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Nanostructured Therapeutics in Inflammation-Associated Cancer: From Molecular Design to Clinical Potential

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ABSTRACT

Nanomaterials offer transformative potential in the treatment of inflammation and cancer—two pathologies intricately linked through shared mechanisms such as oxidative stress, cytokine dysregulation, and immune cell activation. Nanomaterials properties influence cellular uptake, immune recognition, cytokine modulation (IL-6, TNF-α), oxidative stress responses, and tissue-specific accumulation, especially within inflamed or tumor microenvironments. By leveraging properties including size, shape, surface charge, and composition, NPs can exploit the enhanced permeability and retention (EPR) effect, modulate immune responses, and deliver therapeutics with high specificity and reduced systemic toxicity. Distinctions between core composition and surface functionalization such as PEGylation and ligand conjugation (e.g. folate, anti-EGFR antibodies) are clarified, highlighting their combined roles in targeting specificity, immune evasion, and therapeutic outcomes. Size and surface charge further influence biodistribution, cellular uptake, and cytokine production, particularly IL-6 and TNF-α, which are pivotal in both chronic inflammation and tumor progression. The influence of synthesis parameters on nanoparticle behaviour in particle size, crystallinity, and surface reactivity is linked to their biomedical performance and safety profiles. Continued innovations in nanoparticle design, synthesis, and functional integration hold promise for the next generation of onco-inflammatory therapeutics.

Keywords: *Nanomaterials, Inflammation, Cancer, Immune response, Therapeutics.*

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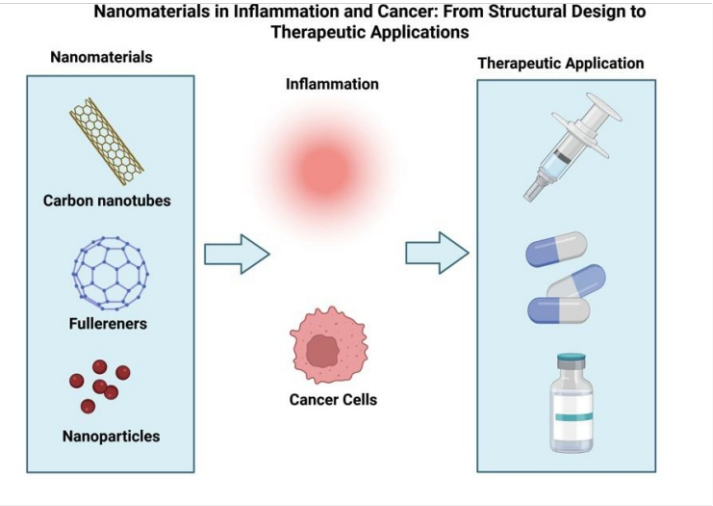

Graphical Abstract

1. Introduction

Nanoparticles, long before their modern scientific conceptualization, have played a historical role in human culture, appearing in ancient glassware, medicines, and pigments as early as the 9th century [1].

The scientific framework of nanotechnology was formally introduced by Richard Feynman in his 1959 lecture "There's Plenty of Room at the Bottom", laying the foundation for manipulating the matter at atomic scale. Since then, the field has evolved into a cornerstone of interdisciplinary innovation, particularly in medicine, energy, and materials science [2].

This review focuses specifically on the role of nanoparticles in addressing two interrelated pathological states: inflammation and cancer. Chronic inflammation is now widely recognized as a precursor to tumorigenesis, contributing to DNA damage, cytokine dysregulation, and the remodelling of the tumor microenvironment. In parallel, cancer progression itself can induce localized or systemic inflammatory responses that complicate treatment outcomes. Understanding the bidirectional interplay between these two conditions is therefore essential for designing advanced therapeutic strategies. Nanoparticles typically defined as materials with diameters between 1 and 100 nanometers exhibit distinct physicochemical properties not seen in their bulk counterparts. These include quantum confinement, high surface-area-to-volume ratios, tunable surface charge, and enhanced reactivity [3].

These features allow for targeted drug delivery, enhanced imaging, and precise modulation of cellular processes in both inflammatory and oncogenic contexts.

Depending on their structure and composition, nanoparticles engineered to selectively accumulate in the inflamed tissues or tumors via the enhanced permeability and retention (EPR) effect. Their size and surface charge influence the biodistribution and immune cell uptake is important for avoiding off-target effects and achieving sustained therapeutic action. For instance, gold nanoparticles, carbon-based nanostructures, and liposomes have all demonstrated utility in delivering anti-inflammatory agents, siRNA, or chemotherapeutics directly to disease sites. Recent advances in the field have highlighted the promise of structure-guided synthesis and surface functionalization to increase specificity and minimize toxicity. Nanoparticles can be tailored to avoid immune detection, bind to overexpressed receptors on cancer or inflammatory cells, and release their payload in response to internal stimuli such as pH or redox potential. However, their successful application also depends on addressing critical challenges such as nanoparticle aggregation, long-term toxicity, and inconsistent clinical outcomes across patient populations. Despite these limitations, the impact of nanotechnology in inflammation and cancer research is substantial and growing. This review aims to consolidate our current understanding of nanomaterial classification, structure–function relationships, and synthesis techniques, with a focus on their biological interactions and therapeutic relevance to onco-inflammatory conditions. The continued convergence of nanoscience, immunology, and oncology holds great promise for next-generation diagnostics and personalized medicine [3,4].

