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Rethinking Nanomedicine: The Promise of Biodegradable Nanoparticles

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Nanotechnology is the science of manipulating matter at the atomic and molecular level and has garnered significant attention since the late 20th century. The term was coined by Nobel laureate Richard Feynman in his seminal 1959 lecture, "There's Plenty of Room at the Bottom." Since then, this field has witnessed remarkable advancements revolutionizing various industries. Nanotechnology has the potential to revolutionize various fields from medicine and electronics to environmental science and materials engineering. It is estimated that the global market for nanoparticles in cosmetic industry alone is worth billions of dollars annually. As research continues to advance, we can anticipate ground-breaking innovations in the years to come.

Nanoparticles (NP) are engineered materials with at least one dimension measuring between 10 and 100 nanometers. Their unique properties enable them to interact with biological systems on a molecular level making them valuable for a wide range of applications. Nanoparticles can be broadly classified into two categories as organic and inorganic. Organic nanoparticles such as nanopolymers often exhibit complex structures including nanospheres, capsules, micelles and dendrimers. Inorganic nanoparticles on the other hand are composed of elemental or compound substances such as metals, non-metals, their oxides or quantum dots. A key advantage of nanoparticles is their exceptionally high surface area-to-volume ratio which significantly amplifies their efficacy compared to larger molecules. This unique property enables nanoparticles to interact more efficiently with biological systems facilitating applications such as drug delivery, imaging, and diagnostics. Nanoparticles are renowned for their exceptional properties and have emerged as indispensable tools in biomedical research. Their unique characteristics including catalytic, magnetic, optical, steric, mechanical, biological and electrical attributes have been harnessed to address a wide range of challenges.

Several physical, chemical and biological methods have been implemented to synthesize nanomaterials. In order to control the shape and size of NPs, specific methodologies have been adopted such as ultraviolet irradiation, aerosol technologies, lithography, sonochemistry, hydrothermal and photochemical reduction techniques have been utilized successfully to produce nanoscale materials and they remain expensive and involve the use of hazardous chemical reagents.

The Dynamic Nature of Nanoparticles

Nanoparticles, comprising three distinct layers offer a versatile platform for various applications.

(a) Surface layer

(b) Shell layer

(c) Inner Core

The outermost surface layer can be tailored with diverse molecules including metal ions, surfactants and polymers to enhance its properties or functions. The intermediate shell layer is chemically distinct from the core and can be utilized for specific purposes. The central inner core serves as the foundation of the nanoparticle. To ensure biocompatibility and minimize adverse interactions with the host immune system, nanoparticles often undergo surface modifications. By tagging the surface layer with linker molecules, researchers can equip nanoparticles with functionalities such as fluorescence, drug delivery or ligand binding. Additionally, the inner shell layer can be employed to carry molecules that are toxic to the host, but can be safely released at targeted sites.

There are many thrust areas of research in the field of nanomedicines. Repair, construction and control of biological systems using devices built upon nanotechnology standards are the recent advents. Nanoparticles enters cells through a process known as endocytosis, which is influenced by their size and surface charge. Smaller and intermediate-sized nanoparticles are typically internalized through caveolae-mediated or clathrin-dependent endocytosis, while larger particles are often taken up by cell pinocytosis. The surface charge of the nanoparticle also plays a crucial role in its cellular uptake and subsequent effects. Negatively charged nanoparticles can penetrate cells, but their toxicity is generally restricted to the cytosol due to the negatively charged nucleic acids within the nucleus.

While the size of nanoparticles can influence their toxicity, careful design and engineering can mitigate these concerns. By optimizing nanoparticle composition and surface modifications, researchers can create biocompatible materials that minimize adverse effects while maximizing therapeutic benefits. Further the toxicity of nanoparticle is dose and size dependent with their surface

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charge affinity to the biological system. Moreover, the unique size and properties of nanoparticles allow them to traverse biological barriers more effectively than traditional molecules. This enhanced permeability is crucial for targeting specific cells or tissues, enabling targeted therapies and improving therapeutic outcomes.

