investigation as promising biomaterials. Their various utilizations across multiple fields have been significantly exemplified by carbon nanotubes, which showcase an impressive versatility. The unique and extraordinary properties that are inherent to these nanocarbon structures enable them to be employed in a broad and exciting spectrum of applications that aim to tackle the significant technological challenges we face in today's world. When considering prospective clinical applications, it is crucial to acknowledge that the use of nanocarbons may expose patients to potential health risks in ways that are not typically encountered with alternative products present in the market. Thus, the careful consideration of biosafety associated with the usage of nanocarbons emerges as a matter of paramount importance, particularly when weighing the prospects of their commercial exploitation and thoughtful integration into medical practices designed to benefit patients. The extensive and abundant body of ongoing research surrounding the toxicity and biopersistence of these innovative materials indicates that, depending on their specific structural forms and inherent nature, nanocarbons can exhibit a wide and concerning range of adverse effects. Some of these negative outcomes are notably similar to those observed with asbestos exposure, which raises significant and serious concerns among researchers and health professionals alike. For instance, the hair-like carbon nanotubes have been shown to penetrate deep into biological systems, potentially resulting in serious pulmonary complications and various other health issues that may arise. Furthermore, the market for carbon nanotubes continues to expand dynamically, spurred on by their remarkable applications in lithium-ion batteries, composite materials, and low-friction bearings, among numerous other innovative uses. Given this ever-growing interest and increasing demand across industries, monitoring the potential hazards associated with carbon nanotubes remains absolutely crucial. The ongoing urgency for dedicated research into their health effects is indispensable as we strive to balance innovative advancement with essential patient safety and broader environmental considerations in this rapidly developing and evolving field of nanocarbon technology [46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56].

Nanocarbons, which include carbon nanotubes (CNTs), carbon nanohorns (CNHs), and carbon nanofibers (CNFs), have undoubtedly captured significant attention within the scientific community for their potential clinical applications that could transform modern medicine. Recent industrial advancements have successfully yielded the large quantities of these materials required for various clinical uses; however, the practical applications of nanocarbons have, up to this point, been largely constrained to only a limited number of specific cases. This limitation primarily stems from ongoing concerns surrounding their biosafety. In the ongoing process of meticulously evaluating biosafety and assessing the biocompatibility of these materials for clinical application, several critical points have emerged, each being particularly noteworthy. One crucial prerequisite that has been identified is that biomaterials should have the capacity to interact with the body transiently, thus ensuring that both biodegradability and biocompatibility are essential characteristics that must be meticulously ensured to avoid any adverse effects. In general terms, while it is widely recognized that nanocarbons demonstrate a strong degree of biocompatibility, they typically exhibit poor biodegradability capabilities, which raises significant concerns regarding their long-term presence and effects within biological systems. Following the groundbreaking discovery of fullerenes, which showcase remarkable anti-oxidant properties, the pronounced biocompatibility exhibited by various forms of nanocarbons has been effectively utilized; however, this utilization has yet to be translated into substantial clinical applications. Notably, these advantageous properties can sometimes present unique benefits—for instance, in particular cases, they may allow for a relaxation of the strict biodegradability requirement when biomaterials are specifically sought after to achieve a targeted therapeutic effect or desired outcome, thereby enabling their strategic and informed use in carefully selected medical contexts where such properties are essential [57, 49, 58, 59, 60, 61, 62].

4.3 Polymeric Nanoparticles

Polymeric nanoparticles (PNPs) represent a unique and distinct category of nanosystems, meticulously engineered to offer innovative and effective platforms for the efficient delivery of drugs and a plethora of various bioactive molecules to specific and targeted sites within the complex environment of the body. By significantly enhancing solubility, allowing for controlled release, and facilitating targeted delivery, PNPs have opened up entirely new avenues in the treatment, prevention, and management of a wide array of prevalent clinical disorders. These include, but are not limited to, serious conditions such as cancer, cardiovascular diseases, diabetes, respiratory diseases, and various inflammatory ailments. There exists a multitude of comprehensive and diverse methods for the preparation of polymeric nanomaterials, which encompass a broad spectrum of both synthetic and biological techniques, each tailored to achieve specific goals and outcomes in the realm of drug delivery. Various sophisticated and refined approaches for the formation of PNPs include emulsification solvent evaporation, which involves meticulous and carefully controlled techniques to create stable and homogeneous emulsions, nanoprecipitation for the rapid and efficient formation of nanoparticles by diffusion, emulsification solvent diffusion that leads to effective phase separation, salting-out processes to encourage the targeted formation of nanoparticles through salting mechanisms, emulsion polymerization that creates durable polymers by polymerizing reactive monomers within an emulsion medium, surfactant-free emulsion polymerization that systematically eliminates the need for surfactants, mini-emulsion polymerization which utilizes smaller droplets to yield nanoparticles of specific sizes, and micro-emulsion polymerization that leverages micro-emulsions to achieve a fine and uniform dispersion of solid particles, ultimately enhancing the efficiency and effectiveness of drug delivery systems based on polymeric nanoparticles [63, 64, 65, 66, 67, 68, 69, 70, 71].

Despite the broad diversity and innovative potential of these different methods, attaining reproducible control over nanoparticle size distribution, along with effectively scaling up production processes for industrial application, remains a formidable technical challenge for researchers and engineers alike. A considerable number of PNP formulations that are synthesized at laboratory scale fail to progress into clinical trials or gain market approval, and this is often due to physicochemical properties that do not meet the necessary biocompatibility requirements as established by regulatory authorities. In this respect, polyhydroxyalkanoate (PHA) nanoparticles emerge as optimal drug carriers, as they satisfy crucial regulatory criteria concerning biodegradability, stability, and non-toxicity while maintaining the ability to deliver therapeutic agents effectively. The bacterial synthesis of PHA nanoparticles via either *in vivo* or ex vivo strategies offers a truly green and environmentally benign approach to their effective fabrication, significantly reducing the environmental footprint associated with traditional synthetic methods. PNPs are extensively employed as highly specialized drug delivery vehicles that are engineered to concentrate therapeutic agents precisely at specific tissue sites, thereby significantly enhancing treatment efficacy and improving patient outcomes. Furthermore, they hold substantial promise for various diagnostic applications in both clinical and laboratory settings, providing a multitude of benefits that could transform the way we approach disease diagnosis and treatment strategies in the future, fostering an era of more personalized and efficient medical care [72, 73, 74, 75, 76, 77].

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Nanotechnology in Medicine

Nanotechnology holds considerable promise across an extensive range of applications within the medical sector, presenting an exciting frontier for scientific advancement. It involves the intricate design, meticulous synthesis, and careful manufacture of engineered devices that possess specific physiochemical and biological properties at the remarkably small nanoscale, typically defined as ranging from 1 to 100 nanometers. These innovative nanomaterials, which exist at such minute dimensions, profoundly influence the intricate biological and physiological processes of living cells at the molecular level. They accomplish this by reaching out to and directly interacting with crucial cellular components, including nucleic acids, proteins, and small molecules, thereby altering their natural behavior and functionality in significant ways. The field of nanotechnology has been further extended and expanded to generate an innovative and emerging discipline known as nanomedicine. This crucial branch of scientific study is focused specifically on the applications aimed at targeted cell killing or the development of sophisticated and effective repair strategies for damaged or diseased cells, thereby opening new paths for treatment and recovery. As research continues to flourish and thrive, numerous sub-branches of nanomedicine have since been developed to specifically address the diverse needs of different medical specialties. These include nanooncology, which is primarily focused on cancer treatment and therapeutics; nanoneurology, which addresses the challenges posed by neurological disorders; nanocardiology, aimed at addressing heart-related health issues; nanoorthopedics, which is concerned with maintaining and improving bone and joint health; and nanoophthalmology, which deeply explores innovative applications in eye care and vision. Although many of these cutting-edge technologies are still largely in the research and experimental phases, it is noteworthy and promising that several advanced targeting technologies have made significant progress and have already advanced to the stage of clinical trials, with some even having reached commercialization, showcasing their remarkable potential in the medical field. However, it is essential to note that forthcoming developments in this fast-evolving area will generally require a far more in-depth understanding of nanoparticle safety profiling, toxicology, and clearance mechanisms. Such comprehensive knowledge is paramount to ensure the safe and effective integration of nanomedicine into standard healthcare practices, which is crucial for patient safety and treatment efficacy [78, 79, 30, 80, 81, 82, 83, 84].

5.1 Drug Delivery Systems

Nanotechnology is an exciting and rapidly emerging field that intersects a wide variety of disciplines such as physics, chemistry, biotechnology, and material science. It has been innovatively applied in both medicine and the environment with the primary purpose of significantly improving current practices and methodologies that are in use today. The concept of controlled drug delivery has been actively pursued since the early 1950s, when pioneering scientists first began to consider the innovative idea of injecting a polymeric drug reservoir as a means for long-term delivery to patients who would benefit from such advancements. Since that foundational moment in research history, a great deal of considerable progress has been made in the exploration and utilization of various suitable biomaterials, which can serve not only as effective drugs themselves but also as carriers that enhance drug delivery mechanisms in various therapeutic contexts. Many intricate morphologies that involve the core principles of nanotechnology have been reported in scientific literature and successfully applied within the expansive and diverse field of drug delivery. Although liposomes and micellar systems have been widely used for the encapsulation of drugs, the investigation into controlled release mechanisms has primarily been directed toward the development of biodegradable polymeric microcapsules, which hold great promise for the future of pharmacology and patient treatment strategies. Moreover, nanoparticles have occasionally been engineered with the specific intention of decorating the surfaces of these innovative microcapsules, thereby potentially increasing the rate of delivery for the encapsulated drugs, leading to more effective therapeutic outcomes and improved patient outcomes overall. As research continues to advance in this dynamic and ever-evolving field, the possibilities for innovative applications in drug delivery are continually expanding, opening new avenues for exploration and implementation in medical science [30, 85, 86, 87, 88, 89, 90, 91].

An alternative strategy consists of initially producing stable therapeutic-load-carrying nanoparticles that can maintain their efficacy over time and through various conditions. These specially engineered nanoparticles may then be effectively incorporated within biodegradable microcapsules, which grants the novel delivery system the remarkable capability to be adapted according to the unique treatment regimen of each individual patient. Nevertheless, both liposomes and micellar systems suffer from a notoriously low level of stability when placed in aqueous media; consequently, unusual and extra care must be taken in handling them both *in vitro* and *in vivo* to ensure that their intended functionality is retained throughout their usage. The effect of biological fluids must also be meticulously factored in, especially considering that these fluids can quickly and significantly clear liposomes and microemulsions, such as micelles, from the systemic circulation of patients. Organically modified ceramic nanoparticles have been successfully explored and utilized for innovative bioimaging techniques that pave the way for advancements in diagnostics and treatment monitoring. Additionally, the field of nanotechnology is currently under active development in many exciting and promising directions, ranging from breakthrough gene therapy methods and their applications through effective anticancer drug delivery systems to advanced radiotherapy applications, novel diagnostic tools, and tissue engineering strategies aimed at repairing or regenerating damaged tissues. The continual evolution of these transformative technologies holds great promise for the future of medical treatments, patient care, and overall healthcare outcomes in a variety of clinical settings [92, 93, 94, 30, 95, 80].

5.2 Diagnostic Applications

Nanoscience has increasingly expanded the vast and dynamic realm of biosensing platforms through the comprehensive exploration of unique and remarkable features that are inherently present in various nanomaterials. These features are specifically aimed at significantly enhancing the diagnostic applications available today. Nanomaterials themselves demonstrate extraordinary electromagnetic, optical, and piezoelectric properties, characteristics that enable the sensitive and precise detection of an extensive spectrum of disease biomarkers, pathogens, and other critical analytes, which are essential for effective diagnosis. Their exceptional affinity for biomolecules plays a crucial role in facilitating the innovative design of a plethora of biosensing systems, which includes, but is not limited to, aptasensors, immunosensors, enzymatic sensors, sandwich assays, and many other advanced biosensing technologies that are currently being developed and refined. Exciting recent developments in this innovative field involve the introduction of groundbreaking components such as monomolecular nanomotors and nanocages. These novel components serve as pivotal elements of advanced biosensors, thereby significantly improving their functionality, efficiency, and sensitivity. Nanomaterial-based diagnostics not only offer advantages such as rapid response times and low operational costs but also provide ease of use, making them accessible to a broader range of healthcare applications. Furthermore, they exhibit the potential to greatly outperform traditional sensing technologies when it comes to accuracy, efficiency, and reliability. The continuously evolving field of nanotechnology further enriches the landscape by providing versatile solutions for advancing various diagnostic modalities. These advancements ensure faithful measurement and detection of critical pathological signs and symptoms that are vital for patients' health. *In vivo* diagnostic tools, particularly those utilizing nanoparticle contrast agents, play an instrumental role in enhancing techniques like magnetic resonance imaging and ultrasound, which lead to significantly improved imaging quality and superior diagnostic outcomes. Meanwhile, *in vitro* approaches harness sensitivity amplification methods alongside innovative analyte measurements through sensors that are meticulously constructed from nanotubes, nanowires, and atomic force microscopy techniques. These cutting-edge technologies collectively promise to significantly augment the capability to detect early manifestations of a wide array of diseases, thereby facilitating advancements in personalized healthcare as well as tailored medical interventions that are increasingly necessary in modern medicine [96, 97, 98, 99, 100, 101, 102, 103, 104].

5.3 Therapeutic Applications

Effective management of therapeutic agents is fundamentally dependent on sophisticated and intricate multistage delivery systems that have evolved to meet the increasing demands of contemporary medical treatments. These advanced systems are specifically designed to facilitate the controlled, precise, and timed release of active ingredients in direct response to the various physiological signals that are typically encountered within the human body. In addition to this vital function, these systems can also autonomously respond to a wide array of external stimuli, such as light, ultrasound, magnetic fields, or electric fields, thereby broadening their application spectrum and enhancing their utility across diverse therapeutic domains.

The detection of specific targets by medicinal agents usually involves complex and nuanced affinity interactions between native or specially engineered molecular receptors. These receptors can encompass a wide variety of proteins, peptides, or oligonucleotides that specifically bind to the antigens that are present on the surfaces of their target receptors, which may reside on various cell types or tissue structures. This selective binding is crucial for ensuring that therapeutic agents reach their intended destinations with high specificity and minimal off-target effects. Nanoparticles, owing to their extraordinarily small size coupled with a remarkably high surface-to-volume aspect ratio, present unique opportunities and advantages that can be harnessed to enhance the payload capacity and delivery efficiency of medicinal agents dramatically.

This significant enhancement in delivery capabilities can subsequently lead to noteworthy improvements in both diagnostic and therapeutic procedures, while also effectively reducing the overall toxicity associated with a wide variety of applications. The efficiency of nanoparticles in targeting tumors is primarily and predominantly attributed to the enhanced permeation and retention (EPR) effects that uniquely occur within the affected regions of the body. Furthermore, their diminutive size not only contributes to increased surface attachment but also extends systemic circulation time, which effectively minimizes off-target effects and substantially boosts overall therapeutic efficiency in clinical settings.

Because of the modular and customizable nature inherent in their design, nanoparticles with diverse compositions can be ingeniously transformed into highly functional multifunctional nanocomposites. These advanced nanocomposites possess the remarkable capability to integrate several therapeutic modalities into a single cohesive nanoassembly, thereby significantly enhancing their overall effectiveness in treating a variety of medical conditions and ailments. This innovative approach not only showcases the remarkable adaptability of nanotechnology in tackling diverse medical challenges, but also paves the way for exciting future breakthroughs in the management and treatment of complex diseases. This illustrates the immense potential that lies in the application of nanomedicine, as it opens new avenues for researchers and clinicians alike to explore more effective strategies for patient care and treatment outcomes [105, 106, 107, 108, 109, 110, 111, 112, 113, 106, 107, 114, 115, 116, 117, 112, 118].

5.4 Regenerative Medicine

Biosynthesis of NPs Using Microorganisms Living organisms, including various types of microorganisms such as bacteria, fungi, and yeast, are increasingly being harnessed as a natural and eco-friendly alternative to synthesise nanoparticles (NPs). This trend is emerging as a significant response to the limitations posed by traditional chemical and physical synthesis methods, which often demand high temperatures, elevated pressures, and complex setups. These conventional strategies not only consume substantial energy but also tend to produce toxic by-products or hazardous substances. Such by-products could pose significant risks to both human health and the environment, leading to potential ecological disruptions. Furthermore, the process of synthesising NPs in solutions can introduce numerous challenges and difficulties, as these nanoparticles have a natural tendency to aggregate or form clumps when mixed. This aggregation can lead to poor monodispersity, which inherently compromises the desirable surface properties needed for optimal performance of the nanoparticles. Consequently, it alters their catalytic behaviour, reactivity, and the efficacy of their subsequent biomedical applications. Given these substantial issues associated with conventional synthesis methods, the innovative use of biological cells and microorganisms for NP synthesis emerges as an ideal and promising route. This alternative approach is largely attributed to the unique enzymatic and metabolic properties that these biological entities possess, which enable them to effectively and safely reduce metal salts, acids, or chlorides into nanoparticles with greater efficiency and under milder conditions than traditional methods. Such biogenic processes not only enhance the quality of the nanoparticles generated but also significantly reduce the potential environmental impact, making them a pivotal player in the future of nanotechnology [119, 120, 121, 122, 123, 124].

Microorganisms such as bacteria, algae, fungi, and actinomycetes possess the remarkable ability to reduce metal salts through the activity of enzymes present in metal-rich cells, effectively acting as nature's own nanofactories. The accumulation of metal ions within these cells may serve as an intrinsic cellular defense mechanism, utilized by nature to detoxify hazardous heavy metal ions via various reduction processes. Among the nanoparticles (NPs), CuNPs, ZnONPs, SeNPs, and AgNPs are some of the notable examples synthesized using this innovative green method involving bacteria. The application of nanoparticles synthesized through these microelements has shown great promise in the field of regenerative medicine. The primary aim of tissue engineering is to promote the maturation of both embryonic and adult stem cells into specialized cells that correspond to mesodermal, ectodermal, and endodermal tissues, which have the potential to replace damaged or dysfunctional tissues and restore the overall functionality of organs. However, one significant limitation faced in these advanced procedures is the absence of a biocompatible scaffold that is capable of adequately supporting the differentiation of stem cells. The ideal scaffold should possess porosity, allowing for the seamless transfer of essential oxygen, nutrients, and metabolites throughout the structure.

Moreover, the scaffold is required to closely mimic the extracellular matrix of the specific tissue that is intended to be regenerated, thus fostering a conducive environment for directed stem cell differentiation. This unique intersection of nanotechnology with mesenchymal stem cell-based therapies and tissue engineering serves as a bridge to effectively surmount this existing challenge. The incorporation of nanoparticles into three-dimensional scaffolds can result in the attainment of tissue- and organ-specific mechanical properties, optimizing the overall performance and effectiveness of regenerative strategies [125, 126, 127, 128, 129, 130, 131].

Chapter - 6

Nanotechnology in Environmental Applications

Nanotechnology in Environmental Applications has emerged as a crucial field, offering innovative solutions that enhance sustainability and address significant environmental challenges effectively [132].

Nanotechnology presents a range of potential solutions to several of the most pressing environmental challenges that we are currently confronting in today's world. For instance, the control and prevention of pollution can be effectively achieved through the innovative application of nanoparticles, which possess the unique ability to capture or degrade harmful toxic substances and various pollutants that can be found in air, water, or soil. Furthermore, the process of water treatment can be notably improved with the incorporation of nanotechnology, leading to significant reductions in the cost associated with water decontamination and purification. This advanced technology not only enhances the efficiency of purification processes but also contributes to environmental sustainability [133, 134, 135].

Some of the notable and significant environmental applications of nanotechnology encompass a diverse array of innovative and cutting-edge methods that are revolutionizing the way we approach environmental challenges. One of the significant applications is the implementation of nanowires in hydrogen energy storage systems, which not only enhance the efficiency of energy management but also promise to make hydrogen a more viable source of clean energy for the future. Additionally, the bioremediation of sewage water utilizing iron nanoparticles presents an astonishing technique, as these nanoparticles actively detoxify and purify contaminated water, making it suitable for reuse and helping to protect groundwater resources. Furthermore, the mitigation of greenhouse gas emissions is being tackled through the use of advanced materials that have been meticulously designed specifically for this purpose, demonstrating the multifaceted potential of nanotechnology in addressing pressing environmental issues.