2. Nanoparticle Architecture in Disease Targeting

The physicochemical behaviour and functional performance of nanoparticles across several applications are largely determined by their structural composition. Most nanoparticles have a hierarchical three-layered architecture made up of the core, shell, and surface layer—each of which adds unique capabilities and tunability to the whole nanostructure (capabilities of Nanoparticles). Usually made of the main material- metallic, semiconductor, or polymeric—the core defines the basic mechanical, optical, magnetic, or electrical features of the nanoparticle. Surrounding the core is the shell, which may consist of an organic layer meant to enhance stability, lower toxicity, or add functionality or an inorganic coating (e.g., silica or alumina). Often functionalised with different ligands, metal ions, surfactants, or polymers, the surface layer creates the outermost interface and improves solubility, targeting capacity, or interaction with biological or environmental systems.

From a single component material, nanoparticles can be made; from several components, hybrid systems can be built to maximise complementary features. Depending on their composition and interfacial chemistry, nanoparticles can exist in several physical states ranging from colloidal dispersions and suspensions to aerosols. Their flexibility qualifies them very well for inclusion into dynamic situations and complicated media. Their size-dependent behaviour, which frequently differs significantly from the bulk phase, is one of the defining traits of nanoparticles. For example, copper nanoparticles under 50 nm show notable rises in hardness and mechanical stiffness, losing the ductility quality of bulk copper because of surface atom densification and changed grain boundary dynamics [4].

This phenomenon shows how nanoscale materials often take on emergent qualities that are not only scaled-down replicas of their macro-scale counterparts. Likewise, size reduction causes dramatic changes in other material systems. In magnetic nanoparticles, the transition to the superparamagnetic state happens below a crucial size barrier, at which point the material shows minimal remanent magnetisation in the absence of an external field perfect for drug targeting and biomedical imaging. Quantum dots, or semiconductor nanoparticles, exhibit quantum confinement characteristics that produce discrete energy levels and allow exact optical emission tuning depending on particle size. Metallic nanoparticles especially those made of noble metals like gold and silver show localised surface plasmon resonance (LSPR), whereby collective oscillation of conduction electrons under incident light causes strong absorption and scattering, an effect with far-reaching consequences for sensing, photothermal therapy, and catalysis [5].

Nanoparticle performance is also influenced by thermodynamic considerations connected to surface energy in addition to quantum and electromagnetic effects. Increased surface free energy produced by the high surface area-to-volume ratio, a characteristic of nanostructures, improves diffusion kinetics at increasing temperatures. This is especially useful in sintering operations as, at lower temperatures than their larger counterparts, nanoparticles can merge. On the other hand, higher mobility might cause unintentional agglomeration in which particles group under van der Waals forces or capillary contacts, hence possibly compromising the homogeneity or functional accessibility of the system. A particularly interesting use of these nanoscale phenomena is in photovoltaics, where nanoparticles have been demonstrated to improve light absorption well beyond that of continuous thin films. Their nanoscale structure allows better interaction with solar radiation by means of several mechanisms LSPR, quantum confinement, and light scattering, which results in improved energy conversion efficiencies in next-generation solar cells. Their adjustable absorption spectra and compatibility with flexible substrates also help them to be fundamental components in new wearable and transparent solar technologies [6].

Though considered together, the structural design of nanoparticles from the molecular architecture of their core to the functionalisation of their surfaces provides a strong toolset for customising performance at the atomic level. Not just for maximising nanoparticle efficacy throughout scientific fields but also for minimising issues connected to stability, toxicity, and reproducibility by means of knowledge and control of these structural components. Precision engineering of nanostructures will be crucial as the sector develops to release their full potential in medicine, energy, and beyond.

3. Nano-Dimensions in Onco-Inflammation

A basic concept underlying the physical behaviour and practical use of nanomaterials is their classification depending on spatial dimensions. At the nanoscale, spatial confinement not only modifies electronic structures and surface reactivity but also governs phenomena like as photonic absorption, mechanical strength, and quantum behavior. A growing body of research backs the link between dimensionality and photo response behaviour; for example, two-dimensional (2D) nanomaterials show far stronger and broader optical absorption across the 300–20,000 nm wavelength range when compared to one-dimensional (1D) nanofibers and zero-dimensional (0D) nanoparticles [6].

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Such differences show how dimensional classification is not only geometric but also fundamental to material performance.

Typically, under 100 nm in each axis, 0D nanomaterials are trapped inside all three spatial dimensions (x, y, z) at the nanoscale. Lacking long structural axes, these materials are usually spherical or quasi-spherical in form. Notable instances are inorganic quantum dots, polymer dots, magnetic nanoparticles, metal nanoparticles, fullerenes, carbon quantum dots, graphene quantum dots [7]. These nanostructures show quantum confinement characteristics, which result in discrete energy levels and size-tunable photoluminescence. Their small size and high surface-area-to-volume ratio allow significant interactions with biological and chemical surroundings, making them perfect for biosensing, fluorescence imaging, pathogen detection, drug delivery, and catalysis. Furthermore, their natural biocompatibility and durability under physiological settings qualify them as top contenders for diagnostic and therapeutic breakthroughs.

