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Review Article

NANOBIOTECHNOLOGY IN HEALTH SCIENCES: CURRENT APPLICATIONS TO FUTURE PERSPECTIVES

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Abstract: *This mini-review provides a comprehensive overview of the current applications and future perspectives of nanobiotechnology in health sciences. Drawing upon recent advancements, the review explores the role of nanoparticles in drug delivery, diagnostic imaging, therapeutics, regenerative medicine, and point-of-care diagnostics. Each application is discussed in detail, highlighting the significant contributions of nanotechnology to precision medicine, targeted therapy, bioimaging technologies, nanorobotics, and bioinformatics integration. Additionally, the review emphasizes the potential impact of nanobiotechnology on improving patient outcomes and advancing healthcare delivery. The review incorporates data from various databases, including PubMed, Web of Science, Scopus, and Google Scholar, to provide a comprehensive and up-to-date analysis of the field.*

Keywords: Bioimaging Technologies, Diagnostic Imaging, Drug Delivery, Nanorobotics, Point-of-Care Diagnostics, Precision Medicine, Regenerative Medicine, Targeted Therapy, Therapeutics

Introduction

Nanobiotechnology has emerged as a transformative field with vast potential to revolutionize various aspects of healthcare, including drug delivery, diagnostics, therapeutics, regenerative medicine, and point-of-care diagnostics (1). At the intersection of nanotechnology and biotechnology, nanobiotechnology harnesses the unique properties of nanomaterials to address complex challenges in healthcare (2). With precise control over size, shape, and surface properties, nanoparticles offer unprecedented opportunities for targeted interventions and personalized treatments (3). This mini-review explores the current applications and future perspectives of nanobiotechnology in health sciences, highlighting its role in advancing disease diagnosis, treatment, and patient care. By leveraging nanoscale innovations, researchers are poised to unlock new frontiers in precision medicine, targeted therapy, bioimaging technologies, nanorobotics, and bioinformatics integration (4-6). This introduction sets the stage for an in-depth exploration of the transformative potential of nanobiotechnology in shaping the future of healthcare.

CURRENT APPLICATION:

Drug Delivery:

Nanoparticles have emerged as promising vehicles for drug delivery due to their unique properties, including small size, large surface area-to-volume ratio, and tunable surface chemistry (7).

These characteristics enable precise drug targeting, enhanced drug solubility, and controlled release kinetics, thereby revolutionizing conventional drug delivery systems. One of the key advantages of nanoparticle-based drug delivery is their ability to target specific tissues or cells within the body, minimizing systemic exposure and off-target effects (8). By functionalizing nanoparticle surfaces with targeting ligands, such as antibodies or peptides, researchers can direct therapeutic agents to diseased tissues or cellular receptors, improving treatment efficacy and reducing side effects.

Moreover, nanoparticles can encapsulate a wide range of drug molecules, including small molecules, proteins, and nucleic acids, offering versatile platforms for delivering various types of therapeutics (9, 10). Encapsulation within nanoparticles can enhance drug stability, prolong circulation time, and improve bioavailability, allowing for lower drug doses and less frequent administration schedules (11, 12).Furthermore, nanoparticles can be engineered to respond to external stimuli or biological cues, enabling triggered drug release at specific sites or under certain conditions. For example, stimuli-responsive nanoparticles can release their cargo in response to changes in pH, temperature, or enzyme activity within the tumor microenvironment, maximizing drug delivery to cancer cells while minimizing exposure to healthy tissues.

Overall, nanoparticle-based drug delivery systems hold great promise for improving the efficacy and safety of therapeutic interventions across a wide range of diseases, including cancer, infectious diseases, inflammatory disorders, and neurological conditions (13). These nanoscale contrast agents can be tailored to interact with specific biological targets, allowing for precise visualization of anatomical structures, pathological changes, and molecular biomarkers (14).

One of the key advantages of nanoparticle-based contrast agents is their ability to enhance the signal-to-noise ratio and improve image quality in various imaging modalities, including magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET)

(15-17). Nanoparticles can be functionalized with imaging probes, such as fluorophores, quantum dots, or magnetic nanoparticles, to provide enhanced contrast and spatial resolution (18).