Nanotechnology-enabled sensors exhibit remarkable capabilities in monitoring air pollutant levels, which is crucial for both public health and environmental advocacy. These sensors promise to provide invaluable data that significantly improves our understanding of the various health impacts linked with air pollution, while simultaneously supporting regulatory efforts aimed at reducing harmful exposures and promoting overall public health more effectively. Moreover, as we continue to innovate, there are numerous nanotechnology applications specifically tailored for limiting the release of greenhouse gases. This includes the development of more efficient automotive fuel cells that can lead to cleaner transportation solutions, various sorbents that are designed for enhanced hydrogen storage, as well as improved energy-storage devices that showcase the potential to operate at higher efficiencies than traditional methods.

Collectively, all of these advancements in the field of nanotechnology can contribute substantially to reducing the overall demand for fossil fuels. Fossil fuels have been shown to play a direct and detrimental role in increasing greenhouse gas emission levels worldwide, making it imperative to seek alternative energy solutions. Through the strategic applications of nanotechnology in energy production, waste management, and air quality monitoring, we stand at the cusp of significant environmental improvement. In conclusion, nanotechnology truly stands to play a transformative and pivotal role in creating a more sustainable and environmentally friendly future, paving the way for innovations that could usher in a new era of ecological balance [35, 136, 137, 138, 139, 140, 141, 142, 143].

6.1 Water Purification

Nanotechnology research is currently experiencing a period of remarkable growth and expansion, offering an extensive array of incredible possibilities across various and diverse fields of technology. These fields include, but are not limited to, medicine, physics, engineering, chemistry, and even space exploration, along with many others that are continually being researched, explored, and developed to find innovative solutions. While the range of applications for both nanoproducts and nanodevices is incredibly vast and remarkably diverse, certain focused initiatives specifically aim to address, confront, and help resolve persistent, pressing global challenges that impact communities worldwide. These significant challenges include the critical and alarming lack of access to clean water resources, as well as the exorbitantly high costs associated with water treatment procedures that many countries struggle to afford.

As the global population steadily continues to grow and the pace of industrialization accelerates exponentially, the availability of clean, safe drinking water is rapidly diminishing, thereby putting immense pressure on natural resources at an alarming and unsustainable rate. The World Health Organization (WHO) has reported that approximately 3.4 million people around the globe tragically lose their lives each year as a consequence of waterborne diseases, which are easily preventable. These diseases include severe and life-threatening conditions such as cholera, typhoid, dysentery, and diarrhea, all of which result from the consumption of contaminated and unclean water sources. It is crucial to recognize and acknowledge that while these diseases are both treatable and curable, a significant number of affected individuals find themselves unable to afford the essential treatment and adequate medical care they desperately need to survive. Consequently, many people tragically die due to the harsh combination of insufficient income, lack of educational resources about health, and restricted access to medical facilities and resources that could otherwise prevent such devastating and unnecessary outcomes [144, 145, 146, 147, 148, 149].

Industrial wastes, along with the facilities that produce them, are significant contributors to the severe and widespread contamination of vital water resources. This substantial pollution inflicts large-scale damage on human beings, aquatic life, as well as a diverse range of various micro and macro-organisms that coexist within our complex ecosystems. Such harmful wastes indiscriminately pollute the water with highly toxic materials like lead, chromium, and mercury, greatly compromising water quality. The dangerous accumulation of these hazardous materials in the bodies of living organisms can lead to a myriad of serious disorders and health issues; tragically, in some cases, this contamination can even result in premature death. Furthermore, poor sanitation practices within many communities contribute to a critical lack of clean and safe water, which is essential for survival and well-being. In numerous developing countries, a significant portion of the population is deprived of access to safe and potable water sources. Frequently, individuals are forced to obtain water from ponds, riverbanks, and other natural surface water bodies that are often heavily contaminated, exposing them to further health risks. A portion of the water derived from these impure sources is utilized for cultivation and agricultural purposes; however, the remainder is needed for essential daily activities such as drinking, cooking, and sanitation, thus compounding the public health crisis. Consequently, accessing clean, safe water remains a major and persistent challenge for a considerable number of people across the globe, adversely impacting their health, well-being, and overall quality of life [150, 151, 152, 153, 154, 155, 156].

6.2 Air Quality Improvement

Nanotechnology holds immense potential and promise to play an incredibly crucial role in the ongoing exploration and discovery of highly effective strategies that are aimed at the substantial improvement of air quality across both urban and rural environments. Air pollution is now widely recognized as a pressing and urgent global issue, with airborne contaminants being identified as the single largest environmental risk factor that poses an overwhelming and significant threat to human health and overall well-being. The extent of air quality degradation, along with the numerous associated adverse health effects, depends in part on several critical factors, including the specific sources and magnitude of the pollutants being emitted into the atmosphere, as well as the duration of exposure to these harmful substances, which can vary significantly among various demographic populations. Nanomaterials exhibit a unique and significant potential to become the foundational basis for an impressively wide variety of high-performance air treatment media that are specifically designed to effectively tackle this serious and ever-growing issue of air pollution. The incredibly small size of nanomaterials introduces a remarkably high surface-area-to-volume ratio that is paired with special surface chemical activities, significantly enhancing their reactivity and overall effectiveness in treating contaminated air. As a direct result of these properties, nanomaterials possess an improved capacity to react with a wide range of harmful substances, effectively converting these dangerous pollutants into harmless products through various complex processes. These distinctive reactivities, when combined with the diverse spectrum of available nanomaterials, make their practical application in the removal and filtration of airborne contaminants not only a challenging task but also an ultimately rewarding objective for researchers and industry professionals alike. The continued study, exploration, and application of nanotechnology in this critical field hold great promise and potential for significantly advancing innovative methods to combat air pollution, improve community health and safety, and protect human well-being on a global scale. The future implications of these advancements could lead to a substantial positive transformation in the atmosphere we breathe and contribute to increased quality of life for all individuals [157, 133, 158, 159, 160, 142, 134, 161, 162].

6.3 Soil Remediation

Advanced oxidation-based technologies, which encompass a variety of sophisticated methods such as ozonation, photocatalytic degradation, and Fenton-like reactions, can be effectively and reliably employed to mineralize a wide range of pathogenic agents. Ozonation, which utilizes the powerful and reactive properties of ozone gas, is widely recognized as an especially effective sterilant that is capable of inactivating all types of microorganisms present within a matter of just a few moments or minutes. This rapid action—characterized by the swift effectiveness of ozonation—makes it an exceptionally efficient choice for various disinfection purposes. Photocatalytic degradation, on the other hand, involves the innovative use of a photocatalyst that actively generates reactive radicals, thereby playing a critical and intricate role in the inactivation of pathogens following exposure to specific light sources. The unique process capitalizes on the remarkable ability of light to effectively activate the photocatalyst, leading to a significant and substantial production of highly reactive species. Additionally, Fenton-like processes leverage the strong oxidizing capabilities inherent in hydrogen peroxide, combined with various transition metal ions, to produce hydroxyl radicals which are highly effective at oxidizing and subsequently inactivating a broad spectrum of different pathogens. These advanced methods provide versatile and powerful solutions for pathogen control across various settings, ensuring enhanced safety and sanitation in numerous environments where health is a crucial concern [163, 164, 165, 166, 167, 168, 169, 170, 171].

Due to their remarkably high surface-area-to-volume ratio and enhanced reactivity, an impressive and diverse range of innovative nanomaterials are exceptionally well suited for an array of various applications in the critical field of environmental remediation. Innovative methods such as degradation, adsorption, and detection have been thoroughly researched and explored for the effective removal of both organic and inorganic contaminants from contaminated soils and water bodies, ensuring cleaner environments. These nanomaterials can be meticulously functionalized with specific chemical groups that enhance their properties in order to induce a preferential affinity toward targeted pollutants, thereby significantly improving their efficiency and effectiveness in real-world scenarios. Furthermore, they can be readily adapted to meet particular remediation or monitoring objectives, making them incredibly versatile in diverse and dynamic environmental contexts. Their unique and advantageous physicochemical properties facilitate the ongoing development of advanced and efficient water remediation technologies that are not only selective in their action but also easy to recover and reusable, contributing significantly to more sustainable and responsible environmental management practices that benefit the ecosystem as a whole [172, 173, 174, 175, 176, 177, 178, 179, 180].

Chapter - 7

Safety and Toxicity of Nanomaterials

Since the onset of nanotechnology, various significant safety concerns related to engineered nanomaterials have been brought to the forefront of not only scientific but also public discussions, especially as these innovative materials have become increasingly integrated into a wide variety of everyday consumer products that we use regularly and often without much thought. Potential exposure routes to these nanomaterials include dermal contact, nasal inhalation, ocular exposure, respiratory inhalation, and oral pathways, signifying the multitude of ways that individuals may inadvertently come into contact with these substances. After entry into the body, the material is transferred through biological fluids to reach systemic circulation, where it has the potential to affect bodily functions before eventually being excreted; yet, despite this seemingly straightforward process, many nanoparticles tend to persist and accumulate in the body over time, particularly in organs that exhibit macrophagic activity and are responsible for clearing such substances from the system. The mitigation of risks associated with these nanomaterials is achieved either through the careful implementation of appropriate operational measures during the processing of these materials or via advanced engineering techniques that are specifically applied at the nanostructural scale. These efforts are indispensable to ensuring safety and compliance with health regulations, thus safeguarding public health while allowing nanotechnology to thrive in diverse applications across multiple industries [181, 182, 183, 8, 184, 185, 186, 114, 187].

Industrial hygiene factors must be thoroughly considered when handling these specific materials. The presence of nanoparticles that are dispersed in colloidal solutions tends to make them less hazardous than their powdered counterparts; however, the drying processes that follow, which yield fine powders, can generate respirable particles of critical sizes, thus posing substantial health risks to those exposed. The stability of these particles is a major concern, particularly in powder form, as agglomeration can significantly increase the effective aerodynamic size of the particles, ultimately altering their toxicity profiles in potentially dangerous ways. To mitigate these risks, complementary control measures must be implemented.

These include non-airborne processing techniques, ensuring effective ventilation within workspaces, isolating equipment to reduce exposure, utilizing personal protective equipment to safeguard workers, and maintaining rigorous hygiene regimens to minimize contamination and exposure [188, 189, 173, 190, 191].

For a wide range of environmental applications and initiatives, it is highly preferred to utilize modified particles that inherently possess a significantly lower ecological impact and reduced toxicity. While there are certain toxicity assessments available for specific compounds, particularly metal oxides and various polymers, the presence of nanoadditives in numerous consumer and industrial products complicates the safety evaluations significantly and raises important concerns. Thus, a comprehensive and broad strategy is absolutely required to effectively complement toxicity measurements and to define suitable and effective test methods that can be employed. This is crucial to properly manage and mitigate the various environmental and health concerns that continuously arise from the growing and widespread use of nanomaterials across different industries and applications, warranting increased attention and action from regulatory bodies and researchers alike [96, 192, 193, 173, 194, 195, 45].

7.1 Health Risks

Given their remarkably small size and exceptionally high reactivity, uncertainties continue to persist regarding the potential adverse human health effects stemming from exposure to nanoparticles. These extremely tiny particles, which can be found in a variety of products and environments, may induce toxicity through a number of various complex mechanisms. These mechanisms include inflammatory responses, oxidative stress, and genotoxic reactions, making the study of nanoparticles a critical area of research. The health effects that may arise from exposure to these particles are influenced significantly by several characteristic features of the materials in question. These features include size, surface area, aspect ratio, chemical composition, surface chemistry, crystallinity, and levels of contamination present in the materials.

Moreover, there exists strong correlations between the intrinsic properties of materials and the associated toxicological effects, as well as their bioapplicability or bioavailability in biological systems. What is particularly concerning is that nanomaterials have the unique ability to cross various biological barriers in the body. This property enables them to distribute themselves systemically and access sensitive tissues throughout the body with potential ease and efficiency. Because of their faster and more efficient access to the human body when compared to larger micro-sized particles, nanoparticles can easily reach the bloodstream through the lungs. This dynamic invokes a considerable risk that necessitates thorough and careful evaluation by researchers and health professionals alike to understand the long-term implications of nanoparticle exposure on human health. The ongoing research and surveillance in this field are critical to ensure safety and establish guidelines for the use of nanotechnology in various industries [96, 18, 196, 197, 198, 199, 200, 86, 201].

7.2 Environmental Impact

Environmental Impact

The environmental impact of nanotechnology is a complex and multifaceted subject that encompasses a wide range of potential effects that engineered nanomaterials (ENMs) may exert on the environment throughout the course of their entire life cycle. This life cycle encompasses all stages from initial resource extraction to final end-of-life disposal. The broad and comprehensive scope of impact not only includes the various hazards associated with the production and manufacture of ENMs but also takes into account their intended and unintended uses, as well as the various methods of disposal—addressing a variety of risks posed to both the delicate environment and human health.

A deep and thorough understanding of the potential pathways for exposure, which can occur through air, water, or soil contamination during the stages of production, use, or disposal, as well as the associated toxicity of various engineered nanomaterials, is crucial for achieving a comprehensive and effective assessment of their environmental impact. Despite the increasing and widespread use of nanomaterials across a multitude of sectors and industries, it is quite surprising that a global chemical inventory currently identifies only a handful of commercial nanomaterials that are actively in circulation.

Several phenomena associated with nanomaterials, including processes such as agglomeration, altered surface properties, and modified toxicity due to significant interactions with waterborne contaminants, can have a profound and significant influence on the behavior of ENMs within aquatic environments and ecosystems. The intricate and complex interactions within these diverse environments can lead to a host of unpredictable consequences that necessitate careful and thorough study as well as monitoring.

Moreover, nanotechnology plays an integral and vital role in the development of advanced techniques and innovative products that can notably benefit the environment. For instance, this includes the creation of ecomaterials that are sustainable, innovative renewable energy nanomaterials, and specialized nanomembranes that are specifically designed for water purification and treatment processes. Remarkably and alarmingly, even extraordinarily low concentrations of nanoparticles (less than 0.2 mg/L) have exhibited notable levels of biological toxicity, which underscores the critical importance of their responsible management and regulation in order to effectively mitigate potential risks.

In summary, a thorough and well-rounded understanding and assessment of the environmental impact of nanotechnology are of paramount importance to ensuring that the numerous benefits of engineered nanomaterials do not come at the cost of ecological integrity or human health. Such awareness and proactive measures are essential for a sustainable future [202, 203, 204, 183, 205, 206, 187].

Chapter - 8

Regulatory Framework for Nanotechnology

Regulatory issues associated with nanotechnology have elicited significant and widespread debate across numerous countries, both at the international and regional levels. This discourse often stems from a recognition of the profound implications nanotechnology holds for various sectors, including healthcare, electronics, and environmental management. In many instances, the uncertainty surrounding potential risks implies not only an absence of comprehensive regulatory regimes but also a lack of adequate frameworks to address the specific challenges posed by nanotechnology that could emerge in the future. Notwithstanding these challenges, various trade groups and oversight communities have proactively developed safety specifications and ethical codes of conduct. They have taken into account both existing regulatory requirements and the various uncertainties that are particularly specific to nanomaterials, which differ fundamentally from those of conventional materials. Ongoing attempts are under way to formulate a comprehensive and cohesive normative framework—which includes elaborate directives on terminology, specific safety specifications, and well-defined safety guidelines—aimed at providing robust global support for the advancement and responsible management of nanotechnologies. Such a framework is essential for instilling confidence amongst stakeholders, fostering innovation, and ensuring public safety while navigating the complexities of this rapidly evolving field [207, 208, 209, 210, 211, 212, 213, 214, 215].

8.1 Global Regulations

Considering the vast and diverse array of interdisciplinary subjects that are intricately woven into the fascinating and ever-evolving topic of nanotechnology, scientists and experts from an array of various fields are strongly urging the urgent development of a comprehensive and effective global cooperation scheme. This critical initiative aims to thoroughly reflect on and address the significant social, ethical, and economic repercussions that arise from the rapid advancement and widespread application of nanotechnologies across many sectors. According to the insights provided by Karim (2013), it is essential that governments and institutions take on the substantial responsibility of providing effective oversight regarding the development of technology overall while paying particular attention to nanotechnology in specific, defined contexts. Furthermore, the European Union's Agency for Health and Safety at Work has identified manufactured nanomaterials as one of the top emerging risks in the workplace environment, leading to the introduction of various restrictions and safety measures designed to safeguard the health and safety of workers. In contrast to this, the U.S. Environmental Protection Agency (EPA) currently does not possess a comprehensive regulatory framework for nanomaterials, with the exception of their limited and narrow regulation in the context of food additives, which raises concerns about public health and safety in broader applications [216, 217, 218, 219, 220, 221, 222, 223].

Although numerous pharmaceutical companies are intensely focused on the independent and autonomous development of superior nanomedicine technologies, it is crucial to understand and acknowledge that collaboration, transparency, and open innovation are indeed essential components required to fully realize the vast and promising opportunities that lie ahead for both science and the realm of human health. The complex and multifaceted task of predicting environmental risks associated with this innovative and rapidly evolving field necessitates the combined expertise of a broad range of disciplines working together in a synergistic manner. To facilitate this comprehensive and multifaceted analysis, a System of Systems (SoS) formulation serves as the foundational system upon which the evaluation and assessment processes are based. A carefully designed and methodologically sound comparative methodology has played a pivotal and instrumental role in informing the main segment of the Study and Prevention of Environmental Risks associated with Nanomedicine (SPeRiN) programme. This ambitious initiative aims to identify, analyze, and address those critical aspects of environmental risk that can be feasibly managed and tackled early in the various stages of the nanomedicine research and development (R&D) process. However, it is important to note and recognize that traditional molecular eligibility, which is guided by classical environmental guidelines, is quite limited in its overall scope, and remarkably few public data, which could prove beneficial, are currently available to assist in these essential assessments [224, 225, 226, 227, 228, 229, 30].

The substantial and extensive knowledge disparity, as well as the notable technology gap, that currently exists between pharmaceutical research and development (R&D) and environmental risk assessment, poses a multitude of additional challenges that can complicate the development and approval processes for innovative therapies. This knowledge gap quickly supersedes traditional methodologies and renders existing technologies and legislative frameworks outdated across the globe due to the remarkably high rates of innovation associated with advanced materials and nanomedicine. While existing guidance for conducting thorough environmental risk assessment might be adapted in an effort to more effectively address the complexities of nanomaterials (NMs), the requirements surrounding NM physicochemistry or their intended utilization remain merely general guidelines that may not adequately capture the nuances necessary for thorough evaluation. Besides these somewhat vague guidelines, the early integration and proactive implementation of regulatory science would significantly benefit from a modular approach to regulation. This approach would encompass not just individual components of the research, but also a deep consideration of the interconnectedness of the entire entity as a cohesive unit operating within an ecosystem. Furthermore, standard safety protocols and efficacy evaluations may gain tremendous advantages by actively fostering interdisciplinary collaboration among different fields of study. This collaboration, in alignment with embracing the innovative principles of Safe and Sustainable by Design (SSbD), would create an environment where safety measures can be effectively integrated into the design phase itself. Such a collaborative effort, alongside the proactive early adoption of the One Health framework, would create vital links between human health and environmental health, helping to promote a more holistic understanding of these critical interdependencies and establishing a framework that anticipates future challenges rather than merely reacting to them after the fact [230, 231, 232, 233, 234, 235, 236, 237].