Exhibiting confinement in two dimensions, 1D nanomaterials have the third extending outside the nanometric range. Common forms are nanowires, nanotubes, nanofibers, and nanorods [8]. High aspect ratios and anisotropic physical characteristics define these structures, which allow directionally dependent electrical, thermal, and mechanical performance. Integral to next-generation optoelectronic devices, field-effect transistors, flexible electronics, and solar energy harvesting systems, their long length enables effective charge carrier transmission [9]. Their high surface-to-volume ratio significantly increases their reactivity, hence allowing effective catalysis and delicate chemical sensing. Moreover, their hollow or porous shapes can allow controlled release and drug encapsulation, hence increasing their use in environmental and biological uses.

While expanding laterally in two dimensions, 2D nanomaterials are restricted to the nanoscale in only one dimension usually thickness. Graphene, transition metal dichalcogenides (TMDs) as MoS\u2082 and WS\u2082, hexagonal boron nitride, and black phosphorus are all included in this category [10]. These atomically thin materials show remarkable mechanical strength, electrical conductivity, and optical anisotropy because of their layered crystalline structures and strong in-plane bonding. High catalytic activity and adsorption capacity are provided by the large surface area and electron confinement, which makes them interesting for energy storage, hydrogen generation, photocatalysis, and tissue engineering [11]. Their adoption into next-generation transistors, flexible devices, and sensors has been hastened by their high carrier mobility, tunability via doping or strain engineering, and compatibility with heterostructure assembly.

Unlike their lower-dimensional equivalents, 3D nanomaterials are made up of linked nanoscale components, hence creating hierarchical or porous structures rather than having any axial tiny confinement. Among the examples are nanosponges, mesoporous materials, nanocubes, dendrimers, and liposomes. These intricate structures show characteristics including multiscale porosity, recyclability, thermal and chemical resilience, and great crystallinity [12]. Their structural complexity allows multi-functionality, hence enabling them to be customised for various uses in drug encapsulation, gene delivery, pollution cleanup, tribology, biosensing, and corrosion resistance [13]. In energy sectors, 3D nanostructures act as electrode scaffolds in supercapacitors and batteries; hierarchical porosity improves ion transport and surface accessibility.

In the synthesis of functional nanomaterials, dimensional classification is not just taxonomic but rather a purposeful design parameter. Dimensional limitations govern electron mobility, phonon scattering, mechanical flexibility, and interaction with outside fields. Understanding the basic behaviour of each dimensional class becomes increasingly important as the science develops towards hybrid nanostructures, where several dimensions are combined into one system (e.g., 0D dots on 2D sheets or 1D tubes embedded in 3D matrices). Such convergence has the possibility to open new synergies in areas such quantum computing, tailored medicine, and photovoltaics.

4. Structure-Driven Nanoparticle Interactions

The physicochemical behaviour and the functional performance of nanoparticles in variety of applications are heavily influenced by their structural composition, particularly in the context of inflammation and cancer. Nanoparticles typically have a three-layered architecture core, shell, and surface layer each with distinct properties that influence their biological interactions. The core determines fundamental properties including magnetism, optical activity, and electrical conductivity, depending on whether it is metallic, polymeric, or semiconductor based. Gold and silver cores are commonly used in hyperthermia, photothermal therapy, and biosensing. The shell affects nanoparticle stability and bioavailability. Inorganic coatings can lower toxicity, whereas organic shells i.e., PEG (polyethylene glycol) increase the circulation time by bypassing the immune detection. The outer surface is frequently functionalized with antibodies, ligands, or polymers, is essential for identifying the inflamed or malignant tissue. Surface modifications of folate, transferrin, anti-EGFR antibodies allow binding to overexpressed receptors on tumour or inflammatory cells.

The increased permeability and retention (EPR) effect allows thecnanoparticles smaller than 50 nm to cross the biological barriers including the blood-brain barrier and reach inflamed tissues or tumour locations. Positively charged nanoparticles increase cellular absorption but may trigger inflammatory responses by activating TLRs on macrophages, leading to increased cytokine production (IL-6, TNF-α). Quantum dots have controllable photoluminescence due to quantum confinement, making them helpful for tumour imaging. Metallic nanoparticles exhibit localised surface plasmon resonance (LSPR), which enhances light scattering and allows for real-time imaging or photothermal ablation of tumour cells. Structure-induced toxicity is a serious issue. High-aspect ratio nanomaterials, such as carbon nanotubes, have been associated to lung inflammation. Nanoparticle aggregation caused by van der Waals forces can result in embolisms or impede distribution in cancer therapy. Surface energy and particle form also influence systemic reactivity, necessitating careful engineering to limit adverse effects.

5. Nanomaterial Dimensions in Cancer and Inflammation

Nanomaterials are classed according to their dimensionality, which governs their surface-to-volume ratio, biological interactions, and therapeutic potential. The physical and functional properties of nanoparticles differ dramatically across 0D, 1D, 2D, and 3D configurations. Dimensionality affects biodistribution, immunological recognition, and cellular absorption. Due of their small size, 0D particles can easily bypass endothelial barriers and concentrate at tumour locations via the EPR effect. In contrast, 2D sheets engage with

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immune cells such as macrophages for extended periods of time, allowing them to modulate chronic inflammation through prolonged contact.

Biomaterial Composition and Disease Modulation:

The material composition of nanoparticles has a fundamental impact on their immunological compatibility, therapeutic potential, and degradation profile in disease micro environments.

