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The role of nanotechnology in biological applications: Review article

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Abstract

Through the use of unique nano-properties for targeted action and increased sensitivity, such as large surface area and quantum effects. By enabling precise manipulation of matter at the molecular level, nanotechnology revolutionizes biology and leads to advances in tissue engineering (biocompatible implants, 3D bioprinting scaffolds), gene editing, drug delivery (targeted cancer therapy, fewer side effects), and diagnostics (ultra-sensitive biosensors for early disease detection, imaging). Since nanotechnology primarily inhibits and destroys germs, it is a powerful tool against antibiotic resistance.

By using nanosensors to enable early detection, enhanced imaging to improve diagnosis, and targeted drug delivery (nanocarriers like liposomes) to improve treatment. Currently, molecular imaging uses a variety of nanoparticles, and in recent decades, the use of nanoparticles for cancer detection and monitoring has attracted a lot of attention. By facilitating targeted drug delivery, painless oral insulin administration, more intelligent glucose monitoring, and regenerative medicine, going beyond injections to offer glucose-responsive systems.

Keywords: nanotechnology, Bacteria, cancer, diabetes

Introduction

By using special nano-properties like high surface area and quantum effects for targeted action and enhanced sensitivity [1]. nanotechnology transforms biology by allowing precise manipulation of matter at the molecular level, resulting in breakthroughs in drug delivery (targeted cancer therapy, reduced side effects), diagnostics (ultra-sensitive biosensors for early disease detection, imaging), tissue engineering (biocompatible implants, 3D bioprinting scaffolds), and gene editing [2].

Biological Applications

Nanoparticles improve drug delivery, enhance efficacy, and reduce toxicity by stabilizing the drug from degradation, targeting specific cells (i.e., cancer), and controlling the release of the drug from the nanoparticle [3].

Nanoparticles and quantum dots can be used as very sensitive fluorescent probes for tracking of biomolecules and labelling of cells, thereby enhancing medical imaging (MRI contrast agents) and early detection of diseases [4].

Nanomaterials are being applied to 3D bioprinting, implants, and scaffolds to promote tissue regeneration, enhance biocompatibility, and fabricate durable and secure medical devices [5].

Due to their unique properties and ability to avoid existing resistance mechanisms, nanoparticles

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provide an alternative method for treating antibiotic-resistant bacteria with reduced side effects compared to existing antibiotics [6]. Nanoscale devices are essential for quick diagnostics and environmental monitoring because they can identify diseases, contaminants, and molecular alterations with great specificity [7].

How It Works

Nanoparticles (1–100 nm) are perfect for customized biological activities because of their high surface-to-volume ratio and quantum effects, which provide control over optical, magnetic, and electrical properties [8].

It is possible to concurrently detect, treat, and monitor biological processes by engineering particles with several layers (such as magnetic and luminous) [9].

As platforms for molecular assembly, nanomaterials enable the development of new biosystems and improved interactions with biological surroundings [10].

The effect of nanotechnology on bacteria

Nanotechnology is a potent weapon against antibiotic resistance since it mainly has an inhibitory and destructive effect on bacteria by physically destroying cell structures and interfering with essential processes. Because nanoparticles can kill germs in numerous ways at once, it is difficult for bacteria to become resistant to them [11].

Mechanisms of Action

Silver (Ag), gold (Au), zinc oxide (ZnO), and titanium dioxide (TiO_2) nanoparticles (NPs) use a variety of techniques to eradicate microorganisms [12].

Cell Membrane Disruption and Damage: NPs have the capacity to adhere to the bacterial cell wall and membrane, increasing permeability and causing intracellular contents to leak out, ultimately resulting in cell death. Because bacterial membranes are usually negatively charged, positively charged nanoparticles are more effective against them [13].

Reactive oxygen species (ROS) generation: By producing free radicals (ROS), which harm vital bacterial components like DNA, proteins, and lipids, many NPs cause oxidative stress. Bacteria have a tough time coping with these huge amounts of internal injury [14]. Examples of ways that nanoparticles can disrupt an organism's metabolism include attaching to enzymes/nucleic acids, interfering with the process of respiration, and preventing cellular replication and growth by obstructing metabolically necessary processes within living cells [15]. Examples of physical/mechanical destruction methods would include rigid nanostructures being able to destroy the bacteria through physical rupturing of either the cell wall or cell membrane [16].

Applications in Medicine and Industry

Antibiotic resistance is a problem worldwide, and scientists address this issue by using nanotechnology's antibacterial properties [17].

Infection Prevention and Management: Nanoparticles are used in coatings for surgical instruments and medical devices to reduce bacterial adhesion and to decrease the incidence of nosocomial (hospital-acquired) infections. They are additionally used in wound dressings to promote healing and to reduce the risk of infection [18].

Advanced Drug Delivery: By allowing for direct delivery of antibiotics to an infection source via nanocarriers, antibiotics become more effective, require lower doses of antibiotics for treatment, and result in fewer side effects [19].