As fundamental and essential building blocks of the future of innovative medicines that will be utilized across a wide array of diverse industries, nanomaterials (NMs) are expected to undergo significant production and experience widespread implementation within various fields of application and research. Nevertheless, the potential for the accumulation of these substances in living organisms raises pressing concerns regarding the increased likelihood of future secondary exposure to nanomaterials. The stress induced by nanomedicine, even when present at sub-lethal levels, is likely to elicit a range of both positive and negative ramifications throughout the different biological hierarchies. This includes the potential promotion of cancer development, as well as the alarming emergence of multi-drug and antibiotic resistance phenomena that threaten the efficacy of existing medical therapies. Additionally, there are crucial phenomena related to gene transfer that could be sustained through the complex mechanisms of horizontal gene transfer, which can have far-reaching implications on genetic diversity and microbial resistance. Current biomedical research strategies strongly advocate that nanomedicine should serve as a foundational starting point for the broad repositioning of industries that are heavily reliant on advancements in medicine. In this evolving context, bio-inspired and materials-driven design has emerged as a central guiding principle that seems to be fundamentally important for the future development of medicinal agents on a global scale. However, there is an urgent need for comprehensive regulations to be established that will adequately assess the far-reaching impact of nanomedicines on environmental health and the ecosystems they influence and interact with. These regulations are crucial to ensure a balanced and responsible approach to their production and use, meticulously taking into consideration both the advancements in medical fields and the potential risks posed to living organisms and vulnerable natural habitats. The integration of safety measures and environmental assessments into the progression of nanomedicine will be vital for fostering innovation while safeguarding public health and ecological integrity [238, 239, 7, 36, 8, 93, 240, 2].

8.2 Ethical Considerations

Nanomedicine simultaneously offers significant therapeutic promise while also raising a host of fundamental ethical issues that must be addressed collectively by clinicians, patients, researchers, and society as a whole. The existing bioethical principles—such as respect for autonomy, beneficence, nonmaleficence, and justice—continue to form a relevant and enduring framework for navigating these challenging ethical waters, despite the increased complexity introduced by the rapidly evolving and continually advancing field of nanoscale medicine. Key concerns in this area encompass a variety of crucial topics, including comprehensive risk assessment processes, the distinctions between somatic-cell versus germline-cell therapy, the contentious and often debated area of human enhancement, the ethical implications of embryonic stem cell research, and the safety and environmental impact of nanoparticles that are increasingly used in therapeutic applications. Because of its inherently multidisciplinary nature, the ethics related to diagnostic and therapeutic applications of nanomedicine require the integration of various scientific and theoretical domains so as to accurately predict the health, safety, and environmental effects of nanotechnology on a broader scale. The wide-ranging applications and potential uses of nanotechnology generate an array of pressing ethical questions and dilemmas, which include considerations about the affordability of advanced nanodrugs within public health systems, and the potential side effects of nanoparticles that may occur beyond their intended targeted sites, thereby posing significant challenges. Research on the biological and environmental behavior of different forms of nanomaterials remains limited and sparse, and findings that pertain to one specific material may not readily be generalized to others, which complicates the ethical landscape further. As such, ethical considerations about nanotechnology can vary significantly among different countries; for example, the principle of justice mandates equal access to essential healthcare services regardless of varying individual characteristics, be they socioeconomic, geographical, or related to other aspects. While nanotechnology is expected to evolve into a multibillion-dollar industry that addresses and serves major public health needs, it simultaneously risks creating a widening 'nano-gap,' whereby developed countries may reap disproportionate benefits, potentially leaving developing nations overly dependent on external research advancements and less capable of independently addressing pressing health and environmental problems that critically affect their populations. It is imperative that these ethical issues are discussed openly and addressed proactively to ensure equitable access and outcomes for all societies globally, fostering a collaborative approach that prioritizes the well-being of all individuals, irrespective of their background or circumstances [17, 241, 242, 243, 244, 245, 246, 247, 248].

Societal and ethical challenges that are inherently associated with the rapidly evolving fields of nanoscience and technology extend significantly and profoundly to a variety of pressing environmental issues. These include, but are not limited to, the potential toxicity and unpredictable behavior of nanoscale materials as they interact with biological systems and ecosystems. Furthermore, the existing regulatory frameworks that govern the use of these innovative materials are not only inadequate but also lag significantly behind the pace of technological advancement, raising serious concerns about the protection of public health and the environment. The inherently complex nature of nanoscale toxicities significantly complicates the processes of risk assessment and the development of effective communication strategies. This complexity has the potential to undermine public acceptance of nanotechnology, which is crucial for its advancement and integration into society. Moreover, the challenge of communicating these risks effectively could hinder necessary investments in nanotechnology, which could otherwise yield substantial benefits across various domains. Equity concerns further arise when addressing the fair and just distribution of both risks and benefits associated with these advanced materials. This encompasses a wide range of issues, including not only workplace safety challenges but also broader societal impacts that could disproportionately affect different communities. Therefore, the urgent development of effective and robust real-time technology assessment tools is essential. Such tools will help manage these multifaceted challenges in a responsible and sustainable manner. Engaging a wide array of stakeholders across multiple sectors can significantly enhance our understanding and ability to navigate the ethical implications that arise in the application of nanoscience and technology effectively. The collaborative efforts of scientists, policymakers, industry leaders, and community advocates will be crucial in ensuring that the benefits of nanotechnology are realized while minimizing potential risks to society and the environment [249, 250, 251, 25, 252, 253, 93, 254].

Chapter - 9

Future Trends in Nanotechnology

Nanomedicine is advancing at an impressively swift pace that effectively addresses grand and pressing health challenges such as infectious diseases, the complex intricacies of the ageing process, the increasingly prevalent problem of drug resistance, and the multifaceted and ongoing battle against various forms of cancer. At the same time, this innovative field is presenting significant and transformative opportunities to redefine and reshape sustainability within the vital realms of health care and modern medicine. However, the rapid development and widespread utilization of diverse nanomedicines also raises critical and pressing concerns regarding their potential environmental impact. Specifically, there is a growing apprehension about the long-term fate of these nanomedicines, particularly when they are administered in large volumes across diverse populations throughout the globe. This intriguing duality of promise and concern highlights the undeniable need for responsible and sustainable development practices at every stage of the nanomedicine lifecycle [230, 255, 224, 256, 257, 258, 259].

A vast array of nanoparticles is currently available on the market, finding applications in numerous fields including medicine, agriculture, food supplements, cosmetics, textiles, electronics, and construction materials. These innovative nanosized drug delivery systems encompass a wide range of sophisticated formats including liposomes, polymeric nanoparticles, and inorganic metal oxide nanoparticles. With the rapid improvement of our understanding of particle-cell interactions, coupled with the identification of specific biomarkers, and the ongoing development of cutting-edge screening tools, researchers are becoming increasingly well-equipped to swiftly and effectively assess the toxicity and biocompatibility of these advanced materials. Such remarkable advancements in the field will foster a safer and more responsible design process for nanoparticles; furthermore, direct diagnostics will play an essential and pivotal role in significantly enhancing safety assessments of these innovative materials. In toxicological studies, nanomaterials can be manufactured to ensure a consistent production process and can systematically vary in critical characteristics such as size, shape, surface chemistry, rigidity, roughness, porosity, and surface charge. This controlled variability is absolutely vital for achieving a deeper understanding of the nuanced role these specific factors play in the field of toxicology, ultimately leading to more comprehensive insights into their diverse effects on biological systems and health outcomes [18, 220, 7, 86, 260, 261, 262, 263, 264].

The direct diagnostics sector has experienced a remarkable and rapid expansion primarily due to the profound impacts of the COVID-19 pandemic and the significant advancements made in nanoparticle research over recent years. Nanomaterials hold immense promise, not only being effective as antimicrobial agents but also serving numerous environmental applications due to their unique and versatile chemical and physical properties. These exceptional properties are largely responsible for their multi-route toxicity towards diverse microbial communities, showcasing both their capability and their potential risk. Although data on the toxicity of nanomaterials remains sparse and limited, a plethora of studies have consistently reported a wide array of adverse effects that highlight potential concerns regarding their use and safety in various applications. This growing body of evidence underscores the necessity for further research to thoroughly understand the implications of nanomaterials in different contexts [265, 266, 120, 267, 268, 269, 270].

9.1 Innovations in Medicine

Nanomedicine stands as an exceptionally intriguing and swiftly developing domain within the broader field of science, making significant headway by employing a diverse range of cutting-edge nanomaterials that play a crucial role in the formulation of advanced drug delivery systems. These innovative systems have not only shown remarkable improvements in diagnostic capabilities but also enhanced therapeutic effectiveness, offering tremendous potential for shaping the future of medicine in profound ways. The strategic application of various metallic, polymeric, and organic nanomaterials in this significant context is essential for the creation of these sophisticated systems, while adeptly working to prevent the denaturation of the drug and safeguarding its pivotal biological activity from degradation. In fact, there exists a variety of nanomedicines that have already been successfully developed for diverse pharmaceutical applications. This includes but is not limited to nanoparticles, micelles, proteins, quantum dots, dendrimers, and liposomes, each of which brings unique advantages and specific functionalities to the evolving field of nanomedicine. This variety contributes to an exciting landscape where continued exploration and innovation promise to transform therapeutic strategies and elevate patient care to a new level of effectiveness and precision [79, 271, 272, 273, 274, 275, 40, 276, 277].

Regenerative medicine represents a truly fascinating and exceptionally innovative application of the ever-evolving field of nanomedicine, in which a variety of nanotechnological techniques are meticulously employed specifically for the remarkable purpose of tissue regeneration and effective repair. The expansive and dynamic field of tissue engineering, when seamlessly combined with the unique and versatile capabilities of advanced nanotechnology, aims to restore and remarkably enhance the functionality of severely damaged tissues through the sophisticated production of biological substitutes. These engineered substitutes are carefully designed to closely mimic the natural properties and characteristics of the tissues they are intended to replace. In this vital context, nanostructured platforms emerge as crucial elements, as they play a major and significant role in the intricate process of tissue engineering by serving not only as supportive matrices that promote the formation of tissues but also as sophisticated and efficient delivery vehicles for essential bioactive molecules. These molecules actively induce, stimulate, and facilitate the intricate process of tissue formation and regeneration, offering exciting possibilities for medical advancements in the future [278, 279, 280, 281, 282, 283, 284, 285].

9.2 Sustainable Environmental Solutions

Nanotechnologies hold the remarkable potential to effectively tackle a variety of pressing global environmental challenges through the development of innovative, sustainable, and comparatively less energy-intensive solutions. These groundbreaking technologies encompass a broad spectrum of applications that can significantly aid in the control of harmful emissions, the efficient remediation of pollutants in our ecosystems, and the enhancement of energy efficiency across numerous sectors. Consequently, this ultimately promotes the establishment of more sustainable environments across the globe. Additionally, advanced therapeutics and nanomedicines possess the capacity to substantially contribute to the creation of more sustainable pharmacological treatments. They achieve this by increasing oral bioavailability, which allows for more effective absorption of medications into the body, and by prolonging the half-life of active compounds. This leads to a reduction in required dosage, a decrease in the frequency of administrations, and a lowering of overall toxicity levels. These substantial improvements not only enhance patient outcomes significantly but may also play a crucial role in mitigating the overall environmental harm that is often linked to traditional small-molecule pharmaceuticals, which are prevalently utilized in medical practices around the world today.

Despite these promising advancements in nanotechnology, it is essential to highlight that the potential environmental impacts associated with the development and usage of nanomedicines necessitate further comprehensive research and a thorough adaptation of regulatory guidance to ensure safety and efficacy. A modular approach that takes into consideration various pivotal building blocks can be instrumental in facilitating precise regulatory assessments as the complexities of nanotechnology continue to expand and evolve. Safety assessments for these cutting-edge therapies benefit immensely from interdisciplinary cooperation and should fundamentally embrace the principles of Safe and Sustainable by Design (SSbD), as well as the One Health framework that interlinks human health with environmental well-being. Currently, risk-benefit assessments for human pharmaceuticals predominantly focus solely on the immediate effects for treated patients, which can lead to a somewhat narrow understanding of their broader implications; however, it is increasingly critical to consider the far-reaching environmental context in which these products exist and operate. A robust One Health approach, which effectively links human health with that of our environment, is incredibly valuable for addressing critical issues such as antibiotic resistance. It can significantly inform safety considerations not only for veterinary products but also for human medicinal products. This ensures a holistic view of health and safety in the face of emerging biotechnologies and their potential impacts on our world [18, 230, 93, 286, 33, 287, 35, 251, 25, 36].

Chapter - 10

Case Studies in Nanotechnology

Nanotechnology has seen incredibly dramatic growth over the last decade across a diverse range of scientific fields, profoundly impacting materials science, electronics, medicine, energy production, and environmental sustainability. Various innovative nanomaterials, including carbon nanotubes, fullerenes, silver nanoparticles, and nanocatalysts, have been synthesized and successfully applied to an impressive array of products ranging from protective coatings, advanced cosmetics, functional textiles, to state-of-the-art electronic displays. This remarkable expansion is largely driven by the unique and beneficial physicochemical properties exhibited by engineered nanomaterials, which include an exceptionally large specific surface-to-volume ratio, significantly enhanced mechanical properties, and fascinating quantum effects that stimulate continuous innovation and generate widespread societal benefits. In the realm of nanomedicine, for instance, remarkable advances are being made in ways that were once thought impossible when it comes to diagnosing and treating a myriad of diseases. Nano-scale contrast agents are ushering in a new age of profound advancements in the detection and visualization of not only cancer but also cardiovascular ailments and neurodegenerative disorders. Additionally, the use of nanoparticles for targeted drug delivery systems and in regenerative medicine is vastly increasing the scope and variety of available therapies, improving treatment tolerance significantly, and opening exciting new perspectives for addressing previously incurable diseases. Meanwhile, visionaries working in environmental nanotechnology are investigating and developing strategies that aim to reduce the environmental footprint left by previous generations. They are exploring means of achieving sustainability through methods such as green design, green chemistry, and environmentally friendly manufacturing processes, alongside innovative approaches focused on effectively remediating soil and water pollutants, thus enhancing our capacity to protect and preserve the natural world [18, 30, 81, 114, 288, 289, 93].

10.1 Clinical Applications

Unique and remarkable physicochemical properties of nanoscale materials pave the way for groundbreaking and innovative approaches to the diagnosis and therapy of a plethora of diseases. In this context, nanopharmaceuticals specifically refer to highly targeted pharmaceutical formulations that possess particle size dimensions that are less than 100 nanometers. These tiny particles are intricately designed to facilitate not just the active delivery of therapeutic agents, but also of imaging agents that are crucial for diagnosis. These diminutive yet powerful particles can exist permanently or circulate dynamically within biological systems, encompassing a diverse range of types, including lipid-based carriers, polymer-based carriers, metal-based carriers, and semiconductor quantum-dot-based carriers. Additionally, they also encompass therapeutic and diagnostic genes that can be effectively utilized in a multitude of treatment and imaging applications.

Furthermore, micro- and nanotechnologies play an increasingly critical role in effectively addressing the multifaceted challenges of clinical translation. These technologies are pivotal in developing advanced devices that focus on two primary objectives: the meticulous replacement and support of failing organ functions. This crucial goal is achieved through the introduction of innovative solutions such as tissue-engineered *in vitro* organ analogs, which are utilized for biological screening platforms and for various experimental applications, as well as artificial internal organ support systems that can function independently to assist patients. These significant advancements not only facilitate the development of more effective treatments but also enhance patient outcomes across various medical conditions. This showcases the immense and transformative potential of nanoscale materials in the rapidly evolving field of modern medicine [290, 291, 292, 293, 294, 295, 296].

The clinical applications of nanotechnology extend into crucial areas such as medical diagnostics and advanced drug delivery systems. A diverse range of nanoscale tools and techniques, along with various innovative carrier systems—comprising liposomes, micelles, dendrimers, polymers, and an array of metals, notably those such as gold and iron oxide—exhibit the potential to function as effective vehicles for the delivery of critical therapeutic and diagnostic agents. These remarkable carriers demonstrate the ability to transport both hydrophobic and hydrophilic drugs and therapeutic genes directly to specific sites necessitating treatment, whether those be areas marked by injury, the presence of disease, or tumor formations. Notably, such carriers can be meticulously engineered to provide an array of functionalities, including controlled release mechanisms, precise intracellular targeting, enhanced penetration into neuronal tissues, and prolonged systemic circulation in the body. Furthermore, the targeting of diagnostic agents allows for exceptionally sensitive monitoring of specific biological molecules at the molecular level. This innovative capability enables timely and early-stage diagnosis, the effective stratification of patients based on their specific conditions, the creation of personalized patient-specific therapies, and pioneering approaches to monitoring disease progression. Moreover, the validation of therapeutic targeting constructs benefits greatly from these advancements. Integration of combination products, which seamlessly incorporate both therapeutic and diagnostic components, opens up novel and innovative pathways for treatment and management of various diseases, enhancing overall healthcare strategies and patient outcomes [297, 30, 81, 298, 299, 300, 301, 302].

10.2 Environmental Projects

Recent advances in the rapidly evolving field of environmental nanotechnology have enabled the highly effective direct transformation of harmful contaminant molecules through the use of nanoscale zero-valent iron particles. This innovative method serves as a powerful means of environmental remediation. The exceptional large surface area to volume ratio of these nanoparticles facilitates rapid and continuous contaminant reduction, eliminating the need for any additional reagents. This process involves the stripping of electrons from incoming molecules, resulting in the formation of harmless salts that can easily be integrated into the environment without adverse effects.

Moreover, nanofiltration membranes have been developed, demonstrating selective permeability for particles that are smaller than 10 nm in size, which is approximately double the size of a typical water molecule. These advanced membranes are designed to effectively facilitate the separation and dissolution of various substances found in wastewater. The distinctive acid properties exhibited by nano-titania surfaces under dry conditions lead to behaviors that differ significantly from those of conventional bulk titania materials.

TiO2 nanomaterials, with their remarkable photo-catalytic properties, are increasingly being sought after for numerous applications, including the manufacture of self-cleaning windows and photo-catalyst agents. These advancements are paving the way for innovative solutions to common environmental challenges. Notably, despite criticism from certain researchers, carbon nanotubes are emerging as a significant player in the field of environmental engineering. Their unique geometry, combined with superior electrochemical and thermodynamic properties, makes them especially valuable for addressing a range of environmental issues and enhances their applicability in various engineering projects [303, 304, 305, 306, 307, 308, 309, 310].

Therefore, nanotechnologies have the potential to deliver innovative solutions to some of the most significant challenges that are confronting the field of environmental science today. These advances can be particularly helpful in crucial areas such as contaminant removal and the degradation or complete elimination of harmful substances, improving water quality, and addressing energy supply issues in a more efficient manner [18, 93, 160, 35].

Chapter - 11

Collaborative Research in Nanotechnology

The inherently multidisciplinary nature of nanotechnology necessitates a robust framework of collaboration among a variety of different stakeholders involved in the field. Through the organized and well-structured joint efforts that involve both well-established, highly reputable research institutions equipped with vast expertise and innovative small businesses dedicated to focusing on cutting-edge developments, the collective capabilities and expansive resources of the nanoparticle synthesis and characterization community throughout the United States are significantly expanded and enhanced. These fruitful collaborations not only support both exploratory research initiatives but also actively foster developmental initiatives that are aimed at advancing the field as a whole, effectively responding to very specific research requirements and addressing the technological challenges that individual researchers often find particularly difficult, if not impossible, to tackle on their own. By strategically leveraging various strengths and assets, these dynamic partnerships pave the way for exciting breakthroughs and groundbreaking discoveries in the ever-evolving field of nanotechnology, which holds immense potential for future applications and innovations [250, 93, 311, 25, 312, 313, 314].

The Collaborative Research in Nanotechnology (CRN) program, which is generously sponsored by the Department of Energy's Basic Energy Sciences, has a distinctly focused mission that specifically targets critical areas of nanoscience. These areas are challenging obstacles that are either prohibitively costly or remarkably complex for individual investigators or small research groups to effectively address on their own accord. By actively fostering, supporting, and promoting a wide array of cooperative activities that encompass numerous aspects of nanoparticle synthesis, assembly, and comprehensive characterization, this invaluable program not only broadens the extensive scope of research endeavors accessible to scientists but also plays a fundamental and crucial role as a preparatory phase for the substantial large-scale efforts that may potentially emerge within the expansive and continuously evolving field of nanotechnology. Through these collaborative and innovative initiatives, researchers have the unique opportunity to share essential resources, invaluable expertise, and groundbreaking ideas, which together can lead to significant advancements and notable breakthroughs that might otherwise remain unattainable in isolation. This synergy of collaboration stands as a testament to the power of collective effort in pushing the boundaries of human knowledge and scientific progress in the realm of nanotechnology [315, 93, 251, 224, 316, 317, 318].