- Metal-based nanoparticles (gold, silver): These produce ROS to aid in tumour ablation or imaging, but they may also worsen inflammation. Gold nanoparticles improve photothermal therapy [14] whereas silver nanoparticles are effective antimicrobials but can stimulate pro-inflammatory pathways.
- Polymeric nanoparticles (PLGA, PEG-PLA) provide for regulated release of anti-inflammatory or chemotherapeutic medicines. Their degradability can be adjusted to chronic inflammatory diseases or solid tumours.
- Lipid-based carriers (liposomes) mimic cell membranes, reducing immune clearance and allowing siRNA delivery to tumour cells. Currently approved in formulations for breast and brain cancers.
- Carbon-based nanomaterials (fullerenes, graphene): Offer excellent photothermal conversion but may cause oxidative stress unless properly functionalised.
- Composition versus Surface Functionalisation: While core composition (gold vs. silica) dictates features like as conductivity and stability, surface coatings (PEG, antibodies, ligands) influence immunological recognition, inflammatory activation, and targeting accuracy.

7. Tailored Synthesis for Disease Targeting

The synthesis technique has a substantial impact on the nanoparticle's size, surface properties, and function, especially for inflammation-sensitive and oncological applications.

- **Size and Shape:** Smaller particles (<100 nm) increase tumour penetration. Rod-like Structures facilitate cellular uptake and directed targeting.
- Surface Charge: Cationic surfaces promote absorption but can cause inflammation through cytokine release. Neutral or zwitterionic surfaces reduce immune detection.
- Crystallinity and morphology affect ROS production and cellular stress responses. The differences between amorphous and crystalline forms have an impact on degradation and therapeutic consistency.
- Green Synthesis: Eco-friendly methods involving plants (Curcuma longa) or bacteria provide safer nanoparticles [15] Silver nanoparticles derived from turmeric extracts have been proven to reduce pro-inflammatory cytokines *in vitro*. Gold nanoparticles produced through citrate reduction are used in tumour photothermal treatment. Zinc oxide nanoparticles produced using green synthesis: Trigger ROS-mediated cancer cell death; if uncoated, may cause inflammation.

8. Nanomaterials in Onco-inflammatory Therapeutics

Nanoparticles have dual effects, regulating inflammation and targeting cancer. This dual therapeutic axis relies heavily on oxidative stress, cytokine signalling, and immune cell interactions. Metallic nanoparticles (Au, Ag, Cu) [16] neutralise ROS, lowering the oxidative stress associated with cancer and chronic inflammation.

Their nanozyme-like activity benefits inflammatory bowel illness, rheumatoid arthritis, and neuroinflammation. Nanoparticles improve the targeted administration of chemotherapeutics, siRNAs, and immunomodulators. They contribute to the elimination of medication resistance and the enhancement of tumour specificity. Liposomes, micelles, and gold nanoparticles have FDA-approved and clinical-stage applications. The tumour microenvironment (TME) is characterised by hypoxia, acidic pH, and aberrant vasculature, all of which nanoparticles can exploit for targeted action. When inflammation persists, it promotes TME and tumour growth. Modulating inflammatory cytokines (IL-6, IL-1β, TNF-α) with customised nanoparticles is now a key approach in onco-immunotherapy (Figure-1).

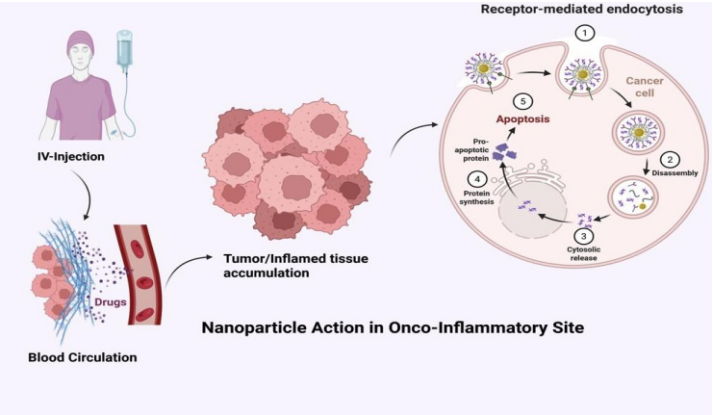

Figure 1: Nanoparticle action in Onco-inflammatory Site

Nanomaterials can be customised structurally, dimensionally, compositionally, and synthetically, opening new possibilities for fighting inflammation and cancer. Nanoparticles act at the intersection of diagnostics and therapies, providing ROS scavenging capabilities as well as EPR-enhanced tumour targeting and cytokine regulation. While their translational potential is clear, structure-related toxicity, immunological activation, and heterogeneity in biodistribution remain major issues. Integrating green synthesis and adaptive design methodologies may help to overcome these limitations, paving the path for next-generation onco-inflammatory nanomedicine.

9. Compositional Diversity of Nanomaterials

Nanoparticles may be small but there are a plethora of categories and types that they can fit in. When we fit the nanoparticles into these categories, we can focus on their specialties respectively. For example, organic nanoparticles have different advantages and material composition compared to carbon-based nanoparticles. Categorization helps focus our interests and utilize each type's advantages.