Rapid Detection: Nanotechnology-based sensor technology provides rapid and sensitive detection of pathogens in food, water, and clinical settings for more targeted and efficient treatment plans [20].

Purifying Water for Drinking: Nanomembranes and nano-adsorbents were developed to filter out waterborne pathogens and kill them in water treatment systems so people can have access to clean drinking water [21].

Potential Concerns

In spite of all of the potential benefits, there needs to be additional research before it will be possible to understand all of the long-term effects that nanoparticles might have, including the effects they will have on the environment and how safe they will be for humans. It has also been shown that certain types of nanoparticles assist antibiotic-resistant bacteria in acquiring antibiotic resistance genes from other bacteria through horizontal gene transfer under certain circumstances [22].

The effect of nanotechnology on cancer

Nanotechnology is changing how we care for cancer patients by offering more accurate, effective, and less harmful methods of managing cancer through earlier detection using nanosensors, improved diagnosis utilizing advanced imaging technologies, and enhanced treatment with targeted delivery of (nanocarriers, such as liposomes) medications that reduce toxicity to healthy cells but increase the concentration of the drug at the tumor site, along with new types of treatment, including photothermal therapy and nanobots [23].

Early Detection & Diagnosis

Promptly diagnosing and treating cancerous cells and biomarkers relies on nanosensor and nanoprobe technology that accurately and quickly detect the presence of these cancerous cells and/or their biomarkers [24].

Tumors can be visualized at high resolution using metals (e.g., iron oxide), quantum dots, and other contrast agents as nanoparticles for MRI, optical, and other types of imaging [25].

Nanocarriers for Targeted Drug Delivery

Chemotherapeutic agents can also be delivered using liposomes, dendrimers, and polymeric nanoparticles encapsulating the drugs to protect them from degradation and release at the tumor site [26].

Reduced Toxicity: Overcomes a significant drawback of traditional chemotherapy by minimizing harm to healthy tissues [27].

Increased Drug Concentration in the Tumor: Enhanced Permeability and Retention (EPR effect) improve efficacy [28].

Novel Therapeutic Strategies

Photothermal therapy uses nanoparticles to kill cancer cells by absorbing light and turning it into heat. Cancer cells receive therapeutic genes from nanoparticles. Nanobots have the ability to physically target and eliminate cancers by coagulating their blood supply, for example [29].

Nanotechnology aids in tumor imaging

Numerous forms of nanoparticles are currently employed for molecular imaging, and the use of nanoparticles in cancer detection and monitoring has garnered significant attention in recent decades [30]. They have become more well-known in current cancer research and diagnosis because of their benefits, which include tiny size, good biocompatibility, and high atomic number. Iron oxide nanocrystals, semiconductors, and quantum dots are examples of nanoparticles utilized in cancer that have optical, magnetic, or structural characteristics uncommon in other molecules [31].

The effect of nanotechnology on diabetes

By enabling more intelligent glucose monitoring, painless oral insulin delivery, targeted drug delivery, and regenerative medicine—moving beyond injections to provide glucose-responsive systems, improved bioavailability, and individualized treatments for better glucose control, fewer side effects, and improved quality of life—nanotechnology is transforming the treatment of diabetes [32].

Highly sensitive nanosensors, which use materials like carbon nanotubes and quantum dots, provide more precise, frequent, and convenient blood glucose readings, which are essential for improved control [33].

Insulin & Drug Delivery

Glucose-Responsive Nanoparticles: These nanoparticles behave like the pancreas and reduce hypoglycemic risk by delivering insulin in response to elevated blood glucose concentrations [34].

Oral Insulin: Nanocarriers allow for painless, oral delivery of insulin instead of needing to inject it because they protect the drug from the destructive elements found in the stomach [35].

Targeted Delivery: By targeting specific tissues (e.g., at a wound site or in pancreatic tissue) with a drug, the use of nanoparticles increases the effectiveness of the treatment and reduces systemic side effects [36].

Gene Therapy and Regenerative Medicine

1. **Cell Therapy:** Nanoparticles deliver genetic material (oligonucleotides) either to modify immune responses in type 1 diabetes or to increase insulin production in stem cells [37].
2. **Wound Healing:** Nanomaterials assist tissue regeneration by delivering regenerative molecules to wounds from diabetes [38].
3. **Nanotheranostics:** This area focuses on using insulin to the pancreas by combining diagnostics and using one probe for both monitoring and treatment of the patient [39].

Nanoparticles for Releasing Insulin in Response to Blood Glucose Levels

Nanoparticle systems that respond to changes in blood glucose levels are being created to mimic how the body responds to changes in blood sugar and to modulate the delivery of insulin in response to those changes. These systems may be able to provide greater glycemic control than conventional self-administered insulin subcutaneously and reduce the incidence of hypoglycemia compared to those methods. The main mechanism for glucose-modulated delivery is the reversible association between insulin and phenylboronic acid (PBA), through its binding to the glucose molecule(s) [40].

Conflict of Interest: NIL

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