11.1 Interdisciplinary Approaches

The integration of a plethora of diverse and innovative approaches that stem from various interrelated fields such as chemistry, biology, medicine, pharmacology, toxicology, engineering, materials science, physics, optics, and electronics constructs a remarkably effective platform for the ongoing and continuous development and advancement of highly innovative applications. This synergistic approach is especially significant in the expansive realm of medicine, where it not only enhances but also tailors its already extensive and widespread usage in critical areas like diagnostics, biosensors, and imaging, all specifically aimed at supporting therapeutic purposes. Nanotechnology stands out as a profound field that uniquely merges the distinctive behavior of materials at the nanoscale level with the invaluable ability to precisely manipulate a variety of critical characteristics. These characteristics include, but are not limited to, particle size, shape, and surface properties, which are all pivotal in determining how materials interact in various contexts. The ultimate and primary aim of this precise manipulation is to produce specialized and highly functional materials that garner significant interest for targeted and specific applications, dramatically broadening the horizons of what can be achieved in both cutting-edge research and practical implementations across various sectors [319, 320, 321, 322, 323, 324, 325, 326].

Through a thorough and detailed evaluation of the diverse range of products involved not only in their manufacture but also in their ultimate use, while additionally considering the potential reach and impact these products may have on the environment, *in vitro* toxicology evaluations have proven to be incredibly useful and beneficial for the initial screening of the toxicity of new materials that are being developed. However, it is crucial and imperative to note that the results obtained from these evaluations must be analyzed with an appropriate level of caution and care, as they need to be carefully correlated with relevant *in vivo* studies in order to gain a more comprehensive understanding of the possible risks that these materials may pose for living organisms and ecosystems alike. In the specific case of copper compounds, which have been widely and extensively utilized across a variety of applications due to their valuable electrical and optical properties, the exciting development of biosynthetic approaches and innovative combinations with other materials opens up new avenues leading to the creation of advanced copper nanomaterials. These newly developed nanomaterials can exhibit significantly enhanced properties that make them suitable for essential central applications in various fields. The following comprehensive review focuses on several critical aspects that are essential for understanding copper nanomaterials, including the synthesis methods, antimicrobial activity, antioxidant capacity, and catalytic properties of these innovative copper nanomaterials, as well as their intricate interactions with the surrounding environment. This review endeavors to provide a holistic overview of the emerging research surrounding copper nanomaterials and emphasizes the importance of ongoing studies in this field [327, 328, 329, 330, 331].

11.2 Industry and Academia Partnerships

The multidisciplinary character of nanotechnology is significantly and rapidly expanding the flow of information, diverse knowledge, and innovative applications, continuously exposing new and exciting opportunities that lead to substantial and notable benefits for both the environment and human health. A recent comprehensive survey has indicated that the market volume for nanotechnology-enabled pharmaceuticals is experiencing remarkable and swift expansion, and the incorporation of nanoparticles into pharmaceutical formulations, particularly in the critical and vital areas of anticancer, antibacterial, and antiviral treatments, stands as the most extensively explored and developed branch of the industry. The conclusions that have been drawn from the survey underscored an increasing and pronounced growth trend in patent filings across a variety of areas within nanotechnology, further pointing to the thriving and dynamic nature of this field. Despite these positive trends and advancements, researchers are still compelled to face several formidable challenges in the piloting and clinical applications of nanoparticles, which is notably attributed to their unique and complex physicochemical and biological properties, characteristics that can complicate their use as well as their effectiveness in practical scenarios and applications [332, 333, 334, 335, 136, 33, 336, 89].

Numerous comprehensive studies have convincingly demonstrated that the multidisciplinary character of nanotechnology is significantly uniting and fusing together the diverse and interdisciplinary fields of environmental science and health disciplines. The increasing number of scholarly publications that are intricately related to various partnerships between environmental science and health serves as a clear, concrete, and robust indicator of the considerable and substantial expansion of numerous applications within the extensive realm of nanoscience. This kind of detailed and meticulous surveillance enables the effective creation of innovative strategies and guides decision-makers in making informed decisions regarding first-level investments while also emphasizing the necessity of investments aimed specifically at generating beneficial spin-offs. The results that have been extensively analyzed reveal and indicate the remarkable motility and adaptability of this dynamic discipline and highlight the fluidity and interconnectedness of its partnerships with other diverse fields and spheres of expertise. On a global scale, the partnership involving "Pharmacology and Pharmacy/Veterinary/Medicine" stands out prominently as it dominates the publication statistics, accounting for a remarkable 55.2% of all articles published in the applied domain of nanoscience; this is primarily directed towards the control, management, and prevention of various diseases. This significant category is closely followed by the collaboration encompassing "Environmental Science/General and Environmental/Occupational Health," which constitutes about 18.1% of the total publications in this field. It is important to note, however, that there are currently no recorded instances of traffic or collaborative interaction between these vital areas of knowledge and expertise in Brazil, which underscores a significant and critical gap in interdisciplinary research endeavors within the country, limiting the potential advancements that could be achieved through collaborative efforts [337, 338, 339, 340, 341, 342].

Chapter - 12

Public Perception of Nanotechnology

Nanotechnology possesses an exceptional potential to induce a transformative paradigm shift that impacts various critical facets of social life in profound and far-reaching ways. This is particularly significant due to the fact that, despite not yet reaching its full level of exploitation and development, it is already ubiquitous through the widespread presence of numerous nanotechnology-enabled products that integrate seamlessly into our everyday lives. The remarkable capabilities of nanotechnology allow for the significant miniaturization of products while simultaneously introducing additional beneficial properties through precise molecular-level modifications to materials at the nanoscale. As a result of these innovations, this leads to the creation of novel product characteristics and performance prospects that can revolutionize various industries. Furthermore, it enhances consumer experiences in ways that were previously thought unimaginable, ushering in a new era of advancements that blur the lines between science fiction and reality. As society continues to adapt to these changes, the implications of nanotechnology will undoubtedly redefine our understanding of what is possible in both personal and professional spheres, opening new pathways for innovation and improvement that we are only beginning to comprehend [343, 33, 344, 345, 346, 347, 348, 349, 350].

A nation's prosperity ultimately relies significantly on the intricate and profoundly extensive nature of its scientific and technological progress and advancements. This dependence is not merely straightforward; rather, it is intricate and multifaceted in its very essence. It encompasses not only the tangible innovations—such as groundbreaking inventions, novel technologies, and sophisticated research methodologies—but also the intangible perceptions that profoundly shape and influence public attitudes toward science and technology. Moreover, this dependence is intricately tied to the comprehensive way in which the community perceives, values, and appreciates the myriad contributions and significance of science and technology in everyday life as well as in promoting long-term sustainable development and economic growth. Therefore, a considerable number of studies, surveys, and research initiatives have been diligently conducted with earnest intent to gain a deeper and more nuanced insight into the perceptions held by the general public toward these vital fields, seeking to gauge levels of public enthusiasm, alongside potential skepticism, concerns, and reservations that may arise. For instance, various innovative products such as clothing items that are embedded with state-of-the-art nano-enhancements, nanocoated utensils that promise significantly better performance, a wide assortment of advanced cosmetics, cutting-edge sunscreens with advanced formulations, and various high-tech types of sprays have already successfully made their way into the flourishing Malaysian market. These products serve to compellingly demonstrate the practical applications and myriad benefits that stem from these remarkable technological advancements. While it is essential to note that nano-products may not completely replace all conventional consumer goods and products that are regularly utilized in daily routines, they certainly play a crucial role in significantly enhancing and improving the existing products already available in the market. Additionally, they can even pave the way for entirely new products aimed at effectively satisfying the ever-evolving demands, preferences, and needs of the increasingly informed public. Such advancements highlight not only the remarkable breakthroughs and innovations occurring in technology but also indicate the continuously changing landscape of consumer preferences, which are increasingly leaning towards more sophisticated, contemporary, and high-tech alternatives that promise enhanced quality, better efficiency, and greater overall satisfaction in the consumption experience [351, 352, 353, 354, 355, 332, 356, 357, 358, 359].

12.1 Awareness and Education

Advancements in nanoparticle development greatly rely on a significantly more comprehensive and integrated approach that combines an extensive range of knowledge across a vast array of scientific fields. This array includes but is not limited to physics, chemistry, biology, engineering, and material science, as well as other relevant disciplines. In this intricately interconnected landscape, the education and training of scientists in the interdisciplinary aspects of these various domains play a crucial and pivotal role in adequately preparing them for the numerous challenges that lie ahead in their careers. The complexity and challenge of creating well-informed citizens who are capable of effectively navigating the intricate complexities of the modern scientific age become not only important but also significantly more difficult and daunting if the work and research in these fields are compartmentalized into isolated specialized groups that do not communicate or collaborate effectively. It is essential that fostering critical thinking in science necessitates employing a robust interdisciplinary approach. Such an approach highlights the fundamental importance of collaboration and knowledge-sharing, which should be paramount in the scientific community. Furthermore, its significance should be clearly reflected and emphasized in the educational system from the very beginning of education. Ideally, this vital integration of knowledge should start as early as early childhood education, thereby laying a strong and solid foundation for future learning, exploration, and innovation within these interdisciplinary fields. A well-designed educational activity focused on nanoparticles implemented at the secondary education level vividly demonstrates how an interdisciplinary approach can facilitate students in effectively grasping and comprehending a challenging topic within the expansive and ever-evolving field of nanotechnology. This innovative method not only enhances their overall understanding of complex scientific principles but also fosters a profound and lasting appreciation of the interdisciplinary connections that are essential in today's world. In a world where science evolves rapidly and impacts every aspect of our daily lives—from health and technology to environmental issues and sustainability—such interdisciplinary methods become even more crucial. Through these educational approaches, the next generation of scientists and informed citizens can effectively emerge, ready to tackle the pressing challenges of our time with a heightened sense of creativity, skill, and an understanding of the collaborative nature of modern science [360, 361, 362, 363, 364, 25, 365, 321].

It would be highly desirable for practical activities to be effectively and purposefully developed in a variety of contexts and settings, where the generation of well-formed, coherent, and insightful knowledge is actively encouraged, nurtured, and facilitated. This development should take into account not only the specific and precise concepts directly involved in the process of learning but also the greater integration of general ideas, broader implications, and overarching themes that intricately connect different and diverse areas of knowledge. The ongoing advancement and unceasing progress of society present a significant, multifaceted, and ever-evolving challenge for humanity as a whole; however, it also comes with a fundamental and profound sense of responsibility that we as educators and citizens must never overlook. It is essentially and fundamentally up to the educators, along with those who are actively involved in the teaching profession, to fully and deeply comprehend the diverse and varied needs of future citizens. They must effectively address these needs in a thoughtful, considerate, and appropriate manner by proposing innovative, engaging, and dynamic activities that are focused, when necessary, on various interdisciplinary aspects and multifaceted approaches to learning. These thoughtfully designed activities can significantly enhance learning and development in a holistic and comprehensive manner, fostering critical thinking, creativity, and problem-solving skills while preparing individuals for the complexities and challenges of an increasingly rapidly changing world [366, 367, 368, 369, 370, 371, 372, 373].

12.2 Media Representation

Materials science and the field of nanotechnology have received an immense amount of attention and focus due to their significant promise to greatly enhance the overall quality of our lives and improve various aspects of daily living. Like many other crucial and important scientific developments throughout history, the ongoing research concerning nanomaterials and their diverse applications has been accompanied by a broad spectrum of social, legal, ethical, and environmental debate and discussions. Emerging social, environmental, and crucial health, safety, and ethical (EHS&E) challenges, which pertain specifically to new nanomaterials and products, arise uniquely from their distinctive nature: their novel behaviors and properties, the limitations of inadequate physical data and exposure models, the existence of new anthropogenic sources, and the complex, rapidly proliferating diversity of new materials on the market, compounded by a quickly expanding public pressure regarding safety and efficacy. However, along with these challenges, there also exists substantial and major opportunities to adopt and use approaches similar to those already utilized with genetically modified organisms, recombinant DNA technologies, and human stem cells, before any additional products reach the consumer market. In order to proactively address the inherent challenges that arise in balancing societal benefits with potential risks, the path toward achieving sustainable nanotechnology must extend beyond mere detection, assessment, and quantification of impacts. It needs to encompass new and enhanced prevention-based approaches, recognizing that the pace of invention is perpetually ahead of our capacity to clean up or properly manage the associated risks [18, 33, 36, 93, 30, 81, 374, 288].

Chapter - 13

Challenges and Barriers to Nanotechnology Adoption

The adoption of nanotechnology applications encounters numerous challenges that stem from the intricate and often complex nature of the diverse materials involved, alongside the pressing requirement for effective cross-disciplinary coordination among various scientific and engineering fields. This complexity is primarily derived from both the microscopic scale inherent to nanomaterials and the diverse composition that characterizes these materials, which not only define their unique physical and chemical properties but also significantly influence the feasibility of their synthesis, precise characterization, and broader implementation in various practical applications. These multifaceted factors must be meticulously managed throughout the entire design-development-deployment cycle, which incorporates crucial considerations such as system stability, long-term safety profiles, and the potential implications for public and environmental health. In addition, the ethical impact of deploying such advanced technologies and the perceptions held by society as a whole must also be diligently taken into account throughout this process. Furthermore, regulatory authorities are increasingly likely to mandate comprehensive assessment methodologies that are able to accurately reflect the diverse impacts arising from different particle shapes, sizes, and chemical compositions. This ensures that all relevant variables are thoughtfully evaluated and taken into consideration, thereby promoting responsible and informed use of nanotechnology across multiple sectors, including medicine, electronics, energy, and environmental management [208, 249, 93, 375, 376, 377, 378, 114, 379].

13.1 Technical Challenges

Nanomedicine stands out prominently as one of the most impactful and influential applications that arise from nanotechnology, drawing substantial attention and interest from a wide and diverse array of participants. These include members of the scientific community, policymakers, entrepreneurs, and various sectors within the pharmaceutical industries. This expanding field is filled with immense potential and promise for the future, but it also encounters significant technical challenges that loom large along the entire chain of processes involved in the intricate and demanding tasks of drug development. This includes not just manufacturing considerations, but also the subsequent application and utilization of the final product. Given the vast array of materials involved and the extensive operational space and complexity required, it becomes virtually impossible to formulate a single, definitive design strategy that would appropriately suit all aspects of nanomedicine effectively. Instead, it becomes evident that alternative approaches must be thoughtfully considered. Multi-scale experiments, coupled with advanced molecular simulations and groundbreaking machine learning techniques, can indeed provide viable and innovative pathways for developing rational manufacturing processes and targeted application strategies. These evolving strategies are not only applicable to the field of nanomedicine but can also be extended to encompass a broader spectrum of other nano-applications, enriching the overall landscape of technology [30, 81, 380, 381, 382, 383, 80].

The COVID-19 pandemic has significantly and remarkably accelerated the rapid adoption and successful integration of cutting-edge nanotechnology-based vaccines into the ever-evolving, dynamic global healthcare landscape. Innovative nanomaterials and colloids, which encompass a vast variety of components such as lipids, cationic polymers, peptides, and an expansive range of both organic and inorganic nanoparticles, have been proposed as groundbreaking and transformative approaches. These approaches are specifically aimed at advanced vaccine development with the goal of effectively combating infectious diseases that pose considerable threats to public health. These remarkable and sophisticated technologies can be broadly classified into three distinct and crucial categories: namely, nanostructured adjuvants, which play an essential role in significantly enhancing the immune response; vaccine nano-carriers, which serve a vital function in the effective transportation and targeted delivery of vaccines to the appropriate sites within the body; and the increasingly relevant and critically important category of nano-vaccines. Nano-vaccines directly incorporate nanotechnology within the very formulation of the vaccine itself, thereby amplifying the overall efficacy and effectiveness of the vaccine. Among these significant categories, lipid nanoparticles (LNPs) have emerged as exceptionally efficient and versatile nano-delivery vehicles. These vehicles are instrumental in facilitating the administration and enhancing the effectiveness of mRNA vaccines, which have gained immense attention and importance. This remarkable efficiency of lipid nanoparticles is largely attributed to their high biocompatibility and their unique ability to permeabilize the plasma membrane. By doing so, they ensure robust uptake of the mRNA by the target cells, which is critical for initiating a potent and robust immune response against a range of pathogens that threaten human health [18, 384, 385, 386, 387, 388, 389, 390].

13.2 Societal Acceptance

Societal acceptance emerges as a critical challenge in the deployment of nanotechnological applications across various sectors and industries. According to expert judgement, the benefits of nanotechnology and its applications constitute the principal determinant of societal response, shaping how communities and individuals perceive these advancements. Additional significant factors encompass the perceived usefulness of these innovations, their necessity in everyday life, the extent of end-user proximity to the technology, and the perceived realism of the applications presented. Benefits are frequently cited prior to the consideration of risk perception; thus, public preference tends to favour the benefits of nanotechnology over the associated risks that may arise from its utilization. Among the various applications, medical applications—particularly those concerning targeted drug delivery—are accordingly appraised as the most societally acceptable by experts in the field. Environmental innovations, such as water filtration methods, soil-water remediation processes, fuel cells, and advanced chemical sensors, are also viewed as significantly beneficial and are likely to gain broad acceptance among the public. In fact, public perceptions of both medical and environmental innovations reveal a prevailing optimism regarding their successful implementation and integration into society. As an emerging construct within the discourse on technology and society, necessity plays a mediating role in societal response and serves to distinguish between applications deemed essential and those categorized as merely "nice to have" products. Water filtration, for example, is simultaneously considered both beneficial and necessary, especially in developing countries where access to clean water remains a pressing issue; similarly, targeted drug delivery is also regarded as requisite for effectively treating various illnesses that afflict many individuals. Conversely, applications found in sports goods or cosmetics, while appreciated for their innovative nature, do not attain similar essential status in the eyes of the public or experts alike [391, 392, 393, 298, 394, 395, 396, 397].

Conclusion

Nanotechnology represents a significant paradigm shift across all scientific and engineering disciplines, driving substantial innovation with immense potential to tackle a wide array of global challenges, particularly in the areas of energy, climate change, water scarcity, food security, agriculture, and health. In 2009, Linkov *et al.* pointed out that the exciting field of nanotechnologies provides new and diverse applications in materials science, electronics, medicine, energy, and the environment, leading to advancements that were previously unimaginable. Many nanomaterials, which include carbon nanotubes, fullerenes, silver nanoparticles, and nanocatalysts, are currently being produced and utilized in a variety of products such as coatings, textiles, cosmetics, and cutting-edge electronic displays. In the realm of medicine, the development of nanoparticle contrast agents allows for advanced imaging techniques that can precisely focus on specific tissues and diseases, enabling clinicians to make more informed decisions. Furthermore, nanocarriers show great promise in improving the targeted delivery of drugs and enhancing diagnostics, while the innovative combination of stem cell therapy with nanotechnology significantly facilitates advancements in regenerative tissue engineering. Environmental nanotechnology plays a crucial role in efforts to reduce pollution levels, effectively remediate pollutants in various ecosystems, and design new materials, chemistry methods, and manufacturing processes that minimize waste production and overall energy consumption. This multidisciplinary approach highlights the transformative power of nanotechnology in creating a sustainable future. Despite the fact that the current economic circumstances have indeed slowed down the pace of scientific progress and innovative developments, the field of nanotechnology continues to hold significant promise and potential for the future. Its ability to transform various industries and enhance technologies remains a beacon of hope for advancing solutions in various fields.