Moreover, nanoparticles can be designed to target specific molecular markers associated with disease progression, enabling early detection and accurate diagnosis of various medical conditions. For example, targeted nanoparticles can selectively bind to receptors overexpressed on cancer cells, allowing for precise tumor localization and staging in oncological imaging studies.

Additionally, nanoparticles can be engineered to accumulate preferentially in diseased tissues or organs, exploiting the enhanced permeability and retention (EPR) effect observed in tumors and inflamed tissues (19). This passive targeting strategy allows for selective imaging of pathological lesions while minimizing background signals from healthy tissues. Figure 1 shows the nanoparticles for ophthalmic drug delivery.

Overall, nanoparticle-based contrast agents offer versatile platforms for enhancing the sensitivity, specificity, and multiplexing capabilities of diagnostic imaging techniques, paving the way for early disease detection, personalized treatment planning, and real-time monitoring of therapeutic responses.

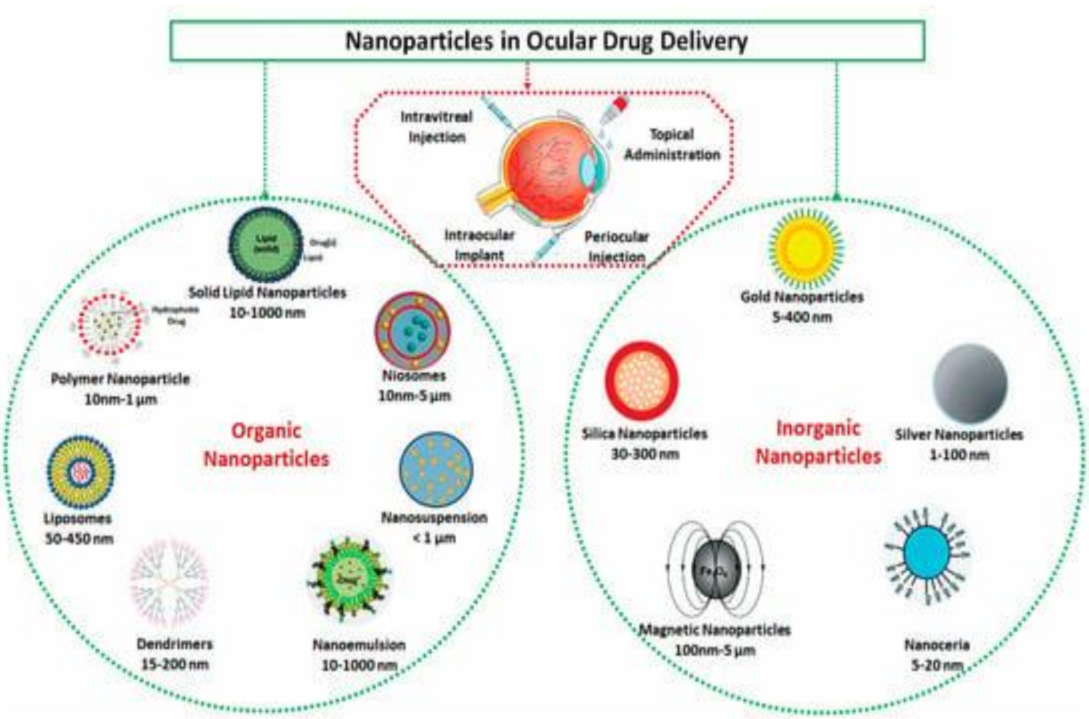

Figure 1. Schematic drawings for potential organic and inorganic nanoparticles for ophthalmic drug delivery (25).

Therapeutics:

Nanoparticle-based therapies have shown promising results in treating a wide range of diseases, including cancer, infectious diseases, and neurodegenerative disorders (20). These innovative approaches leverage the unique properties of nanoparticles to enhance drug delivery, modulate immune responses, and target diseased tissues with precision.