Organic-based nanomaterials are composed of organic materials excluding carbon materials. [17] Organic materials include proteins, carbohydrates, lipids, and polymers. Nanoparticles within this category tend to be bio-degradable and non-toxic. For instance: dendrimers, micelle, and liposome nanoparticles fit into this category. Dendrimers follow the standard nanoparticle structure with a symmetric core, inner shell, and outer shell. This nanoparticle has a unique branch-like design with a hollow cavity inside. This hollow cavity can serve as a holding system for drugs, imaging systems, genes, etc. Dendrimer application beyond theory is available in the commercial world. The most common dendrimer-based application is in HIV medication.

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The product, a topical microbicide called VivaGel, prevents infection by HIV and other STDs. The microbicide was the first dendrimer-based pharmaceutical to be allowed to proceed into the clinical trials by Food and Drug Administration. (Halford) Succeeding this drug there remains ImDendrim for liver cancer, DEP ® docetaxel and DEP ® cabazitaxel for breast cancer, and OP-101 for X-linked adrenoleukodystrophy [18]. Micelles have an amphiphilic structure with both hydrophilic and lipophilic properties. Micelles have hydrophilic heads that tend to mix with water and lipophilic tails that work well with lipids. The lipophilic tails are also hydrophobic. Hydrophobic structures don't mix well with water. Lipophilic tails are good carrying agents for hydrophobic medicine. The organic material that micelles are made of is lipids. Micelles have two unique advantages. Their relatively small size (<50 nm) and their feasibility in large-scale manufacturing improve their in vivo performance of encapsulated drugs Micellar nanoparticles are not only functional in theory but have been in pharmaceuticals. For example, in Estrasorb, an estrogen replacement therapy, MNP (Micellar nanoparticle) technology has been applied with 17b-estradiol (a hormone that can treat symptoms caused by menopause or removal of the ovaries).

The organic materials that Liposomes are made of are lipids and phospholipids. Liposomes have the same building blocks as micelles, but a key distinction is that Liposomes have a bilayer of hydrophilic heads and hydrophobic tails. Where micelles have hydrophobic tails inside and hydrophilic heads outside, liposomes have hydrophilic heads facing inward and hydrophilic heads facing outwards. Liposomes are non-toxic, flexible, biocompatible, completely biodegradable, non-immunogenic for systemic and non-systemic administrations, but their production is costlier, and their half-life is shorter. Due to these advantages, liposomes are currently being developed to pass the blood-brain barrier to reach human glioma (a type of brain tumor originating from glial cells).

Inorganic nanoparticles are not composed of organic or carbon-based components. Inorganic nanoparticles include metal, metal-oxide, semiconductor, and ceramic NPs. Inorganic nanoparticles are generally more stable than organic nanoparticles [19]. Because of their superior light scattering and absorption capabilities, inorganic nanoparticles have the potential to aid in cancer diagnosis and treatment [20]. Metal nanoparticles are inorganic nanomaterials made up of a single element [21]. Metal materials commonly utilised in nanoparticle synthesis include copper, gold, iron, and silver. Metal nanoparticles offer outstanding ultraviolet-visible sensitivity and antibacterial characteristics due to quantum effects and a high surface-to-volume ratio. Metal nanoparticles have also been reported to be beneficial in enhancing targeting, gene silencing, and drug delivery for cancer treatment [20]. Gold nanoparticles are metal nanoparticles with a dielectric nucleus covered by a variable layer of gold. Gold nanoparticles are used in a variety of fields. Unlike some of the other nanoparticles, its applications don't have a relative group they belong to.

Gold nanoparticles are used for a variety of applications, including home pregnancy testing and pollution prevention [22]. They are also utilised extensively in plant green synthesis. Silver nanoparticles are microscopic silver particles ranging in length from 10 to 30 nm (4000 times thinner than a human hair). They are commonly spherical or elliptical in shape, but cubes and diamonds are also feasible. Silver nanoparticle uses are mostly limited to biomedicine, although this does not indicate that they do not exist in other fields. One application is bacterial growth control [23].

Because silver ions and silver-based compounds are extremely poisonous to microorganisms, silver nanoparticles have been employed to inhibit bacterial development in dental procedures, surgery, wound and burn treatment, and biomedical equipment [24]. Copper nanoparticles (CuNPs) have high antibacterial and antimicrobial activity. Beyond this, copper nanoparticles can catalyse redox processes, making them useful in bioremediation. CuNPs can remove heavy elements such as arsenic from wastewater [25]. Iron (Fe) nanoparticles, also known as nanodots or nanopowder, are spherical or faceted metal nanostructured particles with a high surface area.

Iron nanoparticles (FeNPs) exhibit an outstanding magnetic property, a large surface area, electrical and thermal conductivity, and dimensional stability. Because of these properties, FeNPs are known as magnetic nanoparticles. Magnetic nanoparticles find many applications in spintronics, biology, and medicine [26]. Metal-oxide nanoparticles are made up of negative oxygen ions and positive metal ions. Aluminium oxide (Al2O3), silicon dioxide (SiO2), titanium oxide (TiO2), and zinc oxide (ZnO) are some metal-oxide nanoparticles that are routinely synthesised. Metal-oxide nanoparticles have optical features such as photoluminescence, UV and colour absorption within the visible region dichroism [27]. Ceramic nanoparticles made of carbides, carbonates, oxides, carbides, carbonates, and phosphates synthesised by heating and cooling immediately [28]. Ceramic nanoparticles have been employed for a variety of applications, including medication delivery, (photo)catalysis, wound healing, and bioimaging [29]. Semiconductor materials have conductivity that falls between that of conductors (such as metals) and nonconductors/insulators. Semiconductor nanomaterials are semiconductor materials at the nanoscale. Semiconductor nanoparticles, also known as quantum dots (QDs), have demonstrated a highly beneficial feature for biolabeling DNA, proteins, and cells. This nanomaterial is still in the experimental phase, but the prospects appear promising. They have proven beneficial due to their configurable emission spectra, strong photostability, resistance to photobleaching, and customisable surface properties.