References

1. F. Findik, "Nanomaterials and their applications," Period Eng Nat Sci, 2021. academia.edu
2. B. Mekuye and B. Abera, "Nanomaterials: An overview of synthesis, classification, characterization, and applications," Nano select, 2023. wiley.com
3. J. K. Patel, A. Patel, and D. Bhatia, "Introduction to nanomaterials and nanotechnology," in *Emerging technologies for nanoparticle …*, 2021, Springer. [HTML]
4. S. Khan and M. K. Hossain, "Classification and properties of nanoparticles," Nanoparticle-based polymer composites, 2022. [HTML]
5. J. Njuguna, F. Ansari, S. Sachse, and V. M. Rodriguez, "Nanomaterials, nanofillers, and nanocomposites: types and properties," in *Safety of Nanomaterials*, 2021, Elsevier. [HTML]
6. K. Paras, P. Yadav, D. R. Kumar, S. Teja, and S. Chakraborty, "A review on low-dimensional nanomaterials: nanofabrication, characterization and applications," *Nanomaterials*, vol. 2022. mdpi.com
7. Y. Khan, H. Sadia, S. Z. Ali Shah, M. N. Khan, A. A. Shah, "Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review," Catalysts, 2022. mdpi.com
8. A. Barhoum, M. L. García-Betancourt, J. Jeevanandam, *et al.*, "Review on natural, incidental, bioinspired, and engineered nanomaterials: history, definitions, classifications, synthesis, properties, market, toxicities, risks …," Nanomaterials, vol. 12, no. 1, 2022. mdpi.com
9. N. Baig, I. Kammakakam, and W. Falath, "Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges," Materials advances, 2021. rsc.org
10. R. Pisano and A. Durlo, "Nanosciences and Nanotechnologies: A Scientific-Historical Introductory," in *Nanoscience & Nanotechnologies: Critical …*, 2025. [HTML]
11. T. Kumar, R. K. Pandey, R. Kumar, and C. V. Sudheep, "Historical

perspective of nanotechnology and functionalized nanomaterials," in *nanomaterials based*, 2023, Springer. [HTML]

12. S. Srivastava and A. Bhargava, "Green nanotechnology: an overview," in *Green nanoparticles: the future of …*, 2021, Springer. [HTML]
13. R. Pisano and A. Durlo, "Historical Foundations of Nanotechnology: Emergences, Inventions and Discoveries," in *Nanotechnologies: Critical Problems, Science in …*, 2025, Springer. [HTML]
14. R. Pisano and A. Durlo, "Nanosciences and Nanotechnologies: A Scientific-Historical Introductory Review," in *Nanotechnologies: Critical Problems, Science in …*, 2025, Springer. [HTML]
15. J. Pandiarajan, "Characterization, and Applications," in *Nanotechnology Applications in Health and …*, 2021. [HTML]
16. R. Pisano and A. Durlo, "Feynman's frameworks on nanotechnology in historiographical debate," Handbook for the Historiography of Science, 2023. [HTML]
17. M. Ebbesen and T. G. Jensen, "Nanomedicine: Techniques, Potentials, and Ethical Implications," 2006. ncbi.nlm.nih.gov
18. I. Linkov, J. Steevens, G. Adlakha-Hutcheon, E. Bennett *et al.*, "Emerging methods and tools for environmental risk assessment, decision-making, and policy for nanomaterials: summary of NATO Advanced Research Workshop," 2009. ncbi.nlm.nih.gov
19. C. Binns, "Introduction to nanoscience and nanotechnology," 2021. [HTML]
20. P. Thakur and A. Thakur, "Introduction to nanotechnology," Synthesis and applications of nanoparticles, 2022. springer.com
21. K. C. Khulbe and T. Matsuura, "Nanotechnology in membrane processes," 2021. [HTML]
22. R. Sharma, K. S. Sharma, and D. Kumar, "Introduction to nanotechnology," in *Nanomaterials in Clinical …*, Wiley Online Library, 2022. researchgate.net
23. A. Tripathy, A. Y. Patne, S. Mohapatra, "Convergence of nanotechnology and machine learning: the state of the art, challenges, and perspectives," *International Journal of...*, 2024. mdpi.com
24. D. Suhag, P. Thakur, and A. Thakur, "Introduction to nanotechnology," in *Integrated nanomaterials and their …*, 2023, Springer. [HTML]

25. B. Tawiah, E. A. Ofori, and S. C. George, "Nanotechnology in societal development," Nanotechnology in societal development, 2024. [HTML]
26. V. Harish, D. Tewari, M. Gaur, A. Bihari Yadav *et al*., "Review on Nanoparticles and Nanostructured Materials: Bioimaging, Biosensing, Drug Delivery, Tissue Engineering, Antimicrobial, and Agro-Food Applications," 2022. ncbi.nlm.nih.gov
27. D. Sannino, "Types and classification of nanomaterials," Nanotechnology: trends and future applications, 2021. academia.edu
28. P. Thakur and A. Thakur, "Nanomaterials, their types and properties," Synthesis and applications of nanoparticles, 2022. [HTML]
29. S. Kumar, S. Yadav, N. Kataria, A. K. Chauhan, "Recent advancement in nanotechnology for the treatment of pharmaceutical wastewater: sources, toxicity, and remediation technology," Current Pollution, vol. 2023, Springer. [HTML]
30. S. Malik, K. Muhammad, and Y. Waheed, "Emerging applications of nanotechnology in healthcare and medicine," Molecules, 2023. mdpi.com
31. M. K. Rokunuzzaman, "The Nanotech Revolution: Advancements in Materials and Medical Science," in *Advancements in Material Engineering*, 2024. researchgate.net
32. A. Kumar, "FROM NANO TO NATURE: INTEGRATING NANOTECHNOLOGY IN SUSTAINABLE DEVELOPMENT STRATEGIES," in *Nanotechnology for Sustainable Development*, 2025. [HTML]
33. B. Elzein, "Nano Revolution:“Tiny tech, big impact: How nanotechnology is driving SDGs progress," Heliyon, 2024. cell.com
34. M. A. Abdel-Fatah and E. F. Ewies, "Green Nanotechnology for Sustainable Ecosystems: Innovations in Pollution Remediation and Resource Recovery," Egyptian Journal of Chemistry, 2025. ekb.eg
35. F. J. Tovar-Lopez, "Recent progress in micro-and nanotechnology-enabled sensors for biomedical and environmental challenges," Sensors, 2023. mdpi.com
36. S. Malik, K. Muhammad, and Y. Waheed, "Nanotechnology: a revolution in modern industry," Molecules, 2023. mdpi.com
37. J. Patel, G. S. Kumar, H. Roy, B. Maddiboyina, and S. Leporatti, "From nature to nanomedicine: bioengineered metallic nanoparticles bridge the

gap for medical applications," Discover Nano, vol. 2024, Springer. springer.com

38. L. Devi, P. Kushwaha, T. M. Ansari, A. Kumar, "Recent trends in biologically synthesized metal nanoparticles and their biomedical applications: a review," Biological Trace Element Research, vol. 2024, Springer. [HTML]
39. D. Nayak, H. Chopra, I. Chakrabartty, "Opportunities and challenges for bioengineered metallic nanoparticles as future nanomedicine," *Journal for Wound Healing and …*, 2023. [HTML]
40. J. John, "Cutting-Edge Nanoparticle Innovations in Biomedical Science: Synthesis, Applications, Challenges, and Future Prospects," 2025. scientificarchives.com
41. A. Pandey, B. K. Singh, E. Gayathiri, *et al.*, "Nanoparticles in biomedical and clinical research: a current perspective and future implications," in *for biomedical and …*, 2024, Springer. [HTML]
42. M. Mabrouk, D. B. Das, Z. A. Salem, and H. H. Beherei, "Nanomaterials for biomedical applications: production, characterisations, recent trends and difficulties," Molecules, 2021. mdpi.com
43. M. Harun-Ur-Rashid, I. Jahan, T. Foyez, and A. B. Imran, "Bio-inspired nanomaterials for micro/nanodevices: a new era in biomedical applications," Micromachines, 2023. mdpi.com
44. G. A. Croitoru and D. C. Pirvulescu, "Metallic nanomaterials-targeted drug delivery approaches for improved bioavailability, reduced side toxicity, and enhanced patient outcomes," *Journal of Morphology and …*, 2024. nih.gov
45. A. I. Osman, Y. Zhang, M. Farghali, A. K. Rashwan, and others, "Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review," *Environmental Science and Pollution Research*, vol. 2024, Springer. springer.com
46. N. Saito, H. Haniu, K. Aoki, N. Nishimura *et al.*, "Future Prospects for Clinical Applications of Nanocarbons Focusing on Carbon Nanotubes," 2022. ncbi.nlm.nih.gov
47. A. Adhikari and J. Sengupta, "Toxicity of Carbon Nanomaterials," 2021. [PDF]

48. S. Wu, H. Li, D. N. Futaba, G. Chen, and C. Chen, "Structural design and fabrication of multifunctional nanocarbon materials for extreme environmental applications," *Advanced Materials*, vol. 2022, Wiley Online Library. [HTML]

49. N. Saito, H. Haniu, K. Aoki, N. Nishimura, "Future prospects for clinical applications of nanocarbons focusing on carbon nanotubes," *Advanced Materials*, vol. 2022, Wiley Online Library. wiley.com

50. P. K. Jiwanti, B. Y. Wardhana, L. G. Sutanto, D. M. M. Dewi, "Recent development of nano-carbon material in pharmaceutical application: a review," Molecules, 2022. mdpi.com

51. M. Ghasemlou, N. Pn, K. Alexander, "Fluorescent nanocarbons: from synthesis and structure to cancer imaging and therapy," Advanced…, 2024. wiley.com

52. D. Kurniawan, Z. Xia, L. Dai, K. K. Ostrikov, "Zero-dimensional nano-carbons: Synthesis, properties, and applications," *Applied Physics*, vol. 2024. [HTML]

53. P. P. Ray, "A Review on IoT Energy Storage with Nanocarbon Materials: Requirements, State-of-the-Art, Challenges, and Future Scope," in *NanoCarbon: A Wonder Material for Energy …*, 2024, Springer. [HTML]

54. P. Agrawal, S. Ebrahim, and D. Ponnamma, "Advancements in nanocarbon-based catalysts for enhanced fuel cell performance: a comprehensive review," *International Journal of Energy and …*, 2024. springer.com

55. G. S. Das, V. K. Tripathi, J. Dwivedi, L. K. Jangir *et al.*, "Nanocarbon-based sensors for the structural health monitoring of smart biocomposites," Nanoscale, 2024. [HTML]

56. H. Rustamaji, T. Prakoso, H. Devianto, P. Widiatmoko, "Recent status of application of nanocarbon composite materials for electric energy storage and conversion: A mini review," Future Batteries, 2025. sciencedirect.com

57. I. Kokalari, S. Keshavan, M. Rahman, E. Gazzano, *et al.*, "Efficacy, biocompatibility and degradability of carbon nanoparticles for photothermal therapy of lung cancer," Taylor & Francis, 2021. tandfonline.com

58. K. Prasad, A. Rifai, N. Recek, D. Schuessler, "Nanocarbon-Polymer

Composites for Next-Generation Breast Implant Materials," *Applied Materials & Interfaces*, vol. 2024, ACS Publications. [HTML]

59. A. Zieliński and B. Majkowska-Marzec, "Whether carbon nanotubes are capable, promising, and safe for their application in nervous system regeneration. Some critical remarks and research …," Coatings, 2022. mdpi.com
60. W. Fan, X. Fu, Z. Li, J. Ou *et al.*, "Porous ultrahigh molecular weight polyethylene/functionalized activated nanocarbon composites with improved biocompatibility," Materials, 2021. mdpi.com
61. C. H. Kim, S. Y. Lee, K. Y. Rhee, and S. J. Park, "Carbon-based composites in biomedical applications: a comprehensive review of properties, applications, and future directions," *Advanced Composites and Hybrid Materials*, vol. 2024, Springer. springer.com
62. S. J. Malode, S. Pandiaraj, A. Alodhayb, and others, "Carbon nanomaterials for biomedical applications: progress and outlook," ACS Appl. Bio., vol. 2024, ACS Publications. [HTML]
63. G. Singh, A. Faruk, and P. Mohinder Singh Bedi, "Technology Overview and Current Biomedical Application of Polymeric Nanoparticles," 2018. [PDF]
64. T. Pulingam, P. Foroozandeh, J. A. Chuah, and K. Sudesh, "Exploring Various Techniques for the Chemical and Biological Synthesis of Polymeric Nanoparticles," 2022. ncbi.nlm.nih.gov
65. V. A. Spirescu, C. Chircov, A. M. Grumezescu, "Polymeric nanoparticles for antimicrobial therapies: An up-to-date overview," *Polymers*, vol. 13, no. 12, 2021. mdpi.com
66. A. Annu, S. Sartaj, Z. Qamar, S. Md, "An insight to brain targeting utilizing polymeric nanoparticles: effective treatment modalities for neurological disorders and brain tumor," in *Bioengineering and …*, Frontiers in, 2022. frontiersin.org
67. L. La Barbera, E. Mauri, M. D'Amelio, "Functionalization strategies of polymeric nanoparticles for drug delivery in Alzheimer's disease: Current trends and future perspectives," Frontiers in Neuroscience, vol. 16, 2022. frontiersin.org
68. M. A. Beach, U. Nayanathara, Y. Gao, C. Zhang, *et al.*, "Polymeric nanoparticles for drug delivery," *Chemical*, vol. 2024, ACS Publications. nih.gov

69. A. Sartaj, Z. Qamar, F. F. Qizilbash, Annu, and S. Md, "Polymeric nanoparticles: Exploring the current drug development and therapeutic insight of breast cancer treatment and recommendations," *Polymers*, vol. 13, no. 4, 2021. mdpi.com
70. C. Adhikari, "Polymer nanoparticles-preparations, applications and future insights: A concise review," Polymer-plastics technology and materials, 2021. [HTML]
71. L. E. Charelli and G. C. de Mattos, "Polymeric nanoparticles as therapeutic agents against coronavirus disease," *Journal of Nanoparticle Research*, vol. 2022, Springer. springer.com
72. U. Manzoor, S. Masood, S. Nazir, L. Younis, "Limitations and Concerns of Nanotechnology in Obtaining the Desirable Products," in *Based Microbicides and …*, Springer, 2025. [HTML]
73. S. Sharifi, N. Reuel, N. Kallmyer, E. Sun, M. P. Landry, "The issue of reliability and repeatability of analytical measurement in industrial and academic nanomedicine," ACS Publications, 2022. nih.gov
74. C. de Souza Cardoso Delfino *et al.*, "Scaling nanopharmaceutical production for personalized medicine: challenges and strategies," Journal of Nanoparticle Research, vol. 2025, Springer. [HTML]
75. M. Yu, A. Mathew, D. Liu, Y. Chen, J. Wu, Y. Zhang, "Microfluidics for formulation and scale-up production of nanoparticles for biopharma industry," Drug Delivery, 2024. [HTML]
76. J. Wang, W. Zhao, Z. Zhang, X. Liu, T. Xie, "A journey of challenges and victories: a bibliometric worldview of nanomedicine since the 21st century," Advanced..., vol. XX, no. YY, pp. ZZ-ZZ, 2024. researchgate.net
77. Z. Yi, X. Ma, Q. Tong, L. Ma, Y. Tan, D. Liu, *et al.*, "A Library of Polyphenol‐ Amino Acid Condensates for High‐ Throughput Continuous Flow Production of Nanomedicines with Ultra‐ High Drug Loading," *Advanced Materials*, vol. 2025, Wiley Online Library. wiley.com
78. K. K. Y. Wong and X. L. Liu, "Nanomedicine: a primer for surgeons," 2012. ncbi.nlm.nih.gov
79. F. Rehan, M. Zhang, J. Fang, and K. Greish, "Therapeutic Applications of Nanomedicine: Recent Developments and Future Perspectives," 2024. ncbi.nlm.nih.gov

80. C. Domingues, A. Santos, C. Alvarez-Lorenzo, *et al*., "Where is nano today and where is it headed? A review of nanomedicine and the dilemma of nanotoxicology," ACS Publications, 2022. [HTML]

81. A. Haleem, M. Javaid, R. P. Singh, S. Rab *et al*., "Applications of nanotechnology in medical field: a brief review," Global Health Journal, 2023. sciencedirect.com

82. S. Louvel, "How nanomedicine escapes single definitions and why it matters for the knowledge politics of interdisciplinary research," researchgate.net,. researchgate.net

83. N. Gu, "Nanomedicine," 2023. [HTML]

84. V. Weissig, T. Elbayoumi, B. Flühmann, and others, "The growing field of nanomedicine and its relevance to pharmacy curricula," *American Journal of …*, vol. XX, no. YY, pp. ZZ-ZZ, 2021. nih.gov

85. N. A. Saeed and I. H. Hamzah, "The applications of nano-medicine in the breast cancer therapy," *Journal of Physics*, vol. 2021, 2021. iop.org

86. T. M. Joseph, D. K. Mahapatra, A. Esmaeili, Ł. Piszczyk, *et al*., "Nanoparticles: taking a unique position in medicine," *Nanomaterials*, 2023. mdpi.com

87. N. Zulfiqar, R. Nadeem, and O. A. I. Musaimi, "… degradation of antibiotics via exploitation of a magnetic nanocomposite: a green nanotechnology approach toward drug-contaminated wastewater reclamation," ACS omega, 2024. acs.org

88. J. Han, Q. Ma, Y. An, F. Wu, Y. Zhao, and G. Wu, "The current status of stimuli-responsive nanotechnologies on orthopedic titanium implant surfaces," *Journal of …*, 2023. springer.com

89. S. Hussain, R. Yasmin, A. N. Chouhdary, M. Irfan, F. Munir, "... the Convergence of Nuclear Physics, Particle Dynamics, and Nanotechnology to Transform Energy, Revolutionize Medicine, and Advance Environmental …," gsarpublishers.com. gsarpublishers.com

90. X. Kong, P. Gao, J. Wang, Y. Fang, and K. C. Hwang, "Advances of medical nanorobots for future cancer treatments," *Journal of Hematology & …*, 2023. springer.com

91. C. Bhattacharya and N. Rayjada, "Benefits, Risks, and Responsible Use of Nanomaterials in Remediation," in Environmental, 2025. [HTML]

92. Y. Dong, X. Wu, X. Chen, P. Zhou, and F. Xu, "Nanotechnology shaping stem cell therapy: Recent advances, application, challenges, and future outlook," Biomedicine & Pharmacotherapy, vol. 136, 2021. sciencedirect.com

93. L. Pokrajac, A. Abbas, W. Chrzanowski, and G. M. Dias, "Nanotechnology for a sustainable future: Addressing global challenges with the international network4sustainable nanotechnology," ACS Publications, 2021. acs.org

94. R. A. Khan, H. A. Mohammed, and G. M. Sulaiman, "Ionic liquids-gateway to newer nanotechnology applications: advanced nanobiotechnical uses, current status, emerging trends," *International Journal of …*, 2022. mdpi.com

95. P. R. Kumbhar, P. Kumar, A. Lasure, R. Velayutham, "... landscape on nanotechnology-based drug delivery, immunotherapy, vaccinations, imaging, and biomarker detections for cancers: Recent trends and future directions...," Discover Nano, vol. 2023, Springer. springer.com

96. I. Linkov, J. Steevens, G. Adlakha-Hutcheon, E. Bennett *et al.*, "Emerging methods and tools for environmental risk assessment, decision-making, and policy for nanomaterials: summary of NATO Advanced Research Workshop," 2013. [PDF]

97. A. Cafarelli, A. Marino, L. Vannozzi, J. Puigmartí-Luis, and others, "Piezoelectric nanomaterials activated by ultrasound: the pathway from discovery to future clinical adoption," ACS Publications, 2021. acs.org

98. A. Sood, M. Desseigne, A. Dev, L. Maurizi, A. Kumar, "A comprehensive review on barium titanate nanoparticles as a persuasive piezoelectric material for biomedical applications: prospects and challenges," Small, vol. 2023, Wiley Online Library. hal.science

99. P. Tripathi and A. K. Dubey, "Role of piezoelectricity in disease diagnosis and treatment: a review," ACS Biomaterials Science & Engineering, 2024. [HTML]

100. N. Thanjavur, L. Bugude, and Y. J. Kim, "Integration of functional materials in photonic and optoelectronic technologies for advanced medical diagnostics," Biosensors, 2025. mdpi.com

101. Y. Wang, P. Zang, D. Yang, R. Zhang *et al.*, "The fundamentals and applications of piezoelectric materials for tumor therapy: recent advances and outlook," Materials Horizons, 2023. [HTML]

102. J. Ji, C. Yang, Y. Shan, M. Sun, X. Cui, and L. Xu, "Research trends of

piezoelectric nanomaterials in biomedical engineering," *Advanced Materials*, vol. 2023, Wiley Online Library. wiley.com

