Review Article

Integration of Artificial Intelligence in Nanomedicine

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ABSTRACT

The integration of artificial intelligence (AI) and nanotechnology has revolutionized the field of nanomedicine. AI's large-scale data processing and pattern recognition capabilities can enhance the design of nanotechnologies for diagnosis and therapy. This integration can address challenges in fabrication and targeted drug delivery for cancer therapy. AI's rapid data mining and decision-making capabilities can lead to more innovative solutions. The convergence of biology, AI, and nanotechnology is fostering a scientific and technological revolution. Recent studies show that AI can improve the design of nanotechnologies for diagnostics and treatment by processing large datasets and recognizing complex patterns. AI is also used in nanomedicine design to optimize material properties based on interactions with target medications, biological fluids, immune systems, and cell membranes.

Introduction

Nanomedicine, a rapidly growing field that combines physical, chemical, biological, and digital aspects, has made significant progress over the past three decades. It influences various medical fields and is a dynamic tool for developing therapeutics, medical imaging, nanotherapeutics, vaccines, and biomaterials. The integration of AI and nanotechnology in nanomedicine has the potential to revolutionize various aspects of medicine, including drug delivery, imaging, and implants. To improve the design of nanotechnologies, AI algorithms can process vast datasets and recognize complicated patterns. Some of the drawbacks of fabrication and targeted drug delivery for cancer therapy can be solved with the use of AI. Nanomedicine has been made a reality through the use of data science, high throughput, automatization, and

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AI. By accomplishing acquisition, the use of AI in the creation of nanotechnology-based goods may revolutionize the healthcare industry [1]. The use of AI to nanotechnology has been started and is continually proving to be a successful and simple method. Since AI swiftly mines data and makes judgments, combining nanotechnology and AI results in more inventive technologies. A scientific and technological revolution is being sparked by the convergence of biology, AI, and nanotechnology, even though the anticipated integration has not yet occurred [2]. The discipline of nanomedicine has undergone a revolution as a result of the merging of AI with nanotechnology. Nanotechnologies for diagnosis and therapy can be designed and optimized with the help of AI. To maximize the therapeutic efficacy of materials, AI can also be used to predict interactions with the target drug, biological fluids, immune system, vasculature, and cell membranes [3]. Some of the obstacles to targeted medication delivery and manufacture for cancer therapy can be overcome with the aid of artificial intelligence (AI) in nanomedicine. In order to forecast how cells would behave under various conditions, AI systems can find patterns and relationships in cellular activity and interactions. More cutting-edge technologies may result from the combination of AI and nanotechnology. AI and other computational techniques are used in nanoinformatics for designing and implementing nanomaterials. Large-scale biomedical data can be analysed using AI algorithms to find current medications with potential therapeutic value for various diseases. AI can shorten the time and expense required for medical development by reusing already-approved medications [4]. The aim is to integrate artificial intelligence (AI) in nanomedicine to enhance various aspects of nanomedicine by leveraging the power of AI algorithms and techniques. This study tends to explore possible role of AI integration in precision cancer medicine, targeted drug delivery, data science, high throughput, and automatization in Nanomedicine**.** Based on this study, the following were discussed; Integration of AI in Nanomedicine, AI-based Diagnosis and Drug Discovery in Nanomedicine, AI-assisted Nanoparticle Synthesis and Drug Delivery, AI-powered Imaging and Diagnostics in Nanomedicine, Integration of AI and Nanorobotics for Therapeutic Applications, Ethical and Safety Considerations in AI-Enabled Nanomedicine, and Future Directions and Implications in AI-based Nanomedicine Research.

AI-Based Diagnosis and Drug Discovery in Nanomedicine

AI-Based Diagnosis in Nanomedicine

In the context of precision cancer medicine, artificial intelligence (AI) has the potential to revolutionize the field of nanomedicine. By adjusting the properties of nanomedicines, obtaining effective medication co-administration, and reducing nanotoxicity, AI-enabled nanotechnology could increase the accuracy of molecular profiling and early patient diagnosis as well as optimize the design pipeline of nanomedicines, improving their targetability, personalized dosing, and therapeutic potency [5]. To maximize drug distribution, drug delivery nanosystems have been designed, characterized, and manufactured using AI methodologies, where the bulk of AI techniques are used for evaluating and interpreting biological and genetic data as shown in (Figure 1). The time and expense associated with drug discovery, as well as the assessment of the pharmacodynamics and pharmacokinetic profiles of various medications, have been greatly decreased by incorporating AI in nanotechnology and pharmaceutical research. This has also resulted in a decrease in false positive rates [6]. To create a new tool to forecast the efficacy of cancer nanomedicines, researchers are training an artificial neural network, a type of AI technology, with hundreds of datasets from physiologically-based pharmacokinetic (PBPK) computer models. The low delivery efficiency of cancer nanomedicines is a major issue, and the AI-assisted smart model can forecast the efficiency of nanoparticles to tumors [6].