One of the key advantages of nanoparticle-based therapeutics is their ability to overcome biological barriers and deliver therapeutic agents to specific target sites within the body (21). Nanoparticles can be engineered to evade immune surveillance, penetrate biological barriers, and accumulate in diseased tissues through passive or active targeting mechanisms (22, 23).

For example, nanoparticle-based cancer therapies can deliver chemotherapeutic drugs directly to tumor cells while minimizing systemic toxicity and off-target effects. By encapsulating cytotoxic agents within nanoparticles, researchers can improve drug stability, prolong circulation time, and enhance tumor penetration, resulting in enhanced therapeutic efficacy and reduced side effects.

Moreover, nanoparticles can serve as versatile platforms for delivering a wide range of therapeutic modalities, including photothermal therapy, gene therapy, and immunotherapy. For instance, photothermal therapy utilizes light-absorbing nanoparticles to selectively heat and destroy cancer cells, while gene therapy employs nucleic acid-loaded nanoparticles to modulate gene expression and inhibit tumor growth.

Additionally, nanoparticle-based immunotherapies can stimulate or suppress immune responses to target cancer cells or infectious agents, offering new strategies for enhancing host defence mechanisms and overcoming treatment resistance.

Overall, nanoparticle-based therapeutics hold great promise for revolutionizing the treatment of various diseases, offering personalized and targeted approaches to improve patient outcomes and quality of life.

Regenerative Medicine:

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Nanomaterials play a crucial role in advancing regenerative medicine by providing scaffolds for cell growth, enhancing cell adhesion, and promoting tissue regeneration (24). These engineered materials mimic the extracellular matrix (ECM) found in natural tissues, providing structural support and biochemical cues to guide cell behaviour.One of the key advantages of nanomaterial-based scaffolds is their ability to mimic the architecture and mechanical properties of native tissues, facilitating cell attachment, proliferation, and differentiation (25, 26). Nanoscale features, such as surface topography, porosity, and mechanical stiffness, can be precisely controlled to modulate cellular responses and promote tissue regeneration (27).Moreover, nanomaterials can be functionalized with bioactive molecules, such as growth factors, cytokines, and extracellular matrix proteins, to enhance cellular interactions and promote tissue-specific regeneration (28). These biofunctionalized scaffolds can stimulate cell signalling pathways involved in tissue repair and regeneration, accelerating the healing process and restoring tissue function.

Furthermore, nanotechnology enables the development of tissue-engineered constructs with complex hierarchical structures and spatially organized cell populations, resembling native tissues. These engineered tissues can be used for transplantation, organ regeneration, and disease modelling, offering new avenues for regenerative medicine and personalized therapy.

Overall, nanomaterial-based scaffolds hold great promise for advancing regenerative medicine by providing innovative platforms for tissue engineering, organ transplantation, and regenerative therapies. These engineered materials have the potential to revolutionize clinical approaches to tissue repair and regeneration, addressing unmet medical needs and improving patient outcomes.