103. F. Wang, J. Y. Huang, H. Zhang, and Q. D. Shen, "Dielectric, piezoelectric, and ferroelectric nanomaterials in the biomedical applications," IET Nanodielectrics, 2023. wiley.com

104. J. Wu, X. Zhou, C. Y. Tsang, Q. Mei *et al.*, "Bioengineered nanomaterials for dynamic diagnostics *in vivo*," Chemical Society Reviews, 2025. [HTML]

105. D. A., L. H., C. I., and F. R., "Targeted and theranostic applications for nanotechnologies in medicine: Cell-surface engineering with magnetic nanoparticles for regenerative and bioanalytical applications," 2017. [PDF]

106. M. J. Mitchell, M. M. Billingsley, R. M. Haley, *et al.*, "Engineering precision nanoparticles for drug delivery," *Nature Reviews Drug Discovery*, vol. 20, no. 6, pp. 389-406, 2021. nature.com

107. V. Chandrakala, V. Aruna, and G. Angajala, "Review on metal nanoparticles as nanocarriers: Current challenges and perspectives in drug delivery systems," Emergent Materials, 2022. springer.com

108. L. Chen, W. Hong, W. Ren, T. Xu, Z. Qian, "Recent progress in targeted delivery vectors based on biomimetic nanoparticles," Signal Transduction and Targeted Therapy, vol. 6, no. 1, 2021. nature.com

109. N. Parvin, S. W. Joo, and T. K. Mandal, "Enhancing vaccine efficacy and stability: A review of the utilization of nanoparticles in mRNA vaccines," Biomolecules, 2024. mdpi.com

110. S. Bhattacharjee and D. J. Brayden, "Addressing the challenges to increase the efficiency of translating nanomedicine formulations to patients," Expert opinion on drug discovery, 2021. [HTML]

111. A. Abdelkawi, A. Slim, Z. Zinoune, and Y. Pathak, "Surface modification of metallic nanoparticles for targeting drugs," Coatings, 2023. mdpi.com

112. W. Ho, M. Gao, F. Li, Z. Li, and X. Q. Zhang, "Next- generation vaccines: nanoparticle- mediated DNA and mRNA delivery," *Advanced Healthcare Materials*, vol. 10, no. 1, 2021. wiley.com

113. S. Xu, Y. Xu, N. C. Solek, J. Chen, F. Gong, "Tumor- tailored ionizable lipid nanoparticles facilitate IL- 12 circular RNA delivery for enhanced lung cancer immunotherapy," *Advanced*, vol. 2024, Wiley Online

Library. [HTML]

114. X. Ma, Y. Tian, R. Yang, H. Wang, and L. W. Allahou, "Nanotechnology in healthcare, and its safety and environmental risks," Journal of …, 2024. springer.com

115. S. A. Dilliard and D. J. Siegwart, "Passive, active and endogenous organ-targeted lipid and polymer nanoparticles for delivery of genetic drugs," Nature Reviews Materials, 2023. nih.gov

116. M. Vallet-Regí, "Our contributions to applications of mesoporous silica nanoparticles," Acta Biomaterialia, 2022. sciencedirect.com

117. N. R. Sibuyi, K. L. Moabelo, A. O. Fadaka, S. Meyer, "Multifunctional gold nanoparticles for improved diagnostic and therapeutic applications: a review," Nanoscale Research, vol. 2021, Springer. springer.com

118. Y. Liu, Y. Liang, J. Yuhong, P. Xin, and J. L. Han, "Advances in nanotechnology for enhancing the solubility and bioavailability of poorly soluble drugs," Drug Design, vol. 2024, Taylor & Francis. tandfonline.com

119. H. Bahrulolum, S. Nooraei, N. Javanshir, "Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector," Journal of …, vol. XX, no. YY, pp. ZZ-ZZ, 2021. springer.com

120. S. Bharti, "Harnessing the potential of bimetallic nanoparticles: Exploring a novel approach to address antimicrobial resistance," World Journal of Microbiology and Biotechnology, 2024. [HTML]

121. B. Mubeen, A. N. Ansar, R. Rasool, I. Ullah, S. S. Imam, "Nanotechnology as a novel approach in combating microbes providing an alternative to antibiotics," *Antibiotics*, vol. 10, no. 1, 2021. mdpi.com

122. D. Lahiri, M. Nag, H. I. Sheikh, T. Sarkar, "Microbiologically-synthesized nanoparticles and their role in silencing the biofilm signaling cascade," Frontiers in..., 2021. frontiersin.org

123. J. Jeevanandam, S. F. Kiew, S. Boakye-Ansah, S. Y. Lau, *et al.*, "Green approaches for the synthesis of metal and metal oxide nanoparticles using microbial and plant extracts," Nanoscale, 2022. [HTML]

124. R. T. Kapoor, M. R. Salvadori, M. Rafatullah, *et al.*, "Exploration of microbial factories for synthesis of nanoparticles-a sustainable approach for bioremediation of environmental contaminants," *Frontiers in...*, 2021. frontiersin.org

125. M. Shuaib, N. Azam, S. Bahadur, M. Romman, Q. Yu, "Variation and succession of microbial communities under the conditions of persistent heavy metal and their survival mechanism," Microbial..., vol. 2021, Elsevier. [HTML]

126. X. Jin, J. Shan, J. Zhao, T. Wang, W. Zhang, and S. Yang, "Bimetallic oxide Cu-Fe3O4 nanoclusters with multiple enzymatic activities for wound infection treatment and wound healing," Acta Biomaterialia, 2024. [HTML]

127. A. Rana, S. Pathak, D. K. Lim, S. K. Kim, "Recent advancements in plant-and microbe-mediated synthesis of metal and metal oxide nanomaterials and their emerging antimicrobial applications," *ACS Applied Nano*, vol. 2023, ACS Publications. [HTML]

128. Y. Gao, H. Zou, B. Wang, and F. Yuan, "Progress and applications of plant growth-promoting bacteria in salt tolerance of crops," *International Journal of Molecular …*, 2022. mdpi.com

129. P. Sharma and S. Kumar, "Bioremediation of heavy metals from industrial effluents by endophytes and their metabolic activity: Recent advances," Bioresource Technology, 2021. [HTML]

130. M. Shahid, M. T. Zeyad, A. Syed, U. B. Singh, "Stress-Tolerant Endophytic Isolate Priestia aryabhattai BPR-9 Modulates Physio-Biochemical Mechanisms in Wheat (Triticum aestivum L.) for Enhanced Salt …," International Journal of …, 2022. mdpi.com

131. D. T. Nagrale, A. Chaurasia, S. Kumar, *et al.*, "PGPR: the treasure of multifarious beneficial microorganisms for nutrient mobilization, pest biocontrol and plant growth promotion in field crops," *World Journal of …*, 2023. [HTML]

132. A. Kumar, P. K. Tyagi, S. Tyagi, and M. Ghorbanpour, "Integrating green nanotechnology with sustainable development goals: a pathway to sustainable innovation," Discover Sustainability, 2024. springer.com

133. N. Srivastava and G. Mishra, "Nanotechnology for environmental pollution detection and remedies," in *Analytical Devices: Materials and Applications*, 2022. [HTML]

134. A.H. Gondal, "Nanotechnology advancement in the elimination of chemical toxins from air spectrums," *International Journal of Environmental Science and …*, vol. 2023, Springer, 2023. [HTML]

135. R. Shaik, B. Ghosh, H. C. Barman, A. Rout, "Green Nanotech: A

Review of Carbon-Based Nanomaterials for Tackling Environmental Pollution Challenges," *Environmental Science & Pollution Technology*, 2024. neptjournal.com

136. M. Muhammad, A. Arooj, S. Ullah, A. Wahab, "Future of Nanotechnology and Climate Change," in *Nanotechnology for Climate Change*, 2025, Springer. researchgate.net

137. S. Rajendran, P. Ramesh, P. Sengottaiyan, "Clearing the Air: Nanotechnology's Role in Tackling Atmospheric Pollution," in *Through Materials and …*, Springer, 2025. researchgate.net

138. N. C. Godja and F. D. Munteanu, "Hybrid nanomaterials: a brief overview of versatile solutions for sensor technology in healthcare and environmental applications," Biosensors, 2024. mdpi.com

139. L. M. Jennings, "Nanotechnology in Electrochemical Sensors for Environmental Monitoring," *American Journal of Nano Science*, 2025. australiansciencejournals.com

140. F. A. S. Islam and M. A. N. Islam, "AI-Driven Integration of Nanotechnology and Green Nanotechnology for Sustainable Energy and Environmental Remediation," Journal of Engineering Research, 2025. researchgate.net

141. P. Yadav and P. Gupta, "Tiny Tech Big Impact: Harnessing Nanotechnology for Cleaner Air," in 2024 IEEE 4th International Conference on …, 2024. [HTML]

142. D. Ramadevi and K. Ushasri, "NANOTECHNOLOGY APPLICATIONS IN THE ENVIRONMENT," 24th & 25th Feb, 2023. researchgate.net

143. C. Shang, Y. Chen, Z. Dai, Y. Yalikun, L. Qian, and P. S. Lee, "Nanotechnology- Enabled Devices for Ocean Internet of Things," Wiley Online Library, 2025. wiley.com

144. MD Junaid and AF Gokce, "Global agricultural losses and their causes," Bulletin of Biological and Allied Sciences, 2024. bbasr.org

145. D. Mohajan and H. K. Mohajan, "Obesity and its related diseases: a new escalating alarming in global health," Journal of Innovations in Medical, vol. 2023, 2023. paradigmpress.org

146. D. Withrow, S. Pilleron, N. Nikita, J. Ferlay, *et al.*, "Current and projected number of years of life lost due to prostate cancer: A global study," The …, 2022. nih.gov

147. J. McCallum, "Australia's new aged: issues for young and old," 2023. [HTML]

148. S. Ramesh and K. Kosalram, "The burden of non-communicable diseases: A scoping review focus on the context of India," *Journal of Education and Health*, vol. 2023. lww.com

149. S. Naseer, S. Khalid, S. Parveen, K. Abbass, "COVID-19 outbreak: Impact on global economy," *Frontiers in Public Health*, vol. 2023. frontiersin.org

150. G. Tripathi, A. Husain, S. Ahmad, Z. Hasan, "Contamination of water resources in industrial zones," Contamination of …, 2021, Elsevier. [HTML]

151. UB Onyedikachi and FE Mukah, "Water Contamination by Industrial Processes and Sustainable Management Strategies," in *Water Crises and Sustainable Management*, 2024, Springer. [HTML]

152. S. Jahan and A. Singh, "Causes and impact of industrial effluents on receiving water bodies: a review," Malaysian Journal of Science and Advanced, 2023. mjsat.com.my

153. A. Tariq and A. Mushtaq, "Untreated wastewater reasons and causes: A review of most affected areas and cities," Int. J. Chem. Biochem. Sci, 2023. iscientific.org

154. M. Arya, A. Patil, S. Singh, and B. Sharma, "Heavy metal pollution in natural water resources and impact of metal toxicity on human health," Water: Management & …, 2023. researchgate.net

155. N. Akhtar, M. I. Syakir Ishak, S. A. Bhawani, and K. Umar, "Various natural and anthropogenic factors responsible for water quality degradation: A review," Water, 2021. mdpi.com

156. R. K. Mishra, "Fresh water availability and its global challenge," British Journal of Multidisciplinary and Advanced Research, 2023. academia.edu

157. A. Beriso, "Application of Nanotechnology for Environmental Problem," 2018. [PDF]

158. D. Chakraborty, K. Sen, K. Mukhopadhyay, "Application of Nanotechnology in the Mitigation of Air Pollution Exposure for Better Public Health," Emerging Sustainable Technologies, 2024. [HTML]

159. M. O. Zubair, G. Zobair, J. Sharma, and D. A. Dhale, "Improvement of

Air Quality Using Nanomaterials and Nanotechnology," in *Civil and Environmental Engineering*, 2025, Springer. [HTML]

160. M. Taran, M. Safaei, N. Karimi, "Benefits and application of nanotechnology in environmental science: an overview," Research in Applied Biointerfacial Science, vol. 2021. biointerfaceresearch.com

161. R. D. Prasad, N. R. Prasad, N. Prasad, and R. S. Prasad, "A Review on Aspects of Nanotechnology in Environmental Science and Engineering," ES General, 2025. espublisher.com

162. A. Ghosh, R. Chakraborty, A. Das, and A. Kumar, "Abating air pollution using nanoparticles and sustainable technologies through holistic lens," in *Nanotechnology for …*, 2024, Springer. [HTML]

163. A. Roy, A. Sharma, S. Yadav, L. Tesfaye Jule *et al.*, "Nanomaterials for Remediation of Environmental Pollutants," 2021. ncbi.nlm.nih.gov

164. P. Kokkinos, D. Venieri, and D. Mantzavinos, "Advanced oxidation processes for water and wastewater viral disinfection. A systematic review," Food and environmental virology, 2021. springer.com

165. J. A. Silva, "Advanced Oxidation Process in the Sustainable Treatment of Refractory Wastewater: A Systematic Literature Review.," Sustainability (2071-1050), 2025. researchgate.net

166. K. Koirala and N. Basel, "Electrochemical-based hybrid methods for the treatment of PPCPS in water matrix," in Integrated and Hybrid Technologies for Degradation of PPCPs, Elsevier, 2025. [HTML]

167. J. Shamshad and R. U. Rehman, "Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies," Environmental Science: Advances, 2025. rsc.org

168. T. A. Kurniawan, P. S. Yap, and Z. Chen, "Techniques for pollutant removal, nutrient recovery, and energy production from landfill leachates: a review," Environmental Chemistry Letters, 2025. [HTML]

169. W. F. Elmobarak, B. H. Hameed, F. Almomani, and A. Z. Abdullah, "A review on the treatment of petroleum refinery wastewater using advanced oxidation processes," Catalysts, 2021. mdpi.com

170. S. Goodarzi, M. Torabideh, G. Parsaseresht, "Penicillin removal from the aqueous environment based on AOPs/challenges and outlook. A review," *Applied Water Science*, vol. 14, no. 1, 2024. springer.com

171. K. Ahlawat, R. Jangra, and R. Prakash, "Environmentally friendly UV-C

excimer light source with advanced oxidation process for rapid mineralization of azo dye in wastewater," ACS omega, 2024. acs.org

172. F. D. Guerra, M. F. Attia, D. C. Whitehead, and F. Alexis, "Nanotechnology for Environmental Remediation: Materials and Applications," 2018. ncbi.nlm.nih.gov

173. A. Roy, A. Sharma, S. Yadav, and L. T. Jule, "Nanomaterials for remediation of environmental pollutants," *… and Applications*, 2021. wiley.com

174. K. K. Singh, "Role of nanotechnology and nanomaterials for water treatment and environmental remediation," International Journal of New Chemistry, 2022. ijnc.ir

175. R. Thirumalaisamy, R. Suriyaprabha, M. Prabhu, "Role of nanomaterials in environmental remediation: recent advances—a review," in *Strategies and Tools for Environmental Remediation*, Springer, 2022. [HTML]

176. M. L. Del Prado-Audelo and I. García Kerdan, "Nanoremediation: nanomaterials and nanotechnologies for environmental cleanup," in Environmental, vol. 2021. frontiersin.org

177. N. Asghar, A. Hussain, D. A. Nguyen, S. Ali, "Advancement in nanomaterials for environmental pollutants remediation: a systematic review on bibliometrics analysis, material types, synthesis pathways, and …," Journal of …, 2024. springer.com

178. S. Amin, A. R. Solangi, D. Hassan, "Recent trends in development of nanomaterials based green analytical methods for environmental remediation," *Current Analytical Chemistry*, vol. 2021. researchgate.net

179. A. M. Elgarahy, K. Z. Elwakeel, A. Akhdhar, *et al.*, "Recent advances in greenly synthesized nanoengineered materials for water/wastewater remediation: an overview," in *Nanotechnology for Water Treatment*, Springer, 2021. researchgate.net

180. S. Ethaib, S. Al-Qutaifia, N. Al-Ansari, and S. L. Zubaidi, "Function of nanomaterials in removing heavy metals for water and wastewater remediation: A review," Environments, 2022. mdpi.com

181. M. Ahmad Gatoo, S. Naseem, M. Yasir Arfat, A. Mahmood Dar *et al.*, "Physicochemical Properties of Nanomaterials: Implication in Associated Toxic Manifestations," 2014. ncbi.nlm.nih.gov

182.J. Zhao, M. Lin, Z. Wang, and X. Cao, "Engineered nanomaterials in the environment: Are they safe?," Critical Reviews in…, vol. XX, no. YY, pp. ZZ-ZZ, 2021. tandfonline.com

183.F. Albalawi, M. Z. Hussein, S. Fakurazi, "Engineered nanomaterials: The challenges and opportunities for nanomedicines," *International Journal of...*, vol. XX, no. YY, pp. ZZ-ZZ, 2021. tandfonline.com

184.S. Gottardo, A. Mech, J. Drbohlavová, A. Małyska, "Towards safe and sustainable innovation in nanotechnology: State-of-play for smart nanomaterials," NanoImpact, vol. 21, 2021. sciencedirect.com

185.M. Sajid, "Nanomaterials: types, properties, recent advances, and toxicity concerns," Current Opinion in Environmental Science & Health, 2022. [HTML]

186.D. M. Mitrano, P. Wick, and B. Nowack, "Placing nanoplastics in the context of global plastic pollution," Nature Nanotechnology, 2021. [HTML]

187.I. Corsi, A. Bellingeri, M. C. Eliso, G. Grassi, and G. Liberatori, "Eco-interactions of engineered nanomaterials in the marine environment: Towards an eco-design framework," *Nanomaterials*, vol. 11, no. 7, 2021. mdpi.com

188.S. Won Shin, I. Hyun Song, and S. Ho Um, "Role of Physicochemical Properties in Nanoparticle Toxicity," 2015. ncbi.nlm.nih.gov

189.S. Dabagh, S. A. Haris, B. K. Isfahani, *et al*., "Silver-decorated and silica-capped magnetite nanoparticles with effective antibacterial activity and reusability," ACS Applied Bio, vol. 2023, ACS Publications. acs.org

190.A. S. Desai, A. Singh, Z. Edis, S. Haj Bloukh, *et al*., "An *in vitro* and *in vivo* study of the efficacy and toxicity of plant-extract-derived silver nanoparticles," *Journal of Functional Materials*, vol. 2022. mdpi.com

191.P. Szczyglewska, A. Feliczak-Guzik, and I. Nowak, "Nanotechnology-general aspects: A chemical reduction approach to the synthesis of nanoparticles," Molecules, 2023. mdpi.com

192.R. Abbasi, G. Shineh, M. Mobaraki, S. Doughty, "Structural parameters of nanoparticles affecting their toxicity for biomedical applications: a review," *Journal of Nanoparticle Research*, vol. 2023, Springer. springer.com

193.S. M. Shaheen, A. Mosa, Natasha, and H. Abdelrahman, "Removal of toxic elements from aqueous environments using nano zero-valent iron- and iron oxide-modified biochar: a review," Biochar, vol. 2022, Springer. springer.com

194. J. Niu, C. Wang, K. Qiao, M. Liao, Y. Liu, Y. Ding, "… -based organic-inorganic nanohybrid nanoparticles loaded with prothioconazole for efficient management of fungal diseases with minimal environmental impact," International Journal of …, 2024. [HTML]

195. K. M. Z. Hossain, L. Deeming, and K. J. Edler, "Recent progress in Pickering emulsions stabilised by bioderived particles," RSC advances, 2021. rsc.org

196. O. Afşar and Ç Oltulu, "Evaluation of the cytotoxic effect of titanium dioxide nanoparticles in human embryonic lung cells," Turkish Journal of Medical Sciences, 2023. tubitak.gov.tr

197. H. Xu, Y. Zhu, L. Zhu, D. Wang, S. Lv, X. Li, C. Guo, "Warning on the inhalation of silica nanoparticles: Experimental evidence for its easy passage through the air-blood barrier, resulting in systemic distribution and …," Chemico-Biological Interactions, vol. 2025, Elsevier, 2025. [HTML]

198. M. Haripriyaa and K. Suthindhiran, "Pharmacokinetics of nanoparticles: current knowledge, future directions and its implications in drug delivery," Future Journal of Pharmaceutical Sciences, 2023. springer.com