AI-Based Drug Discovery in Nanomedicine

The drugs creation in nanomedicine has the potential to be revolutionized by artificial intelligence (AI). By predicting the 3D structure of molecules, identifying hit and lead compounds, and optimizing the drug structure design, AI can help with structure-based drug discovery [7]. To find prospective drug candidates, refine lead compounds, and anticipate their qualities, AI systems can examine enormous amounts of chemical and biological data. This speeds up the discovery and development of novel therapies. AI has the ability to help with drug discovery and drug design, as well as data processing and analysis of complicated data, which are all issues that nanotechnologies face. By foreseeing the transport efficiency of nanoparticles to tumors, which is a critical issue with low delivery efficiency of cancer nanomedicines, AI may also anticipate the effectiveness of cancer nanomedicines [8].

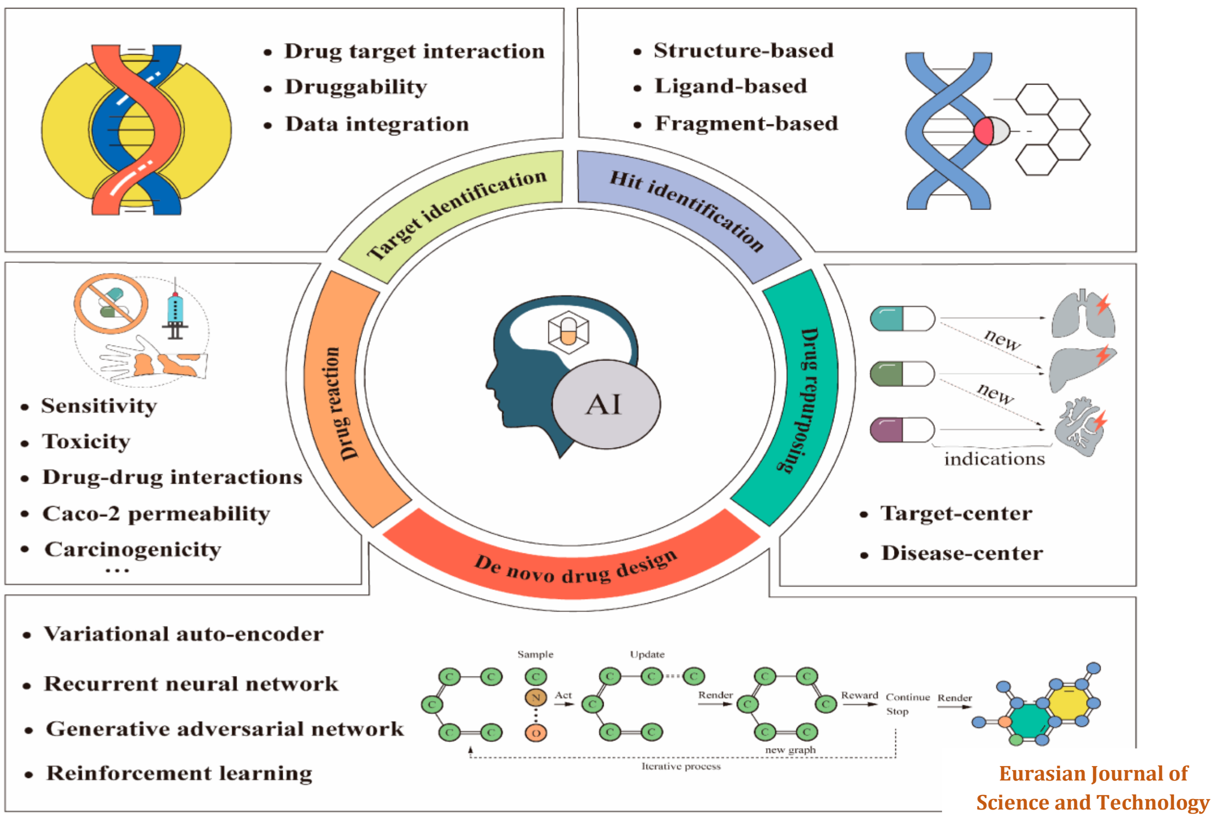

Figure 1 Some applications of artificial intelligence in anti-cancer drug design [8]

AI-Assisted Nanoparticle Synthesis and Drug Delivery

Nanoparticle synthesis and drug delivery are critical components of modern medicine and biotechnology. Nanoparticles, often in the range of 1 to 100 nanometres, possesses unique properties that make them valuable in drug delivery systems. These properties include their high surface area-to-volume ratio, tunable surface chemistry, and the ability to encapsulate and release drugs with precision. However, the synthesis of nanoparticles and their subsequent application in drug delivery systems can be complex, time-consuming, and costly. Artificial intelligence (AI) has emerged as a transformative tool in these areas, revolutionizing how nanoparticles are designed, synthesized, and utilised for drug delivery [9].