Carbon-based NPs, as the name implies, are made up of carbon atoms. Carbon quantum dots, fullerenes, and carbon black nanoparticles are all examples of basic carbon-based nanomaterials. Carbon-based nanoparticles are widely employed for energy storage, photovoltaic devices, medication administration, bioimaging, and environmental sensing to monitor microbial ecology and detect diseases due to their high electrical conductivity [19]. Nanodiamonds and carbon nano-onions are examples of more complicated carbon-based NPs. Fullerenes, also known as carbon nanotubes, have a cage-like structure consisting of 60 carbon atoms arranged in 12 pentagons and 20 hexagons. Their functions are predominantly found in nanotechnology rather than nanomedicine. They can be utilised as transistors, batteries, energy storage devices, sensors, and even medicinal equipment. Carbon black nanoparticles are formed up of agglomerates, which are aggregation of primary particles [30,31,32]. Carbon black nanoparticles: agglomerates, aggregates, main particles] Carbon black NPs are often used to create nanopowder. Nanopowder is widely utilised in electronics, renewable polymers, coatings, inks, and other green technologies. Carbon quantum dots are spherical particles that are affordable, low toxicity, biocompatible, chemically inert, and have good photostability [33,34].

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Carbon quantum dots are utilised in biomedicine as drug transporters, photosensitisers in photodynamic treatment to destroy cancer cells, and as antimicrobial-resistant infections [35]. Nano-diamonds are composed of a diamond core with amorphous carbon surrounding layers. This nanoparticle is considered a more complicated carbon-based NP, hence it is less prevalent than other carbon nanoparticles.

Nano-diamonds can be used to replace semiconductor quantum dots in biological imaging applications [36, 37,38]. They can also serve as magnetic sensors, composites, biomolecules and medicines, and surface chemistries. Carbon nano-onions are nanostructures made up of concentric shells of fullerenes. It is a nanoparticle composed of another nanoparticle, which explains why it is more complicated than other carbon-based nanoparticles. Carbon nano-onions are fullerene layers organised in an onion design [39,40]. Their high biocompatibility and biosafety make them an appealing alternative in a variety of applications, including biological systems. This nanomaterial is low in toxicity, has a high dispersion in aqueous solutions after surface functionalisation, and has good medicinal efficiency.

Composite nanomaterials are a kind of hybrid material that combines different nanostructures whether organic-organic, organic-inorganic, or inorganic-inorganic—to exploit their complementing qualities. Composites provide synergistic effects that enable the exact tuning of mechanical, electrical, optical, and chemical behaviours by combining several material kinds, thereby extending their use across a spectrum of sectors, from biomedicine to energy storage [41]. These hybrid materials provide improved capability that individual components could lack in isolation, therefore enabling adaptable and multifunctional systems that can be customised to fit certain technical requirements. Composite nanomaterials' adaptability is their capacity to surpass the limits of single-component materials [42]. For example, whereas inorganic-organic pairings usually enhance biocompatibility and drug delivery effectiveness, the resulting composites can find a balance between flexibility and durability by combining organic polymers with inorganic nanoparticles. The modification of interfacial characteristics in these systems enables further fine-tune drug release patterns, targeting specificity, and biological interactions [43].

10. Mechanical Uptake and Drug Delivery

The mechanical absorption of nanoparticles (NPs) into cells is a complex process shaped by several variables, including the physicochemical characteristics of the nanoparticles, the biological milieu, and the processes of cellular uptake (Figure-2). Nanoparticles could enter cells by means of phagocytosis, micropinocytosis, endocytosis, direct diffusion, or sticky contacts. While micropinocytosis refers to the absorption of tiny amounts of extracellular fluid containing solutes, phagocytosis usually involves the uptake of bigger particles, such as dead cells or pathogens. Too big to diffuse across the plasma membrane, nanoparticles are mostly internalised by endocytosis, which can happen via clathrin-mediated, caveolin-mediated, or macropinocytosis routes [44]. The absorption efficiency and intracellular localisation are mostly influenced by physicochemical properties of nanoparticles including size, shape, surface charge, and chemical functionalisation. Smaller nanoparticles usually in the range of 10-100 nm—are more easily internalised than larger particles. Furthermore, receptor-mediated endocytosis can be improved by nanoparticles with surface modifications such PEGylation or targeting ligands.

Foundational in the design of nanomedicines for targeted drug delivery systems, this mechanistic knowledge allows for the engineering of nanoparticles to transport therapeutic agents directly to sick tissues, therefore reducing side effects and enhancing treatment effectiveness [45].