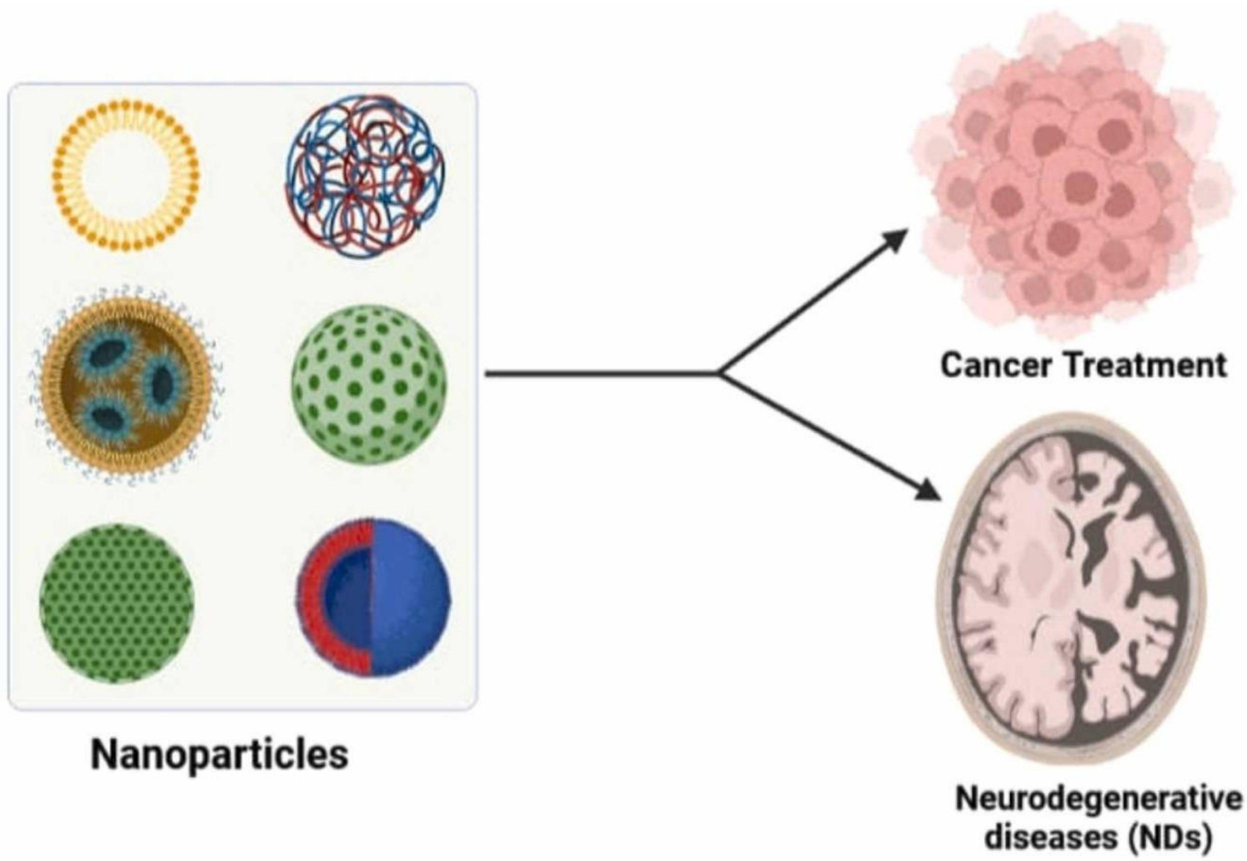

Figure 2. Recent advancements in nanoparticles application in cancer and neurodegenerative disorders (29).

Point-of-Care Diagnostics:

Nanotechnology-based biosensors and assays are transforming point-of-care diagnostics by enabling rapid, sensitive, and cost-effective detection of biomarkers for early disease diagnosis and monitoring (30). These miniaturized devices leverage the unique properties of nanomaterials to enhance detection sensitivity, reduce assay time, and improve portability for use in resource-limited settings (31). One of the key advantages of nanotechnology-based biosensors is their ability to detect biomolecular interactions with high specificity and sensitivity. Nanomaterials, such as nanoparticles, nanowires, and nanotubes, can be functionalized with recognition elements, such as antibodies, aptamers, or nucleic acids, to selectively capture target analytes in complex biological samples (32). Moreover, nanotechnology enables the development of miniaturized and multiplexed biosensor platforms capable of detecting multiple biomarkers simultaneously within a single assay (33). These multiplexed assays can provide comprehensive diagnostic information, improve accuracy, and reduce turnaround time, facilitating timely clinical decision-making and patient management (34).

Furthermore, nanomaterial-based biosensors offer rapid and real-time detection capabilities, allowing for point-of-care testing outside of traditional laboratory settings. These portable devices can be integrated with smartphones or handheld devices for on-site testing in remote or resource-limited environments, enabling early disease detection and surveillance in underserved populations.

Overall, nanotechnology-based biosensors and assays hold great promise for transforming point-of-care diagnostics by providing rapid, sensitive, and portable platforms for early disease detection, personalized medicine, and global health surveillance. These innovative technologies have the potential to revolutionize healthcare delivery and improve patient outcomes worldwide.