199. L. Wang, Y. Rao, X. Liu, L. Sun, J. Gong, H. Zhang, *et al.*, "Administration route governs the therapeutic efficacy, biodistribution and macrophage targeting of anti-inflammatory nanoparticles in the lung," *Journal of …*, vol. 2021, Springer. springer.com

200. S. I. Hossain, Z. Luo, E. Deplazes, and others, "Shape matters—the interaction of gold nanoparticles with model lung surfactant monolayers," *Journal of the Royal Society*, vol. 2021. royalsocietypublishing.org

201. M. Guérin and E. Lepeltier, "Nanomedicines via the pulmonary route: a promising strategy to reach the target?," Drug Delivery and Translational Research, 2024. hal.science

202. S. Stoycheva, A. Zabeo, L. Pizzol, and D. Hristozov, "Socio-economic life cycle-based framework for safe and sustainable design of engineered nanomaterials and nano-enabled products," Sustainability, 2022. mdpi.com

203. A. Umapathi, M. Kumawat, and H. K. Daima, "Engineered nanomaterials for biomedical applications and their toxicity: a review," Environmental chemistry letters, 2022. academia.edu

204. M. Elsamadony, A. Elreedy, A. Mostafa, "Perspectives on potential applications of nanometal derivatives in gaseous bioenergy pathways: mechanisms, life cycle, and toxicity," *ACS Publications*, 2021. [HTML]

205. F. Zhang, Z. Wang, W. J. G. M. Peijnenburg, *et al.*, "Review and prospects on the ecotoxicity of mixtures of nanoparticles and hybrid nanomaterials," *Environmental Science*, vol. 2022, ACS Publications. acs.org

206. K. E. Bassey and K. E. Bassey, "From waste to wonder: Developing engineered nanomaterials for multifaceted applications," GSC Advanced Research and Reviews, 2024. researchgate.net

207. M. E. Karim, "Nanotechnology in Asia: A preliminary assessment of the existing legal framework," 2014. [PDF]

208. H. A. L. A. M. O. D. A. KENZAOUI BLANKA, B. O. X. HELEN, V. A. N. ELK MEREL, G. A. I. T. A. N. SANDRA *et al*., "Anticipation of regulatory needs for nanotechnology-enabled health products," 2019. [PDF]

209. M. Ghosh and R. Kumar, "Regulatory issues in nanotechnology," in *Nanotechnology theranostics in livestock diseases*, Springer, 2024. researchgate.net

210. R. Justo-Hanani, "Governing nanotechnology safety: The politics of risk regulation in Europe and the United States," 2024. [HTML]

211. M. Alizadeh, J. F. Qarachal, and E. Sheidaee, "Understanding the ecological impacts of nanoparticles: risks, monitoring, and mitigation strategies," in *Nanotechnology for Environmental …*, 2025, Springer. researchgate.net

212. A. Gholami, M. Mohkam, S. Soleimanian, "Bacterial nanotechnology as a paradigm in targeted cancer therapeutic delivery and immunotherapy," Microsystems & Nanoengineering, vol. 10, no. 1, 2024. nature.com

213. A. D. Gholap, J. Gupta, P. Kamandar, *et al.*, "Harnessing nanovaccines for effective immunization─ a special concern on COVID-19: facts, fidelity, and future prospective," *ACS Biomaterials Science & Engineering*, vol. 2023, pp. xxx-xxx, 2023. [HTML]

214. M. D. Horgan, C. L. Cummings, J. Kuzma, and M. Dahlstrom, "Beyond the Hype: Stakeholder Perceptions of Nanotechnology and Genetic Engineering for Sustainable Food Production," Sustainability, 2025. mdpi.com

215. O. Danchuk, A. Levchenko, R. da Silva Mesquita, "Meeting contemporary challenges: development of nanomaterials for veterinary medicine," Pharmaceutics, 2023. mdpi.com

216. M. E. Karim, "Nanotechnology law and policy: An introduction," 2013. [PDF]

217. M. Sousa, P. Arezes, and F. Silva, "Occupational exposure to incidental nanomaterials in metal additive manufacturing: an innovative approach for risk management," *International Journal of Environmental …*, 2023. mdpi.com

218. P. Mohammadi and A. Galera, "Occupational exposure to nanomaterials: A bibliometric study of publications over the last decade," *Journal of Hygiene and Environmental Health*, vol. 2023, Elsevier. sciencedirect.com

219. S. McCormick, M. Niang, and M. M. Dahm, "Occupational exposures to engineered nanomaterials: a review of workplace exposure assessment methods," Current environmental health reports, 2021. nih.gov

220. W. S. Khan, E. Asmatulu, and R. Asmatulu, "Nanotechnology emerging trends, markets and concerns," Nanotechnology safety, 2025. [HTML]

221. S. O. Shekaftik, N. Mehrparvar, Z. Peivandi, "Occupational Exposure to Nanomaterials: A Scoping Review," Journal of Cluster, vol. 2025, Springer, 2025. [HTML]

222. M. Sousa, P. Arezes, and F. Silva, "Occupational exposure to ultrafine particles in metal additive manufacturing: A qualitative and quantitative risk assessment," *International Journal of Environmental …*, vol. 2021. mdpi.com

223. H. Panakkal, R. Bhagat, M. Rai, and I. Gupta, "Nanomaterial exposure at workplace and societal levels: workplace standards and occupational risk management," in *Nanotoxicology for Agricultural and …*, Elsevier, 2024. [HTML]

224. R. Prasad, A. Ghosh, V. Patel, B. Peng, B. B. Mendes, "Voices of Nanomedicine: Blueprint Guidelines for Collaboration in Addressing Global Unmet Medical Needs," ACS Publications, 2025. google.com

225. U. D. Patil, "Exploring Nanomedicine Ventures and Latest Developments in Clinical Trials," in *Nanomedicine: Innovations, Applications, and …*, 2024, Springer. [HTML]

226. R. G. L. da Silva, "The advancement of artificial intelligence in biomedical research and health innovation: challenges and opportunities in emerging economies," Globalization and health, 2024. springer.com

227. N. Shmeleva, L. Gamidullaeva, T. Tolstykh, "Challenges and opportunities for technology transfer networks in the context of open innovation: Russian experience," *Innovation: Technology*, vol. 2021. mdpi.com

228. A. V. Singh, P. Bhardwaj, A. K. Upadhyay, A. Pagani, "Navigating regulatory challenges in molecularly tailored nanomedicine," 2024. qu.edu.qa

229. S. R. Jansma and A. M. Dijkstra, "Co-creation in support of responsible research and innovation: an analysis of three stakeholder workshops on nanotechnology for health," *Journal of Responsible Innovation*, vol. 2022, Taylor & Francis. tandfonline.com

230. S. Berkner, K. Schwirn, and D. Voelker, "Too advanced for assessment? Advanced materials, nanomedicine and the environment," 2022. ncbi.nlm.nih.gov

231. A. Schuhmacher, C. Brieke, O. Gassmann, and M. Hinder, "Systematic risk identification and assessment using a new risk map in pharmaceutical R&D," Drug Discovery Today, vol. 26, no. 1, pp. 123-134, 2021. [HTML]

232. T. H. Malik, S. Kabiraj, and F. Lestan, "Prestige of the Decision Ecology and Risk-taking in R&D Project in the Biopharmaceutical Sector," Global Business Review, 2022. theseus.fi

233. H. Taherdoost, "Risk Management in R&D Projects," in *Through Research and Development: Strategies for …*, Springer, 2024. [HTML]

234. B. I. Ashiwaju, C. G. Uzougbo, and O. F. Orikpete, "Environmental impact of pharmaceuticals: A comprehensive review," Matrix Science Pharma, 2023. lww.com

235. V. Choudhary, K. Patel, M. Niaz, and M. Panwala, "Risk Management Strategies for Biotech Startups: A Comprehensive Framework for Early-Stage Projects," Recent Trends In…, 2024. [HTML]

236. F. Mirakhori and S. K. Niazi, "Harnessing the AI/ML in drug and

biological products discovery and development: the regulatory perspective," Pharmaceuticals, 2025. mdpi.com

237. S. N. Wahab, N. Ahmed, and M. S. Ab Talib, "An overview of the SWOT analysis in India's pharmaceutical supply chain," Arab Gulf Journal of Scientific, 2024. emerald.com

238. M. A. Subhan, K. P. Choudhury, and N. Neogi, "Advances with molecular nanomaterials in industrial manufacturing applications," Nanomanufacturing, 2021. mdpi.com

239. I. Chakrabartty, K. R. Hakeem, Y. K. Mohanta, *et al.*, "Greener nanomaterials and their diverse applications in the energy sector," Clean Technologies and …, vol. 2022, Springer, 2022. researchgate.net

240. T. Rambaran and R. Schirhagl, "Nanotechnology from lab to industry-a look at current trends," Nanoscale advances, 2022. rsc.org

241. S. BIROUDIAN, M. ABBASI, and M. KIANI, "Theoretical and Practical Principles on Nanoethics: A Narrative Review Article," 2019. ncbi.nlm.nih.gov

242. K. Jan, I. Ahmed, and I. Ahmad, "Emerging Trend of Nanotechnology: Applications, Mode of Action, and Challenges," in *Aquaculture: Enhancing Food Security*, 2025. [HTML]

243. S. Nithyaasri, R. Karthikeyan, and M. Kalarani, "Nanotechnology: The Gamechanger in Agricultural Production in a Dynamic Environment," *Journal of Soil Science and...*, 2025. [HTML]

244. P. A. Schulte, V. Leso, and I. Iavicoli, "Responsible development of emerging technologies: extensions and lessons from nanotechnology for worker protection," *Journal of Occupational and Environmental Medicine*, vol. 2024. lww.com

245. JT Mathew, CO Adetunji, A Inobeme, "Nutritional Qualities of Agricultural Crops After Application of Nanobioherbicides," in Handbook of …, 2024, Wiley Online Library. [HTML]

246. E. Alp-Erbay, "Nanomaterials utilized in food packaging: State-of-the-art," Food Engineering Reviews, 2022. [HTML]

247. R. Kushwaha and A. A. Shehu, "Biosensors and Their Applications: A Revolution in Analytical Detection," kronika.ac,. kronika.ac

248. Y. K. Mohanta, A. Nongbet, J. Panda, I. Chakrabartty, "Nanobiotechnology in genetic engineering for abiotic stress resistance

in crops," in *Nanotechnology for...*, 2024, Elsevier. [HTML]

249. D. Baird and T. Vogt, "Societal and ethical interactions with nanotechnology (SEIN) - an introduction," 2005. [PDF]

250. C. Amutha, A. Gopan, I. Pushbalatatha, M. Ragavi, "Nanotechnology and governance: regulatory framework for responsible innovation," in *Nanotechnology in …*, Springer, 2024. [HTML]

251. U. T. Khatoon and A. Velidandi, "An overview on the role of government initiatives in nanotechnology innovation for sustainable economic development and research progress," Sustainability, 2025. mdpi.com

252. F. D. Rodríguez-Gómez, D. Monferrer, O. Penon, *et al.*, "Regulatory pathways and guidelines for nanotechnology-enabled health products: a comparative review of EU and US frameworks," *Frontiers in...*, 2025. frontiersin.org

253. K. Rasmussen, P. Sayre, A. Kobe, M. Gonzalez, "25 years of research and regulation: Is nanotechnology safe to commercialize?" Frontiers in…, 2025. frontiersin.org

254. M. A. Subhan and T. Subhan, "Safety and global regulations for application of nanomaterials," Nanomaterials recycling, 2022. [HTML]

255. A. Yadav, P. Thakur, A. Thakur, "Challenges in Scaling Nanobiology for Clinical Use," Advancements in..., 2025. [HTML]

256. S. Heydari, N. Masoumi, E. Esmaeeli, "Artificial intelligence in nanotechnology for treatment of diseases," Journal of Drug..., 2024. [HTML]

257. M. A. Syed, S. Ali, and T. Hussain, "Microbiology in the Era of Artificial Intelligence: Nanotechnology, Quantum, and Next Generation Sequencing," 2025. [HTML]

258. P. Kia, U. Ruman, A. R. Pratiwi, "Innovative therapeutic approaches based on nanotechnology for the treatment and management of tuberculosis," *Journal of Nanomedicine*, vol. 2023, Taylor & Francis. tandfonline.com

259. G. Prasad, U. Chakraborty, E. S. Matete, "Innovation of Bio-Inspired Materials for Next-Generation Defense Applications," in *Materials for Next Generation Defense Applications*, 2025. [HTML]

260. K. Kant, R. Beeram, L. G. Cabaleiro, Y. Cao, *et al.*, "Roadmap for

plasmonic nanoparticle sensors: current progress, challenges and future prospects," Nanoscale, 2024. rsc.org

261. Z. Farka, J. C. Brandmeier, M. J. Mickert, *et al*., "Nanoparticle- based bioaffinity assays: from the research laboratory to the market," *Advanced...,* 2024. wiley.com

262. M. Arafat, M. Sakkal, R. Beiram, and S. AbuRuz, "Nanomedicines: emerging platforms in smart chemotherapy treatment—a recent review," Pharmaceuticals, 2024. mdpi.com

263. A. Saha, P. Mishra, G. Biswas, and S. Bhakta, "Greening the pathways: a comprehensive review of sustainable synthesis strategies for silica nanoparticles and their diverse applications," RSC advances, 2024. rsc.org

264. J. Ferlak, W. Guzenda, and T. Osmałek, "Orodispersible films—Current state of the art, limitations, advances and future perspectives," Pharmaceutics, 2023. mdpi.com

265. S. Rahman, S. Sadaf, M. E. Hoque, A. Mishra, "Unleashing the promise of emerging nanomaterials as a sustainable platform to mitigate antimicrobial resistance," RSC, 2024. rsc.org

266. S. K. Mondal, S. Chakraborty, and S. Manna, "Antimicrobial nanoparticles: current landscape and future challenges," RSC Pharmaceutics, 2024. rsc.org

267. T. Naseem and M. Waseem, "A comprehensive review on the role of some important nanocomposites for antimicrobial and wastewater applications," *International Journal of Environmental Science*, vol. 2022, Springer. [HTML]

268. N. Parvin, S. W. Joo, and T. K. Mandal, "Nanomaterial-based strategies to combat antibiotic resistance: mechanisms and applications," Antibiotics, 2025. mdpi.com

269. N. J. Anyaegbunam, I. E. Mba, A. O. Ige, *et al*., "Revisiting the smart metallic nanomaterials: advances in nanotechnology-based antimicrobials," World Journal of..., vol. XX, no. YY, pp. ZZ-ZZ, 2024. [HTML]

270. A. Ghareeb, A. Fouda, R. M. Kishk, and W. M. El Kazzaz, "Unlocking the potential of titanium dioxide nanoparticles: an insight into green synthesis, optimizations, characterizations, and multifunctional applications," Microbial Cell Factories, 2024. springer.com

271. A. Vikal, R. Maurya, S. Bhowmik, and P. Patel, "From conventional to cutting-edge: a comprehensive review on drug delivery systems," Drug Delivery, 2024. researchgate.net

272. P. Chatterjee and S. Dhibar, "Nanomaterial marvels: Pioneering applications and cutting-edge advancements in drug delivery," Nano and Medical Materials, 2023. acad-pub.com

273. R. Tenchov, K. J. Hughes, M. Ganesan, K. A. Iyer, "Transforming medicine: cutting-edge applications of nanoscale materials in drug delivery," ACS Publications, 2025. acs.org

274. P. K. Prabhakar and A. Prakash, "Cutting-edge Applications of Nanomaterials in Biomedical Sciences," 2024. [HTML]

275. H. K. Ibrahim, "From nanotech to AI: the cutting-edge technologies shaping the future of medicine," African Journal of Advanced Pure and Applied …, 2024. aaasjournals.com

276. A. Mahor, P. P. Singh, P. Bharadwaj, N. Sharma, and S. Yadav, "Carbon-based nanomaterials for delivery of biologicals and therapeutics: a cutting-edge technology," C, vol. 2021, 2021. mdpi.com

277. R. Chaudhari, V. Patel, and A. Kumar, "Cutting-edge approaches for targeted drug delivery in breast cancer: beyond conventional therapies," Nanoscale Advances, 2024. rsc.org

278. A. Escudero Belmonte, B. Pelaz, R. A. Alvarez Puebla, L. Ballerini *et al.*, "Diverse Applications of Nanomedicine," 2017. [PDF]

279. A. Matić, E. K. Sher, E. K. Farhat, and F. Sher, "Nanostructured materials for drug delivery and tissue engineering applications," Molecular biotechnology, 2023. springer.com

280. S. A. Shah, M. Sohail, P. Nakielski, C. Rinoldi, *et al.*, "Integrating micro-and nanostructured platforms and biological drugs to enhance biomaterial-based bone regeneration strategies," ACS Publications, 2024. acs.org

281. J. Bag, S. Mukherjee, and D. Karati, "Recent advancement of nanostructured materials: a compatible therapy of tissue engineering and drug delivery system," Polymer Bulletin, 2024. [HTML]

282. Y. Zheng, X. Hong, J. Wang, L. Feng, T. Fan, *et al.*, "2D nanomaterials for tissue engineering and regenerative nanomedicines: recent advances and future challenges," *Advanced Materials*, vol. 33, no. 45, 2021. google.com

283. A. Mondal, A. K. Nayak, and P. Chakraborty, "Nanostructured materials for tissue engineering," 2023. [HTML]

284. S. Farjaminejad and R. Farjaminejad, "Nanoparticles in bone regeneration: a narrative review of current advances and future directions in tissue engineering," Journal of Functional Materials, 2024. mdpi.com

285. W. Frączek, A. Kotela, I. Kotela, and M. Grodzik, "Nanostructures in orthopedics: advancing diagnostics, targeted therapies, and tissue regeneration," Materials, 2024. mdpi.com

286. X. Huang, M. Auffan, M. J. Eckelman, *et al.*, "Trends, risks and opportunities in environmental nanotechnology," Earth & Environment, 2024. rice.edu

287. A. Kumar, "FROM NANO TO NATURE: INTEGRATING NANOTECHNOLOGY IN SUSTAINABLE DEVELOPMENT STRATEGIES," in *Nanotechnology for Sustainable Development*, 2025. [HTML]

288. S. Anjum, S. Ishaque, H. Fatima, W. Farooq, C. Hano, "Emerging applications of nanotechnology in healthcare systems: Grand challenges and perspectives," *Pharmaceuticals*, vol. 14, no. 3, 2021. mdpi.com

289. P. K. Sharma, S. Dorlikar, P. Rawat, V. Malik, N. Vats, "Nanotechnology and its application: a review," in *Nanotechnology in...*, Elsevier, 2021. [HTML]

290. J. Dolai, K. Mandal, and N. R. Jana, "Nanoparticle size effects in biomedical applications," ACS Applied Nano Materials, 2021. [HTML]

291. F. Caputo, D. Mehn, J. D. Clogston, M. Rösslein, "Asymmetric-flow field-flow fractionation for measuring particle size, drug loading and (in) stability of nanopharmaceuticals. The joint view of European Union …", *Journal of Chromatography A*, vol. 2021, Elsevier. sciencedirect.com

292. Z. M. Mazayen, A. M. Ghoneim, R. S. Elbatanony, *et al.*, "Pharmaceutical nanotechnology: from the bench to the market," Future Journal of Pharmaceutical Sciences, vol. 2022, Springer, 2022. springer.com

293. R. Wang, K. Hong, Q. Zhang, J. Cao, T. Huang, and Z. Xiao, "A nanodrug simultaneously inhibits pancreatic stellate cell activation and regulatory T cell infiltration to promote the immunotherapy of

pancreatic cancer," Acta Biomaterialia, 2023. [HTML]

294. M. Beus, L. Božičević, I. Mamić, P. Turčić, N. Ventosa, "Introduction to Nanomedicine and Nanopharmaceuticals," 2024. [HTML]

295. S. A. Patil, A. A. Bakliwal, V. S. Chudiwal, *et al.*, "Nanopharmaceuticals for Drug Delivery," *Advances in Novel*, vol. 2023, Wiley Online Library. [HTML]

