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NANOTECHNOLOGY STEP AHEAD ON SCIENCE

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ABSTRACT:

Nanotechnology, a field rooted in the manipulation of materials at the atomic and molecular scales, has revolutionized numerous domains including medicine, food processing, and material science. This technology, which enabled the visualization and manipulation of individual atoms, laid the groundwork for the precision control inherent in nanotechnology today. In recent decades, nanotechnology has profoundly impacted various sectors. In the food industry, it has improved food safety and quality through innovations in food packaging and processing. Nano-based materials enhance packaging strength, barrier properties, and antimicrobial capabilities, while nano-sensors advance the detection of contaminants and pathogens. In medicine, nanotechnology enables targeted drug delivery, precise control of drug properties, and advancements in tissue engineering, offering new solutions for regenerative medicine and improved implant integration. Additionally, nanomaterials have bolstered diagnostic techniques with enhanced sensitivity and specificity, revolutionizing genomics and proteomics.

This review paper tells about nanotechnology's diverse applications underscore its potential to drive innovation and address complex challenges in both industrial and biomedical contexts, promising sustainable and impactful solutions across various sectors.

1. INTRODUCTION:

Nano science involves the manipulation of materials, systems, and devices at atomic, molecular, and macromolecular levels, whereas nanotechnology encompasses techniques for designing, synthesizing, characterizing, and applying structures, materials, devices, and systems by manipulating their shape and size at the nanometre scale. At this scale, individual molecules and their interactions become crucial compared to the macroscopic properties of the material or device. Precise control at the nanometre scale and manipulation of fundamental molecular structures allows for the regulation of the bulk macroscopic chemical and physical properties of materials and devices. Typically, dimensions are frequently less than 100 nm (1).

The concept of nanoscience was introduced by physicist Richard Feynman in 1959 during a lecture at the American Physical Society. Nanotechnology, on the other hand, was first termed by Norio Taniguchi in 1974, describing the increasing precision in dimensional accuracy over time. Taniguchi foresaw dimensional accuracies better than 100 nm by the late 1980s, coining the term nanotechnology for these future advancements. Initially, physicists and engineers pioneered nanotechnology by realizing Feynman's ideas, which predicted technologies capable of manipulating atoms to create new chemical analogues.

In 1981, two scientists in Zurich developed the scanning probe microscope, which won the Nobel Prize in 1986. This microscope uses a sharp metal tip to scan surfaces and visualize individual atoms. Building upon this technology, Eigler and his team explored physical and quantum mechanical phenomena. In 1989, they famously used the scanning probe microscope to spell "IBM" using xenon atoms on a surface near absolute zero temperature. Meanwhile, Gimzewski advanced nanotechnology further by manipulating single molecules on surfaces at room temperature using similar scanning probe technology, pioneering extreme nanotechnology.

2. ADVANCEMENT IN NANOTECHNOLOGY:

Nanotechnology has been extensively utilized across various fields, benefiting from advancements in materials science, chemistry, and engineering in recent decades. It plays a critical role in determining fundamental properties in fields ranging from physics, engineering, and chemistry to biology and medicine. For instance, nanoparticles of cadmium telluride are utilized with precision in labelling biological molecules. Titanium dioxide nanoparticles effectively block UV radiation and are a key component of sunscreens (2).

In 1985, Harry Kroto, Richard Smalley, and Robert Curl discovered the carbon-60 molecule, earning them the Nobel Prize in 1996. Subsequently, in 1991, carbon nanotubes were discovered by Iijima. A type of nanotechnology known as "bottom-up nanotechnology" leverages the self-assembling properties observed in biological systems, such as DNA molecules, to control the organization and structure of carbon nanotubes (3).

- **NANOTECHNOLOGY IN FOOD PROCESSING:**

Nanotechnology has been increasingly integrated into the food industry over the past decades to enhance the quality, taste, and texture of foods, as well as to protect them from pathogen infestations. It is employed to extend the shelf life and improve the storage conditions of food materials by preventing microbial infestations. Nano-carriers are now utilized as delivery systems for food additives, maintaining the basic morphology of food intact.

In nutraceuticals, nano-carriers are considered ideal delivery systems for precisely distributing active compounds at specific rates to target locations. The development of nano-polymers has made nanotechnology an integral part of food processing and food packaging. Additionally, nano-sensors have been developed to detect contaminants, pathogens, and toxic materials in food products (4).

- **NANOTECHNOLOGY AND FOOD PACKAGING:**

Nano-based food packaging offers several advantages over traditional methods due to its enhanced mechanical strength, improved barrier properties against gas and moisture permeability, and antimicrobial capabilities for pathogen detection. Nanocomposites play a crucial role in enhancing food packaging materials. Organic compounds such as essential oils, organic acids, and bacteriocins are incorporated into polymeric matrices as antimicrobial agents, although they are sensitive to environmental conditions.