Nanoparticle Synthesis

I. Traditional Methods

Traditional nanoparticle synthesis methods involve chemical and physical processes such as chemical precipitation, sol-gel synthesis, and physical vapour deposition. These methods often rely on trial-and-error experimentation and can lead to variations in nanoparticle characteristics. Such processes require significant time and resources.

II. AI-Assisted Nanoparticle Synthesis

AI is being used to optimize nanoparticle synthesis in several ways:

- *Material Selection*: AI algorithms can predict suitable precursor materials for nanoparticle synthesis based on desired properties. Machine learning models, trained on vast material databases, can recommend materials with specific characteristics, reducing the need for extensive experimentation [10].

- *Process Optimization*: Machine learning models can optimize reaction conditions, such as temperature, pressure, and reactant concentrations, to improve nanoparticle size, shape, and distribution. This reduces the number of needed experiments and accelerates the optimization process [11,12].

- *Real-time Monitoring*: AI-powered sensors and data analysis can monitor synthesis reactions in real time, allowing for immediate adjustments. This results in consistent nanoparticle production [13].

- *Predicting Nanoparticle Properties*: AI models can predict the physical and chemical properties of nanoparticles based on synthesis parameters, aiding in the design of nanoparticles for specific applications [14].

Drug Delivery

I. Conventional Drug Delivery Systems

Traditional drug delivery systems face limitations, such as inefficient drug release kinetics, poor targeting, and potential toxicity. Nanoparticles offer a solution to these challenges by enabling controlled drug release, improved targeting, and reduced side effects [15].

II. AI-Enhanced Drug Delivery

AI has revolutionized drug delivery in the following ways:

i. *Precision Targeting*: AI algorithms analyse patient data, such as genomics and medical history, to determine the most effective drug delivery route and dosage. This personalized approach maximizes treatment efficacy [16,17].

ii. *Optimized Formulations*: Machine learning models can predict the ideal nanoparticle formulations for specific drugs, considering factors like drug solubility and release kinetics [18].

iii. *Real-time Drug Release Control*: AI-based drug delivery systems can dynamically adjust drug release rates based on patient responses, ensuring optimal therapeutic outcomes [19].

AI-powered Imaging and Diagnostics in Nanomedicine

The integration of artificial intelligence (AI) with advanced imaging techniques has significantly transformed the field of nanomedicine. Nanomedicine leverages nanoparticles and nanoscale materials to diagnose, treat, and monitor diseases with unprecedented precision. AI, in conjunction with cutting-edge imaging modalities, plays a pivotal role in enhancing early diagnosis, treatment efficacy, and patient outcomes [20].

Imaging in Nanomedicine

I. Traditional Imaging Techniques

Traditional medical imaging techniques such as X-ray, magnetic resonance imaging (MRI), and computed tomography (CT) provide valuable information but have limitations in terms of resolution, sensitivity, and specificity. These constraints can hinder early disease detection and targeted drug delivery.

II. AI-Enhanced Imaging

AI is revolutionizing medical imaging in the following ways:

i. *Enhanced Image Analysis*: AI algorithms can process and analyse large datasets, enabling the detection of subtle anatomical and pathological changes that may go unnoticed by human radiologists [21].

ii. *Image Enhancement*: Machine learning models can improve image quality, reduce artefacts, and enhance contrast in images, aiding in the visualization of nanoscale structures and materials [22].

iii. *Multi-Modal Imaging Integration*: AI can integrate data from different imaging modalities, providing a more comprehensive view of nanoscale interactions in the body, and improving the accuracy of diagnosis and treatment planning.

iv. *Real-Time Imaging*: AI algorithms enable real-time monitoring of nanoparticles, allowing for dynamic adjustments in drug delivery and treatment plans.

Diagnostics in Nanomedicine

I. Conventional Diagnostics

Traditional diagnostic methods, such as blood tests and tissue biopsies, are invasive, time-consuming, and may not provide real-time information. Nanomedicine seeks to replace or complement these techniques with minimally invasive and highly specific diagnostics.

II. AI-Enhanced Diagnostics

AI is reshaping diagnostics in nanomedicine in the following ways:

- *Biomarker Identification*: AI can discover and validate new biomarkers for various diseases by mining large datasets of clinical and molecular information [23].
- *Early Disease Detection*: Machine learning models analyse patient data to predict disease risk and enable early intervention, enhancing the chances of successful treatment [24].
- *Point-of-Care Diagnostics*: AI-powered nanosensors and devices enable rapid, on-site diagnostics, reducing the need for centralized laboratory testing [25].