296. H. Xiang, S. Xu, J. Li, S. Pan *et al.*, "Particle size effect of curcumin nanocrystals on transdermal and transfollicular penetration by hyaluronic acid-dissolving microneedle delivery," Pharmaceuticals, 2022. mdpi.com

297. A. Singh and M. M. Amiji, "Application of nanotechnology in medical diagnosis and imaging," Current opinion in biotechnology, 2022. [HTML]

298. S. Sim and N. K. Wong, "Nanotechnology and its use in imaging and drug delivery," Biomedical reports, 2021. spandidos-publications.com

299. M. X. Luo, S. Hua, and Q. Y. Shang, "Application of nanotechnology in drug delivery systems for respiratory diseases," *Molecular Medicine*, vol. 2021, 2021. spandidos-publications.com

300. O. Afzal, A. S. A. Altamimi, M. S. Nadeem, S. I. Alzarea, "Nanoparticles in drug delivery: from history to therapeutic applications," *Nanomaterials*, vol. 12, no. 2022, pp. 1-20, 2022. mdpi.com

301. L. W. Allahou and S. Y. Madani, "Investigating the application of liposomes as drug delivery systems for the diagnosis and treatment of cancer," *International Journal of …*, 2021. wiley.com

302. T. C. Ezike, U. S. Okpala, U. L. Onoja, C. P. Nwike, and E. C. Ezeako, "Advances in drug delivery systems, challenges and future directions," Heliyon, 2023. cell.com

303. Y. Liu, T. Wu, J. C. White, and D. Lin, "A new strategy using nanoscale zero-valent iron to simultaneously promote remediation and safe crop production in contaminated soil," Nature Nanotechnology, 2021. [HTML]

304. S. H. Gebre, "Nanoscale zero-valent iron for remediation of toxicants and wastewater treatment," Environmental Technology Reviews, 2023. [HTML]

305. B. Wang, C. Deng, W. Ma, and Y. Sun, "Modified nanoscale zero-

valent iron in persulfate activation for organic pollution remediation: a review," *Environmental Science and Pollution Research*, vol. 28, no. 7, pp. 8345-8360, 2021. [HTML]

306. M. Namakka, M. R. Rahman, K. A. B. M. Said, and A. Muhammad, "Insights into micro-and nano-zero valent iron materials: synthesis methods and multifaceted applications," RSC advances, 2024. rsc.org

307. D. Liang, G. Zeng, X. Lei, and D. Sun, "Advancements and Challenges in Nanoscale Zero-Valent Iron-Activated Persulfate Technology for the Removal of Endocrine-Disrupting Chemicals," Toxics, 2024. mdpi.com

308. A. Priyadarshini, P. K. Sahoo, A. Ghosal, *et al*., "Stabilization of zero-valent iron for wastewater treatment: Challenges and future prospective," Materials Today, 2022. [HTML]

309. N. Liu, J. Liu, H. Wang, S. Li *et al*., "Microbes team with nanoscale zero-valent iron: A robust route for degradation of recalcitrant pollutants," Journal of Environmental Sciences, 2022. [HTML]

310. W. Xue, J. Li, X. Chen, H. Liu, S. Wen, X. Shi, and J. Guo, "Recent advances in sulfidized nanoscale zero-valent iron materials for environmental remediation and challenges," *Environmental Science and Pollution Research*, vol. 2023, Springer. [HTML]

311. V. Verma, P. Gupta, P. Singh, and N. K. Pandey, "Considerations in the Development and Deployment of Nanotechnology," in *Nanotechnology in Societal …*, 2024, Springer. [HTML]

312. N. Islam, S. B. Gyoshev, and D. Amona, "Internal Dynamics and Innovation Performance of Collaborative Partnerships in Nanotechnology R&D Organisations," Available at SSRN 5261123,. ssrn.com

313. Y. A. Shah, "Foundation of Universal Knowledge: Bridging Science and Technology Across Disciplines," SAUS-Journal of IT and Computer Sciences, 2023. saus.com.pk

314. B. Joy, I. Loveth, A. Okunola, and G. Oladosu, "Adapting Agile Project Management Practices for Nanotechnology in Healthcare Settings," 2024. researchgate.net

315. M. C. Roco, "National Nanotechnology Initiative at 20 years: enabling new horizons," Journal of Nanoparticle Research, 2023. nseresearch.org

316. J. Bauer, "Teaching nanotechnology through research proposals," Journal of Chemical Education, 2021. acs.org

317. S. Talebian, T. Rodrigues, J. Das Neves, B. Sarmento, "Facts and figures on materials science and nanotechnology progress and investment," ACS Publications, 2021. google.com
318. R. A. Meidl, "Recommendations for Realizing the Full Potential of Nanotechnology and Carbon Nanotubes in the Energy Transition," 2021. rice.edu
319. M. Nayak and S. K. Moharana, "Quantum Computing and Nanotechnology," in Exploring Synergies in Nanotechnology and Quantum Computing, 2025, Springer. [HTML]
320. D. Suhag, P. Thakur, and A. Thakur, "Introduction to Nanobiology," Advancements in Nanobiology, 2025. [HTML]
321. B. Patel, P. Darji, P. I. J. Fnu, S. Nalla, and V. Khatri, "A comprehensive review and insight into the latest advancements in nanotechnology," Biosciences, 2024. biotech-asia.org
322. R. Barman, "Nanophotonics: Manipulating Light at the Nanoscale for Advanced Technologies," General Academic Journals, P-ISSN 3050, 2025. eduacademic.co.in
323. Y. Yin, B. Liu, Y. Han, Q. Liu, J. Kou, "Nanoscale 3D Printing for Empowering Future Nanodevices," *Advanced Materials*, 2025. [HTML]
324. S. Zafar and N. Rana, "The convergence of nanotechnology and artificial intelligence: unlocking future innovations," Recent Innovations in Chemical Engineering, 2025. [HTML]
325. M. B. Agarwal, M. Mehrotra, M. K. Panday, P. Mittal, "Nano AI Synergy: Advancements in Smart Materials, Devices and Intelligent Systems," in *Nanotechnology and …*, Springer, 2025. [HTML]
326. P. Sharma, V. Singh, A. Thakur, and A. K. Malik, "Nanotechnology, artificial intelligence, and the future of manufacturing," in *Nanotechnology in Societal …*, 2024, Springer. [HTML]
327. A. Tabernilla and B. dos Santos Rodrigues, "*In vitro* liver toxicity testing of chemicals: a pragmatic approach," *International Journal of …*, 2021. mdpi.com
328. F. Pognan, M. Beilmann, H. C. M. Boonen, "The evolving role of investigative toxicology in the pharmaceutical industry," Nature Reviews Drug Discovery, vol. 2023. nature.com

329. E. Filaire, R. Nachat- Kappes, C. Laporte, "Alternative *in vitro* models used in the main safety tests of cosmetic products and new challenges," *Journal of Cosmetic Science*, vol. 2022, Wiley Online Library. wiley.com

330. M. Noga, J. Milan, A. Frydrych, and K. Jurowski, "Toxicological aspects, safety assessment, and green toxicology of silver nanoparticles (AgNPs)—critical review: state of the art," *International Journal of …*, 2023. mdpi.com

331. F. Caloni, I. De Angelis, and T. Hartung, "Replacement of animal testing by integrated approaches to testing and assessment (IATA): a call for in vivitrosi," Archives of Toxicology, 2022. springer.com

332. S. Mitra, P. K. Singh, R. K. Mohapatra, "A Perspective on the Global Market of Micro-and Nano-Smart Materials in Pharmaceutical Industries," in *Journal for Pharmaceutical...,* 2024. [HTML]

333. M. Motamedi and M. S. Tabatabaei, "Novel Drug Delivery Systems: Approach to the Market," in *Novel Drug Delivery Systems*, 2025. Wiley Online Library. [HTML]

334. N. Desai, D. Rana, M. Patel, N. Bajwa *et al.*, "Nanoparticle Therapeutics in Clinical Perspective: Classification, Marketed Products, and Regulatory Landscape," Small, 2025. wiley.com

335. M. Punetha, J. Bhagat, R. Pathak, S. Bhatt, "Industrial Scale Production, Commercialization, and Global Market of Functionalized Carbon Nanostructures," in *From Synthesis Methods*, 2024, Springer. [HTML]

336. L. K. Durgam and T. L. Oroszi, "Revolutionizing healthcare: the transformative potential of nanotechnology in medicine," Frontiers in Drug Delivery, 2025. frontiersin.org

337. A. Oliveira, "Social Sciences in Brazil: From a Broad Interdisciplinarity to a Restricted Interdisciplinarity," Global Perspectives, 2023. [HTML]

338. C. M. Gomes, G. Marchini, J. Bessa, G. Carvalhal, "The landscape of biomedical research funding in Brazil: a current overview," *International Brazilian Journal*, 2024. scielo.br

339. A. P. Ritto, A. L. de Araujo, C. R. R. de Carvalho, *et al.*, "Data-driven, cross-disciplinary collaboration: lessons learned at the largest academic health center in Latin America during the COVID-19 pandemic," Frontiers in Public Health, 2024. frontiersin.org

340. G. Litre, D. P. Lindoso, and M. Bursztyn, "A long and winding road toward institutionalizing interdisciplinarity: Lessons from environmental and sustainability science programs in Brazil," Institutionalizing …, 2022. [HTML]

341. T. C. Araujo-Jorge and R. R. Ferreira, "ArtScience social technology for health and science education—A case study in Brazilian endemic areas of Chagas disease with an active search of chronic cases," PLoS Neglected Tropical Diseases, vol. 15, no. 8, 2021. plos.org

342. L. V. Santos, G. R. Maklouf, C. Z. S. do Nascimento, *et al*., "Unveiling the Frontiers of Synthetic Biology in Brazil: Pioneering the National Synthetic Biology Network," ACS Publications, 2025. acs.org

343. M. Ershadul Karim, S. Akhter, A. Bakar Munir, F. Muhammad-Sukki *et al*., "Malaysian tertiary level students and their understanding, knowledge and perception of nanotechnology.," 2017. [PDF]

344. K. Ariga, "Molecular nanoarchitectonics: unification of nanotechnology and molecular/materials science," Beilstein Journal of Nanotechnology, 2023. beilstein-journals.org

345. R. Rathore, A. Yadav, D. Suhag, "Molecular Nanodevices & Nanocarriers," in *Advancements in …*, 2025. [HTML]

346. L. R. G. Palacios and A. G. Bracamonte, "Development of nano-and microdevices for the next generation of biotechnology, wearables and miniaturized instrumentation," RSC advances, 2022. rsc.org

347. K. Ariga, "Nanoarchitectonics: what's coming next after nanotechnology?," Nanoscale Horizons, 2021. [HTML]

348. S. Singhal, "Exploring the nano frontier: A chemist's personal perspective on nanoscience and nanotechnology," International Journal of Engineering, Science and …, 2023. [HTML]

349. T. Narmadha and G. S. Sahoo, "The Impact of Nanotechnology on Modern Microelectronics," in *Optimization Computing*, 2024. [HTML]

350. H. S. Das, A. Basak, and S. Maity, "Materials science and nanotechnology," in *Energy Efficient Construction Through...*, 2025. [HTML]

351. M. Ershadul Karim, S. Akhter, A. Bakar Munir, F. Muhammad-Sukki *et al*., "Understanding, knowledge and perception of nanotechnology among private universities' students in Malaysia.," 2019. [PDF]

352.S. T. I. Enabling and P. Nation, "NATIONAL NANOTECHNOLOGY POLICY & STRATEGY 2021-2030," aipalync.org,. aipalync.org

353.A. I. Puiu, R. Ianole-Călin, and E. Druică, "Exploring the Consumer Acceptance of Nano Clothing Using a PLS-SEM Analysis," Stats, 2023. mdpi.com

354.C. I. Idumah, "Influence of nanotechnology in polymeric textiles, applications, and fight against COVID-19," The Journal of the Textile Institute, 2021. academia.edu

355.G. F. Huseien, N. H. A. Khalid, and J. Mirza, "Nanotechnology for smart concrete," 2022. [HTML]

356.L. M. Shaker, A. Al- Amiery, W. N. R. W. Isahak, "Vinyl polymers as key materials in contact lens design: A review of progress and future directions," Starch, 2024. [HTML]

357.A. H. Jasni, A. A. Ali, S. Sagadevan, *et al.*, "Silver nanoparticles in various new applications," in *Silver Micro*, 2021. intechopen.com

358.Z. H. Lin and P. J. Chen, "Evaluation and Trend of Smart Clothing Research: Visualization Analysis Based on Bibliometric Analysis and Quantitative Statistics," Fibers and Polymers, 2024. [HTML]

359.R. Singh, M. Behera, N. Kumari, S. Kumar, "Nanotechnology-based strategies for the management of COVID-19: recent developments and challenges," *Current Nanotechnology*, vol. 2021. [HTML]

360.M. Ajaz, W. Rasool, and A. Mahmood, "Comprehensive Review of Nanotechnology: Innovations and Multidisciplinary Applications: Comprehensive Review of Nanotechnology," Futuristic Biotechnology, 2024. fbtjournal.com

361.SADH Hassan, MNS Almaliki, ZA Hussein, "Development of nanotechnology by artificial intelligence: a comprehensive review," Journal of …, 2023. kashanu.ac.ir

362.S. Patra, "Unveiling the Synergy: Exploring Multidisciplinary Paradigms in Cutting-Edge Research," upload.wikimedia.org,. wikimedia.org

363.A. Kumar, "Integrative Approaches: A Comprehensive Review of Interdisciplinary Research in Social and Life Sciences," Library of Progress-Library Science, Information, 2024. researchgate.net

364.H. Jangid, S. Singh, P. Kashyap, A. Singh, "Advancing biomedical applications: an in-depth analysis of silver nanoparticles in antimicrobial, anticancer, and wound healing roles," Frontiers in..., 2024. frontiersin.org

365. P. Lakhani, D. Bhanderi, and C. K. Modi, "Nanocatalysis: recent progress, mechanistic insights, and diverse applications," Journal of Nanoparticle Research, 2024. [HTML]

366. B. Eager and R. Brunton, "Prompting higher education towards AI-augmented teaching and learning practice," in *Journal of University Teaching and Learning Practice*, 2023. [HTML]

367. T. S. Suban, "Teaching speaking: activities to promote speaking skills in EFL classrooms," Journal of Language and Language Teaching, vol. 2021. unwira.ac.id

368. S. Chuang, "The applications of constructivist learning theory and social learning theory on adult continuous development," Performance Improvement, 2021. [HTML]

369. M. M. Asad, A. Naz, P. Churi, "Virtual reality as pedagogical tool to enhance experiential learning: a systematic literature review," Education Research, vol. 2021, Wiley Online Library, 2021. wiley.com

370. P. Tynjälä, S. Beausaert, I. Zitter, "Connectivity between education and work: Theoretical models and insights," in *Education and Work*, 2021. [HTML]

371. R. Parker, B. S. Thomsen, and A. Berry, "Learning through play at school-A framework for policy and practice," Frontiers in Education, 2022. frontiersin.org

372. W. Yang, "Artificial Intelligence education for young children: Why, what, and how in curriculum design and implementation.," Comput. Educ. Artif. Intell., 2022. researchgate.net

373. M. Mlambo, C. Silén, and C. McGrath, "Lifelong learning and nurses' continuing professional development, a metasynthesis of the literature," BMC nursing, 2021. springer.com

374. M. A. Alghamdi, A. N. Fallica, N. Virzì, *et al.*, "The promise of nanotechnology in personalized medicine," *Journal of Personalized Medicine*, vol. 12, no. 5, 2022. mdpi.com

375. D. E. Uti, E. U. Alum, I. J. Atangwho, O. P. C. Ugwu, "Lipid-based nano-carriers for the delivery of anti-obesity natural compounds: advances in targeted delivery and precision therapeutics," Journal of …, 2025. springer.com

376. S. El Afia, A. Cano, P. Arévalo, and F. Jurado, "Rechargeable Li-Ion Batteries, Nanocomposite Materials and Applications," Batteries, 2024. mdpi.com

377. M. Nandipati, O. Fatoki, and S. Desai, "Bridging nanomanufacturing and artificial intelligence—a comprehensive review," Materials, 2024. mdpi.com

378. G. Zheng, B. Zhang, H. Yu, Z. Song, X. Xu, Z. Zheng, "Therapeutic applications and potential biological barriers of nano-delivery systems in common gastrointestinal disorders: a comprehensive review," in *Materials and Hybrid Materials*, 2025. springer.com

379. H. Aljibori, A. Al-Amiery, and W. N. R. Isahak, "Advancements in corrosion prevention techniques," Journal of Bio-and Tribo-Corrosion, 2024. [HTML]

380. T. J. Webster, "Nanomedicine: Technologies and applications," 2023. [HTML]

381. M. Rasool, A. Malik, S. Waquar, M. Arooj, S. Zahid, "New challenges in the use of nanomedicine in cancer therapy," Taylor & Francis, 2022. tandfonline.com

382. F. Vahedifard and K. Chakravarthy, "Nanomedicine for COVID-19: the role of nanotechnology in the treatment and diagnosis of COVID-19," Emergent materials, 2021. springer.com

383. Q. Zhao, N. Cheng, X. Sun, L. Yan, and W. Li, "The application of nanomedicine in clinical settings," *Frontiers in Bioengineering*, vol. 2023. frontiersin.org

384. X. Li, J. Qi, J. Wang, W. Hu *et al.*, "Nanoparticle technology for mRNA: Delivery strategy, clinical application and developmental landscape," Theranostics, 2024. nih.gov

385. L. Yang, L. Gong, P. Wang, X. Zhao, F. Zhao, and Z. Zhang, "Recent advances in lipid nanoparticles for delivery of mRNA," *Pharmaceutics*, vol. 14, no. 1, 2022. mdpi.com

386. W. Tao, "Nano-bio interactions in mRNA nanomedicine: Challenges and opportunities for targeted mRNA delivery," 2025. figshare.com

387. H. N. Jung, S. Y. Lee, S. Lee, H. Youn *et al.*, "Lipid nanoparticles for delivery of RNA therapeutics: Current status and the role of *in vivo* imaging," Theranostics, 2022. nih.gov

388. X. Li, X. Guo, M. Hu, R. Cai *et al.*, "Optimal delivery strategies for nanoparticle-mediated mRNA delivery," Journal of Materials Chemistry B, 2023. [HTML]

389. M. Cheng, Y. Chai, G. Rong, C. Xin, L. Gu, "Nanotechnology-based strategies for vaccine development: accelerating innovation and delivery," Biomaterials, 2025. nih.gov

390. S. Chen, X. Huang, Y. Xue, E. Álvarez-Benedicto, "Nanotechnology-based mRNA vaccines," *Nature Reviews*, 2023. google.com

391. N. Gupta, A. R. H. Fischer, I. A. van der Lans, and L. J. Frewer, "Factors influencing societal response of nanotechnology: an expert stakeholder analysis," 2012. ncbi.nlm.nih.gov

392. A. Ahmad, M. Imran, and N. Sharma, "… in drug development: current trends and challenges in safety and toxicity implications of customized multifunctional nanocarriers for drug-delivery applications," Pharmaceutics, 2022. mdpi.com

393. V. A. Tran, V. Thuan Le, V. D. Doan, and G. N. L. Vo, "Utilization of functionalized metal-organic framework nanoparticle as targeted drug delivery system for cancer therapy," Pharmaceutics, 2023. mdpi.com

394. S. Javed, B. Mangla, M. H. Sultan, Y. Almoshari, "Pharmaceutical applications of therapeutic deep eutectic systems (THEDES) in maximising drug delivery," Heliyon, 2024. cell.com

395. K. Naik, R. K. Goyal, L. Foschini, C. W. Chak, "Current status and future directions: the application of artificial intelligence/machine learning for precision medicine," Clinical..., 2024. [HTML]

396. A. Thakuria, B. Kataria, and D. Gupta, "Nanoparticle-based methodologies for targeted drug delivery—an insight," Journal of Nanoparticle Research, 2021. [HTML]

397. Y. Zhuo, Y. G. Zhao, and Y. Zhang, "Enhancing drug solubility, bioavailability, and targeted therapeutic applications through magnetic nanoparticles," Molecules, 2024. nih.gov