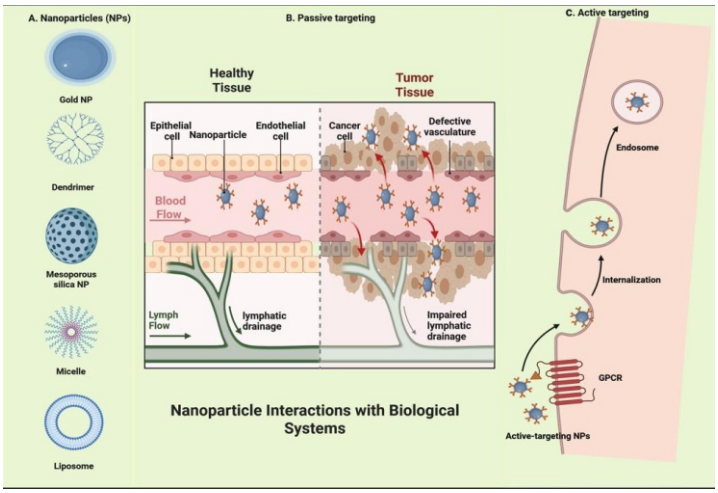

Figure 2: Nanoparticle Interaction with Biological Systems

11. Antioxidant Properties of Nanoparticles

Particularly those constructed from metallic nanoparticles (NPs), which have attracted great interest for their capacity to scavenge reactive oxygen species (ROS) and reduce oxidative stress, nanoparticles show extraordinary antioxidant qualities. Oxidative damage caused by an overproduction of ROS and free radicals is linked to a great variety of diseases, including cancer, neurological disorders, and cardiovascular conditions [46]. Metallic nanoparticles, including gold, silver, and copper oxide NPs, have the capacity to mimic enzyme-like behaviour, especially their capacity to neutralise free radicals, which makes them strong candidates for therapeutic antioxidant uses [47,48]. Many times, the mechanism of antioxidant effect in nanoparticles is ascribed to the creation of surface-active sites interacting with ROS, hence lowering their concentrations. In drug delivery systems, where nanoparticles can shield delicate therapeutic compounds from oxidative destruction, therefore enhancing their stability and bioavailability, this can be especially useful. A rising field of study is the combination of nanoparticles with other antioxidant compounds or biomolecules, which could be used in anti-aging therapies, cosmetic formulations, and neuroprotective treatments [49].

12. Antimicrobial Properties of Nanoparticles

Through many mechanisms including direct physical interactions with microbial cell membranes, the production of reactive oxygen species (ROS), and nano-biofilm disruption—nanoparticles show considerable antibacterial effect. Renowned for their inherent antibacterial, antifungal, and antiviral qualities are metallic nanoparticles, especially silver (Ag) [50,51,52]. copper (Cu), and titanium dioxide (TiO2). Usually, the antibacterial effect of these nanoparticles is ascribed to their capacity to disrupt microbial cell membrane integrity, disturb intracellular processes, and cause oxidative stress in microbial cells [53,54]. The antibacterial efficacy of nanoparticles depends significantly on their surface chemistry. For example, the surface charge, shape, and functionalisation of nanoparticles affect their capacity to attach to and penetrate bacterial cells. The synergistic effects of nanoparticles in combination with traditional antibiotics also provide interesting possibilities for the creation of antibiotic-free

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treatments that could assist fight the rising danger of antimicrobial resistance (AMR). This has generated interest in nanoparticle-based biocidal coatings, wound dressings, and antiseptic compositions for industrial, agricultural, and medical uses [55,56].

13. Nanoparticles in Cancer Therapy

In cancer treatment, nanotechnology is revolutionary since it provides creative solutions to several problems related to traditional treatment methods, including low selectivity, toxicity, and drug resistance [57]. Through passive targeting (increased permeability and retention effect, EPR) or active targeting (via surface modification with ligands particular to tumour biomarkers), nanoparticles can be created to specifically target tumour cells. Nanoparticles' size and surface characteristics let them gather in tumour tissues more effectively than larger therapeutic molecules [58,59]. Nanoparticles—including liposomes, micelles, and gold nanoparticles—can enclose therapeutic compounds like small interfering RNAs (siRNAs), radionuclides, or chemotherapy medicines, hence improving their bioavailability and therapeutic index. Moreover, the multifunctionality of nanoparticles makes multimodal therapy possible, including medication delivery, thermal ablation, photodynamic therapy, and radiotherapy, thereby providing a synergistic approach to cancer therapy. A major benefit of nanoparticles in enhancing treatment results is their capacity to circumvent drug resistance mechanisms like p-glycoprotein overexpression [60,61,62]. Tumour detection, treatment efficacy monitoring, and real-time visualisation of medication release and distribution can also be accomplished using nanoparticle-based imaging methods including magnetic resonance imaging (MRI) and fluorescence imaging. Research is revealing the combination of nanoparticles with immunotherapy—such as checkpoint inhibitors and immune checkpoint-targeted delivery systems as a potential way to improve anti-tumor immune response [63].

14. Global Market and Future of Nanomaterials

Spanning several sectors including medical, electronics, agriculture, and environmental cleanup, nanotechnology has shown to be a disruptive force. In the medical sector, nanoparticles are particularly important for immunotherapy, diagnostics, cancer treatment, and targeted medication delivery [64]. Nanoparticles in materials science help to create lightweight, high-strength, high-conductivity materials for engineering, textiles, and electronic applications. Moreover, in environmental remediation, they are used for water purification, air filtration, and the elimination of pollutants; in agriculture, nanoparticles are being used to improve crop protection, fertiliser efficiency, and animal health. With a projected development from USD 68.0 billion in 2023 to USD 183.7 billion by 2028, the worldwide nanotechnology industry is set for notable expansion, showing a compound annual growth rate (CAGR) of 22.0. Rising use of nanoparticles in many industries and growing research initiatives aimed at optimising nanoparticle design and manufacturing techniques fuel this increase. Innovations in nanomedicine, nanoelectronics, and sustainable nanomaterials are anticipated to transform sectors and enhance quality of life all around as nanotechnology progresses. Furthermore, guaranteeing the safe and responsible incorporation of nanoparticles into society will depend on ongoing study on eco-friendly synthesis techniques and the legal framework for nanoparticle use [65].