The indiscriminate use of nanoparticles across various industries has surged dramatically, driven by the burgeoning global market for nanotechnology products. However, this rapid proliferation raises significant concerns regarding the potential environmental and ecological consequences. Nanotoxicity can manifest through various mechanisms, including cytotoxicity, genotoxicity, oxidative stress and inflammation. Nanoparticles can pose a substantial threat to aquatic ecosystems. When released into water bodies, these particles can undergo aggregation or dissociation depending on factors such as pH and temperature. This can lead to the formation of larger particles or the release of smaller or more toxic components. The presence of nanoparticles in aquatic environments can disrupt the delicate balance of the ecosystem. These particles can be ingested by benthic organisms or accumulate on zooplankton, ultimately entering the food chain. As nanoparticles bio accumulate and bio magnify through the food web, they can pose a significant risk to human health.

These adverse effects underscore the urgent need for comprehensive research to assess the long-term environmental impacts of nanoparticle pollution and to develop strategies for mitigating these risks. Recent advancements in green chemistry have focused on developing sustainable methods for nanomaterial synthesis. Bio nanotechnology, integrating principles of biosynthesis and surface engineering has played a pivotal role in this endeavour. Biosynthesized and surface-functionalized nanomaterials are emerging as promising green products with potential applications in bio imaging, bio sensing, drug delivery, and biomedicine. However, further research is imperative to fully understand their biological interactions and potential toxicity.

Alternative Materials for Nanomedical Research

Researchers are increasingly advocating for the development of environmentally sustainable nanoparticle synthesis strategies. Microbial biotechnology offers a promising green approach, enabling the biosynthesis of various nanoscale materials including metals, alloys, semiconductors and composites. Surface functionalization, a critical aspect of nanoparticle design can significantly influence particle uptake, biological responses and bio distribution. By modifying surface properties, researchers can enhance the circulation time of nanocarriers within the bloodstream, minimize non-specific distribution and achieve targeted delivery to specific tissues or cells.

To mitigate the potential adverse effects of traditional nanoparticles in biomedical research, scientists are exploring alternative materials. Among these, organic biodegradable nanoparticles offer a promising avenue. While materials like dextran, chitosan and mannans have gained prominence in recent years, their limitations in terms of drug payload, biodegradability and long-term toxicity warrant

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further investigation. Poly (lactide-co-glycolide) (PLGA) is an FDA-approved synthetic biodegradable polymer and its NPs are attractive for tumor-targeted therapy and imaging. PLGA can be surface stabilized by polyethylene glycol (PEG) to minimize opsonisation and enhance prolongation of blood circulation and this interface can be functionalized with a variety of biological agents for tumor-specific targeting. Chitosan and heparin-functionalized surfaces of PLGA NPs provided a suitable environment for cell membrane adsorption and improved the desired cellular uptake for effective tumor accumulation.

Lipid-based nanoparticles represent another promising class of nanomaterials. These particles have demonstrated significant potential for targeted drug delivery and the controlled release of biomolecules such as proteins and nucleic acids. By carefully selecting and optimizing these alternative materials, researchers aim to develop safer and more effective nanotechnology-based solutions for biomedical applications.

To address the environmental challenges associated with traditional nanotechnology, green nanotechnology has emerged as a sustainable approach. This paradigm emphasizes the utilization of environmentally friendly materials and processes to minimize adverse effects. One key strategy within green nanotechnology is the development of functionalized mesoporous nanomaterials. These materials offer enhanced properties such as increased surface area and controlled release of encapsulated substances making them ideal for applications like drug delivery and catalysis.

Conclusion

While biologically synthesized nanoparticles may currently exhibit certain limitations such as stability, size distribution, synthesis rate and standardization, their long-term potential advantages over chemically synthesized nanoparticles make them a promising avenue for future research in nanotechnology. The environmental benefits, biocompatibility and potential for unique properties offered by biologically synthesized nanoparticles position them as a valuable tool in the pursuit of sustainable and innovative nanomaterial development.

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