Inorganic nanoparticles, with their potential antibacterial activity even at low concentrations, are increasingly used in antimicrobial food packaging. This type of packaging effectively inhibits the growth of microbes that may be present on food surfaces. Metals such as silver and copper, along with chitosan-based nanoparticles and metal oxide nanoparticles, are known for their antibacterial properties and are utilized in food packaging materials (5).

Nanocomposites and nanolaminates provide effective barriers against extreme thermal and mechanical shocks, thereby extending the shelf life of food products. By incorporating nanoparticles into polymers, manufacturers can create packaging that is more resistant and durable at a minimal cost. Fillers such as silicate, silica ($SiO2$) nanoparticles, and chitosan strengthen polymer matrices, providing improved fire resistance and thermal properties (6).

Antimicrobial films are created by embedding fillers in polymers, offering additional benefits such as structural integrity and enhanced barrier properties. This approach ensures that food remains safe and of high quality for longer periods.

- **NANOPARTICLES AS NANO SENSORS:**

Nanomaterials provide high sensitivity in food microbiology. Nano-biosensors have been developed to detect microbes during food processing, in plants, and for quantifying food ingredients, alerting both consumers and suppliers to food safety concerns. They also serve as indicators that respond to environmental changes such as microbial contamination in storage areas and product degradation. Various nanoparticles and nanofibers show promising applications as biosensors.

Optical immunosensors employ sophisticated detection systems. These sensors use thin nano-films or sensor chips loaded with specific antibodies, antigens, or protein molecules to generate signals upon detecting target molecules. For instance, an immunosensor has been developed to detect foodborne pathogens like E. coli, utilizing dimethyl siloxane integrated with specialized antibodies immobilized on nanoporous alumina membranes, which produce electrochemical impedance spectra upon pathogen detection.

Nanotechnology has significantly advanced detection techniques for pesticides, pathogens, and toxins. Biosensors based on carbon nanotubes are particularly popular due to their rapid response, simplicity, and cost-effectiveness in detecting microbes, waterborne toxins, and contaminants in food and beverages. Additionally, modified quartz crystal surfaces are used to detect small molecules by incorporating different functional groups such as amines, lipids, enzymes, and polymers.

- **NANOMATERIALS IN MEDICINE**:

In medicine, nanomaterials are specifically designed to interact at the cellular level and engage with living cells and tissues at the molecular level. These nanomaterials and devices are crucial advancements in biomedical engineering, finding applications in medicine and physiology with high precision. They facilitate a seamless integration between technology and biological systems (8).

Manipulating drugs, active compounds, and devices at the nanoscale enables precise control and alteration of their essential properties and bioactivity. This capability allows for the control of drug solubility, controlled release mechanisms, and targeted drug delivery strategies.

- **TISSUE ENGINEERING:**

Regenerative medicine and tissue engineering have emerged as groundbreaking fields aimed at restoring and improving lost tissue functions, representing significant advancements over traditional therapeutic approaches in recent decades. These techniques hold promise in treating a wide range of conditions, from bone defects to organ failures, by harnessing the body's natural healing processes and integrating advanced technologies.

Nanotechnology plays a pivotal role in enhancing tissue engineering strategies, particularly in the development of biomedical implants like hip or knee prostheses. Unlike natural bone surfaces, which feature intricate nanostructures around 100 nm in size (9), engineered prosthetic surfaces can be designed with nano-sized features that mimic natural bone morphology. These nanostructures help reduce the risk of implant rejection by promoting better integration with surrounding tissues and stimulating the activity of osteoblasts, the bone-forming cells.

In addition to enhancing implant integration, nanotechnology enables precise control over biomaterial properties such as surface texture, mechanical strength, and biocompatibility. This control is crucial for optimizing the performance and longevity of implants in clinical settings. Furthermore, nanomaterials and nanoscale therapies are being developed to deliver therapeutic agents directly to affected tissues, promoting accelerated healing and minimizing complications.

Overall, the integration of nanotechnology into tissue engineering and regenerative medicine represents a promising frontier in medical science, offering innovative solutions to improve patient outcomes and quality of life. Continued research and development in this field hold the potential to revolutionize healthcare by providing personalized, effective treatments for complex tissue disorders and injuries.

- **MANIPULATION OF BIOMOLECULES AND CELLS:**

Magnetic nanoparticles serve various purposes, including cell separation and probing. Typically spherical, these nanoparticles can also be engineered into cylindrical shapes using metal electrodeposition onto nanoporous alumina templates. Additionally, different ligands can be selectively attached to specific segments of these nanoparticles. For example, porphyrins can be linked to nickel segments via carboxyl linkers, while thiols can adhere to gold segments.

This approach enables precise functionalization of magnetic nanoparticles, enhancing their utility in biomedical applications such as targeted drug delivery, magnetic resonance imaging (MRI), and biosensing. The ability to manipulate nanoparticle shape and surface chemistry facilitates tailored interactions with biological systems, advancing research and development in fields ranging from diagnostics to regenerative medicine.