FUTURE PROSPECTIVE:

Precision Medicine:

Nanobiotechnology holds immense promise in advancing the field of precision medicine, which aims to deliver tailored therapeutic interventions based on individual genetic profiles, disease characteristics, and environmental factors (35). Nanoparticles offer unique advantages in this regard, as they can be engineered to carry specific therapeutic agents, target specific cell types or tissues, and respond to cues within the microenvironment (21).

For example, the use of nanoparticle-based drug delivery systems allows for the precise administration of medications to diseased tissues while minimizing exposure to healthy cells. By incorporating targeting ligands or responsive elements onto the surface of nanoparticles, these drug carriers can selectively bind to receptors or biomarkers overexpressed in diseased tissues, thereby enhancing drug accumulation and efficacy at the target site.

Furthermore, advances in nanotechnology enable the development of multifunctional nanoparticles capable of carrying multiple therapeutic agents simultaneously or integrating diagnostic and therapeutic functionalities within a single platform. This multifaceted approach enables clinicians to tailor treatment regimens to the specific molecular profiles of individual patients, optimizing therapeutic outcomes and minimizing adverse effects.

In the future, the integration of nanobiotechnology with high-throughput genomic sequencing, transcriptomics, and proteomics technologies will further enhance our ability to identify personalized treatment strategies for patients with complex diseases such as cancer, cardiovascular disorders, and neurodegenerative conditions.

Targeted Therapy:

The evolution of nanoparticle design has paved the way for precise targeting of diseased tissues, offering significant improvements in therapeutic efficacy while minimizing off-target effects (36). Nanoparticles can be engineered to exhibit specific physicochemical properties that enable passive or active targeting mechanisms, allowing for selective accumulation and retention within tumor tissues or diseased organs. Passive targeting relies on the enhanced permeability and retention (EPR) effect, wherein nanoparticles preferentially accumulate in leaky tumor vasculature due to their small size and prolonged circulation time (37). This phenomenon allows for increased drug delivery to tumor sites while minimizing exposure to healthy tissues, thereby enhancing therapeutic outcomes and reducing systemic toxicity (38).

In contrast, active targeting involves the functionalization of nanoparticles with targeting ligands, such as antibodies, peptides, or small molecules, that recognize and bind to specific receptors or biomarkers overexpressed on the surface of diseased cells. This targeted approach enables nanoparticles to selectively deliver therapeutic payloads to tumor cells or diseased tissues, increasing local drug concentrations and improving treatment efficacy (39).

Moreover, the development of stimuli-responsive nanoparticles that can release therapeutic agents in response to specific cues within the tumor microenvironment, such as pH, temperature, or enzymatic activity, further enhances the precision and efficacy of targeted therapy. These smart nanocarriers can be engineered to release drugs only in the presence of disease-related stimuli, minimizing off-target effects and maximizing therapeutic benefits.

In the future, advancements in nanotechnology will continue to drive innovations in targeted therapy, enabling the development of personalized treatment regimens tailored to the unique characteristics of individual patients and diseases.

Bioimaging Technologies:

Next-generation nanoprobes and contrast agents hold the potential to revolutionize diagnostic imaging technologies by enhancing sensitivity, specificity, and resolution (40). Nanoparticles offer unique optical, magnetic, and acoustic properties that can be harnessed to develop novel imaging probes capable of visualizing biological processes at the molecular and cellular levels.

For example, quantum dots, semiconductor nanoparticles with tunable fluorescence properties, have emerged as promising fluorescent probes for bioimaging applications. These nanocrystals exhibit exceptional photostability, narrow emission spectra, and high quantum yields, making them ideal candidates for multiplexed imaging of biological targets in vitro and in vivo.

Similarly, superparamagnetic iron oxide nanoparticles (SPIONs) have been widely used as contrast agents for magnetic resonance imaging (MRI) due to their strong magnetic properties and biocompatibility. By functionalizing SPIONs with targeting ligands or responsive elements, researchers can selectively label and track specific cell populations or biomolecules within complex biological systems, enabling non-invasive imaging of disease progression and treatment response.