15. Future Perspectives

The fast growth of nanomaterials and nanotechnology continues to push the boundaries of biomedical science, diagnostics, and therapy delivery. While the current landscape has produced encouraging clinical and preclinical results, several critical areas must be explored to fully realise nanotechnology's transformative potential across disciplines. First, nanoparticle precision engineering, which includes fine-tuning physicochemical properties such as size, shape, surface charge, and functionalisation, remains a critical step towards boosting biological selectivity, minimising off-target effects, and optimising pharmacokinetics [66]. The combination of machine learning and nanoscale design holds promise for predictive modelling and personalised nanoplatforms adapted to disease-specific requirements. Second, the combination of nanomaterials with immunotherapeutic and gene-editing technologies (e.g., CRISPR-Cas systems) represents a next-generation strategy to treating complicated diseases such as resistant cancer and genetic disorders. However, there are significant obstacles to attaining targeted intracellular distribution and long-term biocompatibility. Third, scaling up green synthesis methodologies is critical for developing environmentally sustainable and economically feasible manufacturing pipelines [67].

The creation of biodegradable, biosafe, and regulatory-compliant nanomaterials will be critical for clinical translation. In parallel, the toxicological and regulatory landscapes must change. Systematic and longitudinal investigations are required to evaluate the chronic exposure, biodistribution, and immunological effects of different nanomaterials. Regulatory frameworks must change to accommodate nanosystem's complicated behaviour in biological contexts. Finally, global market expansion and equal access will determine nanotechnology's societal influence. Strategic public-private partnerships, multinational research collaborations, and open-access innovation ecosystems will speed up the translation of laboratory breakthroughs into accessible, scalable, and cost-effective real-world solutions [68]. In essence, the future of nanomaterials is determined not only by their molecular architecture, but also by the ethical, ecological, and translational frameworks that enable their use. Nanotechnology, with its interdisciplinary synergy and dedication to responsible innovation, is set to play a critical role in creating the next era of scientific discovery and human health [69].

16. Conclusion

Nanomaterials can be customised structurally, dimensionally, compositionally, and synthetically, opening new possibilities for fighting inflammation and cancer. Nanoparticles act at the intersection of diagnostics and therapies, providing ROS scavenging capabilities as well as EPR-enhanced tumour targeting and cytokine regulation. While their translational potential is clear, structure-related toxicity, immunological activation, and heterogeneity in biodistribution remain major issues. Integrating green synthesis and adaptive design methodologies may help to overcome these limitations, paving the path for next-generation onco-inflammatory nanomedicine. Despite their small size, nanomaterials represent a large and transformational field with far-reaching ramifications for science and technology. This paper has provided a thorough examination of nanoparticles' fundamental properties, including structural configurations, dimensional dimensions, and origin-based classifications.

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Furthermore, the major benefits of nanomedicine and nanomaterial applications in various industries have been explored, with a focus on their potential to revolutionise therapeutic tactics and materials science. While this overview has attempted to cover essential areas of nanomaterials. The scope of nanoscience is significantly broader, with many aspects yet to be completely investigated. The subject is evolving rapidly, with new applications, technology, and unique interactions developing on a regular basis. Notably, nanoparticles' biocompatibility, targeted drug delivery capabilities, and precision diagnostics make them an important component of future medical therapies, notably in the treatment of complicated diseases such as cancer, diabetes, and neurodegenerative disorders. However, despite their promise, there are significant unknowns about nanomaterials' long-term safety, biological interactions, and environmental implications, necessitating additional research to limit any risk. As nanotechnology improves, it has the potential to address some of today's most serious issues in healthcare, energy, and environmental sustainability. The intersection of nanoscience and transdisciplinary research provides unmatched prospects for innovation, therefore investing in this sector is not only an investment in the future of medical and technological achievements, but also a step towards influencing the next era of scientific discovery. As a result, education and collaborative research in nanoscience remain critical to realising its full potential, guaranteeing responsible development, and realising transformational capabilities across global industries. This version improves the material by focussing on the growing frontiers of nanoscience, future applications, and the crucial need for ongoing research into safety and sustainability. It is consistent with the style and tone of Nature journals, which address both the potential and ongoing challenges of emerging technologies. Please let me know if you require any other revisions.

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Authorship Statement

Daksha Karthikeyan: Data curation, Methodology, Original draft preparation. Rashmi R.R: Data curation, Writing- Reviewing. Suganya Kanakgaraj: Visualization, Original draft preparation. Sakthivel. K.M: Figures, Writing- Reviewing and Editing. Soundarya. S: Resources; Software. Ranjith Santhosh Kumar. D.S: Software, Validation. Mythili Saravanan: Conceptualization, Formal analysis, Methodology, Writing- Reviewing and Editing.

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