- **PROTEIN DETECTION:**

Proteins play critical roles as essential macromolecules in the body, serving important functions. Gold nanoparticles are commonly utilized in immunohistochemistry to identify protein-protein interactions. Additionally, surface-enhanced Raman spectroscopy is employed to recognize and characterize single dye molecules. Combining these techniques into a single nanoparticle probe enhances the detection limits and multiplexing capabilities of protein probes.

This integration of gold nanoparticles with surface-enhanced Raman spectroscopy not only improves the sensitivity and specificity of protein detection but also facilitates the simultaneous analysis of multiple proteins in complex biological samples. Such advancements are pivotal in advancing our understanding of protein interactions and their implications in health and disease.

- **NANOTECHNOLOGY IN DIAGNOSTICS:**

The advancement of genomics and proteomics has revolutionized disease detection by allowing abnormalities to be identified at the molecular level. Nanotechnology has played a crucial role in enabling the estimation of gene expression and RNA production levels in both diseased and normal tissues.

DNA chips utilizing nanotechnology are extensively employed for gene expression analysis. These chips feature an inert support capable of hosting microarrays comprising hundreds to thousands of single-stranded DNA molecules with diverse base sequences (10). By using radioactive or fluorescently labelled DNA from tissue samples, researchers can pinpoint specific sequences by their binding to complementary sequences on the chip DNA. Moreover, the sequencing of DNA molecules can be achieved by threading them through nanopores in a membrane under the influence of an electric potential difference.

This integration of nanotechnology in genomics not only enhances the accuracy and efficiency of gene expression profiling but also facilitates rapid and precise sequencing of DNA, contributing significantly to advancements in personalized medicine and biomedical research.

- **DISINFECTION:**

Silver has long been recognized for its role as a disinfectant, and its use has been revitalized due to bacterial resistance against other agents. The antiseptic effect of silver ions is well-established, as they inhibit essential enzymes involved in oxygen metabolism. Additionally, silver ions disrupt bacterial cell membranes and impede cell division. The diverse mechanisms of action make it difficult for bacteria to develop resistance against silver.

Silver nanoparticles are particularly effective due to their large surface area, which enhances interaction with the environment. They can easily bind with proteins and polymers, acting as reservoirs that continuously release silver ions. Furthermore, titanium dioxide nanoparticles exhibit bactericidal properties. When exposed to UV radiation in the presence of water and oxygen molecules, these nanoparticles generate free hydroxyl and per hydroxyl radicals, effectively killing microorganisms. They are used to create antiseptic surfaces that are activated under UV radiation.
Fullerenes also demonstrate antimicrobial effects, especially in the presence of light.

These applications highlight the versatility of nanotechnology in developing effective antimicrobial strategies, utilizing materials like silver and titanium dioxide nanoparticles to combat bacterial resistance and create hygienic environments.

- **IDENTIFICATION, LOGISTICS AND SECURITY:**

Radio Frequency Identification (RFID) labels consist of a microchip attached to a radio antenna, which stores information about the product or material to which it is affixed. When scanned, the scanning device activates the chip via the antenna and transmits the stored information to a designated location. This information is utilized for identification and security purposes (11).

RFID labels are widely employed in public settings, particularly in healthcare institutions and hospitals. They are increasingly utilized for patient and sample identification, supplementing traditional barcodes. These labels, often the size of a grain of rice, can be implanted under the skin for continuous tracking. The Food and Drug Administration (FDA) in the United States approved RFID labels for human use in 2004 (12), enabling the storage of patient histories and records.

Beyond healthcare, RFID labels play a significant role in food and agricultural technologies, enhancing traceability and inventory management. They contribute to improved efficiency and security across various industries, demonstrating their versatility and widespread adoption in modern technological applications.

3. CONCLUSION:

Nanotechnology plays a pivotal role not only in food packaging, processing, and cancer therapy but also holds promise in regenerative medicine and beyond, offering long-term potential for competitive and innovative methods. Enhancements in the food system through improved nutritional value and food safety are among its notable contributions. Nanotechnology facilitates the development of products such as contaminant sensors, high-barrier plastics, antimicrobials, and UV protections.

In agriculture, nanotechnology enables the creation of novel pesticides, efficient delivery systems for agrochemicals, sensors for monitoring soil conditions, and targeted genetic engineering techniques. Furthermore, nano sensors are pivotal in food characterization, water purification, mineral and vitamin fortification, as well as nutraceutical and nutrient delivery, enhancing nutritional outcomes.

These advancements address existing challenges in medicine and the food industry, offering positive impacts on both sectors and healthcare. Understanding the environmental and medical impacts of nanoparticles is crucial as nanotechnology provides a range of capabilities that must be employed in a responsible and thoughtful manner.

Overall, nanotechnology offers a diverse array of solutions that can be harnessed effectively to benefit society, ensuring sustainable and impactful applications across various domains.

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