In addition to traditional imaging modalities, emerging techniques such as photoacoustic imaging, nanoparticle-enhanced computed tomography (CT), and surface-enhanced Raman spectroscopy (SERS) offer exciting opportunities for advancing bioimaging capabilities (41). These label-free or contrast-enhanced imaging approaches leverage the unique optical and acoustic properties of nanoparticles to visualize biological structures and processes with unprecedented sensitivity and specificity (42).

In the future, the integration of nanotechnology with advanced imaging modalities and machine learning algorithms will enable real-time monitoring of disease dynamics, early detection of pathological changes, and personalized treatment guidance, ultimately improving patient outcomes and quality of life.

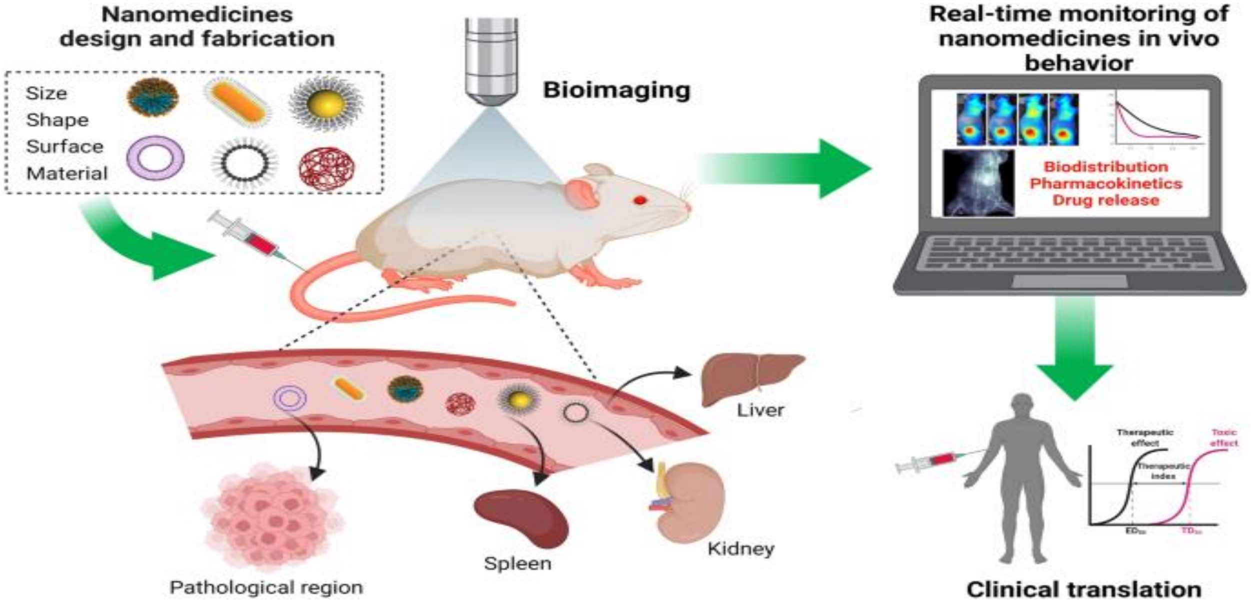

Figure 3. Bioimaging guided pharmaceutical evaluations of nanomedicines for clinical translations (43).

Nanorobotics:
The development of nanoscale robots, or nanorobots, holds tremendous potential for revolutionizing medical interventions by providing unprecedented precision, control, and versatility. Nanorobots are programmable devices typically ranging from 1 to 100 nanometers in size, capable of performing a wide range of tasks within biological systems, including targeted drug delivery, tissue repair, and minimally invasive surgeries (44, 45).
One of the most promising applications of nanorobotics is in targeted drug delivery, where nanoscale carriers equipped with sensors, actuators, and drug payloads can navigate through the bloodstream to specific target sites, such as tumours or diseased tissues. These smart nanorobots can respond to external stimuli or biological cues, such as changes in pH, temperature, or biomarker expression, to deliver therapeutic agents with precision and efficiency, while minimizing off-target effects.
Furthermore, nanorobots can be engineered to perform complex tasks within the body, such as cell manipulation, tissue engineering, and regenerative medicine. By leveraging nanoscale components, such as nanowires, nanotubes, or DNA origami structures, researchers can design nanorobots capable of interacting with biological systems at the molecular and cellular levels, enabling precise control over cellular processes and tissue regeneration.
In addition to therapeutic applications, nanorobots hold promise for advancing diagnostic and imaging technologies, enabling real-time monitoring of physiological parameters, drug pharmacokinetics, and disease progression. By integrating nanorobotic systems with imaging modalities, such as MRI, CT, or fluorescence microscopy, researchers can visualize and track the movement of nanorobots within the body, providing valuable insights into their biodistribution, efficacy, and safety profiles.
In the future, the convergence of nanotechnology, robotics, and artificial intelligence (AI) will enable the development of autonomous nanorobotic systems capable of performing complex tasks with minimal human intervention. These intelligent nanorobots could revolutionize healthcare by providing personalized, on-demand therapeutic interventions tailored to the unique needs of individual patients, ultimately improving treatment outcomes and quality of life.

Bioinformatics Integration:
Integration of nanotechnology with bioinformatics and artificial intelligence (AI) promises to accelerate drug discovery, optimize treatment strategies, and enhance patient outcomes through data-driven approaches (46, 47). By leveraging the vast amounts of data generated from nanotechnology-based experiments, such as high-throughput screening assays, omics profiling, and imaging studies, researchers can gain insights into the underlying mechanisms of disease, identify novel therapeutic targets, and predict treatment responses.
For example, AI algorithms can analyze multi-omics data sets, such as genomics, transcriptomics, proteomics, and metabolomics, to identify biomarkers associated with disease progression, drug resistance, and treatment outcomes. By integrating nanotechnology-based platforms with bioinformatics tools, researchers can uncover complex molecular signatures and signalling pathways underlying disease pathogenesis, enabling the development of targeted therapies tailored to individual patients. Furthermore, AI-driven approaches can optimize the design and synthesis of nanomaterials for specific biomedical applications, such as drug delivery, imaging, and tissue engineering (46).
Machine learning algorithms can predict the physicochemical properties, biological interactions, and pharmacokinetic profiles of nanoparticles, guiding the rational design of nanocarriers with enhanced therapeutic efficacy and safety profiles (48).
In the future, the convergence of nanotechnology, bioinformatics, and AI will enable the development of personalized medicine strategies that leverage the synergistic interactions between nanomaterials, biological systems, and computational models. By integrating diverse data sources, predictive algorithms, and experimental validations, researchers can unlock new opportunities for precision medicine, tailored therapies, and improved patient care.

Conclusion

In conclusion, nanobiotechnology has emerged as a powerful tool in the field of health sciences, with current applications spanning drug delivery, diagnostic imaging, therapeutics, regenerative medicine, and point-of-care diagnostics. Nanoparticles offer unprecedented precision and versatility in drug delivery systems, diagnostic imaging modalities, and therapeutic interventions, enabling targeted therapies, enhanced disease detection, and improved patient outcomes. Moreover, nanomaterials hold great promise in regenerative medicine by providing innovative scaffolds for tissue engineering and organ regeneration. Additionally, nanotechnology-based biosensors and assays are revolutionizing point-of-care diagnostics by enabling rapid and sensitive detection of biomarkers for early disease diagnosis and monitoring. Looking ahead, continued advancements in nanobiotechnology hold the potential to further transform healthcare delivery, personalized medicine, and global health outcomes.

Declarations

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All data generated or analyzed during the study are included in the manuscript.
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Approved by the department concerned.
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Conflict of interest

The authors declared the absence of a conflict of interest.

Author Contribution

ASMA ALI
Coordination of collaborative efforts.
Study Design, Review of Literature.
Conception of Study, Development of Research Methodology Design, Study Design, Review of manuscript, final approval of manuscript.
AAYESHA KAMRAN
Conception of Study, Final approval of manuscript.
Manuscript revisions.

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