Integration of AI and Nanorobotics for Therapeutic Applications

Incorporating AI (Artificial Intelligence) and nanorobotics for therapeutic purposes is an intriguing and incredibly hopeful junction of two cutting-edge technological fields. By enabling focused, minimally invasive, and accurate therapies, this synergy has the potential to change medicine. AI includes several different types of technology, such as deep learning, machine learning, and natural language processing. Massive amounts of data may be processed and analysed by AI systems, which can also spot patterns and base predictions or choices on them. Small machines or gadgets with dimensions at the nanoscale (usually below 100 nanometers) are known as nanorobots [26]. These nanoscale robots can be created for a number of purposes, including the delivery of drugs, surgery, and tissue healing. The integration of AI with nanorobotics has a great deal of potential for medical applications (Figure 2). Collectively, these two disciplines can offer therapies that are accurate, individualized, and minimally intrusive, vastly increasing patient outcomes. Realizing this promise will require addressing the accompanying difficulties, such as safety, control, and ethical issues. Exciting developments in healthcare are predicted to result through continuing research and development in the fields of artificial intelligence (AI) and nanorobotics [27].

Therapeutic applications, especially in targeted medication administration and precision medicine, have the potential to be revolutionized by the merging of AI with nanorobotics. Even though there are obstacles to be solved, current innovations in engineering and bio-nanotechnology offer encouraging progress in incorporating intelligent sensors, power, and AI in nanorobots. The integration provides unmatched diagnostic and therapeutic precision while limiting harm to healthy tissue. Nanorobots can provide these customized remedies after AI analyzes a patient's genetic and health data. Nanorobots can complete tasks without the need for large incisions, minimizing patient suffering and speeding up healing [28].

Figure 2 Integration of AI in molecular system [29]

Therapeutic Applications of AI-Nanorobotics include:

i. *Drug Delivery*: Drugs can be transported and delivered by nanorobots to specific parts of the body, as presented in Figure 2. They can be guided to the desired location by AI, resulting in precise and effective drug delivery [29].

ii. *Cancer Therapy*: By fusing AI and nanorobots, highly focused cancer therapies are possible. While nanorobots directly deliver therapeutic payloads to cancer cells, AI can analyse imaging data to identify cancer cells

iii. *Surgery*: Minimally invasive surgeries can be carried out by nanorobots, and AI can help in planning and directing these procedures to increase precision.

iv. *Tissue Repair*: Nanorobots can assist in repairing damaged tissues at the cellular level, and AI can monitor the healing process.

v. *Diagnostic and Imaging*: Nanorobots can be used to carry out on-site diagnostic testing or supply contrast chemicals for medical imaging, and AI can evaluate medical images to find irregularities [30].

Ethical and Safety Considerations in AI-Enabled Nanomedicine

As this cutting-edge science develops, ethical and safety issues in AI-enabled nanomedicine are of the utmost importance. It is essential to address ethical, safety, and regulatory concerns as the use of AI and nanotechnology in medicine grows more widespread in order to assure responsible and secure implementation [31]. The integration of AI and nanorobotics for therapeutic use raises questions about ethics and safety that need to be answered. AI-enabled nanomedicine has the potential to transform healthcare by providing customized, precise, and effective therapies. To ensure ethical and egalitarian use of new technology, however, safety and ethical issues must come first. Informed consent, privacy, accountability, bias, safety, regulation, transparency, and ethical decision-making are all challenges that should be addressed if AI and nanorobotics are to be successfully and morally integrated into medicine. To fully benefit from AI-enabled nanomedicine and reduce potential hazards, the correct balance between innovation and accountability must be struck [32]. Some of the ethical and safety considerations of AI-Enabled Nanomedicine include:

i. *Legal and Ethical Issues*: Legal and ethical considerations in AI-enabled nanomedicine include privacy and data security, informed consent and autonomy, transparency and accountability, bias and fairness, intellectual property rights, regulatory frameworks, long-term monitoring and accountability, and addressing ethical concerns. Privacy and data security involve complying with data protection laws, ensuring transparent practices, and obtaining informed consent for personal health data collection and use. Informed consent and autonomy involve establishing clear protocols for obtaining consent from patients and respecting their autonomy. Transparency and accountability involve developing regulations requiring transparency in AI algorithms and accountability for system failures. Bias and fairness involve addressing algorithmic bias and proactively identifying and mitigating biases to ensure fair treatment for diverse patient populations. Intellectual property rights for AI-enabled nanomedicine inventions should be defined to encourage innovation while balancing IP protection with accessibility to essential medical advancements. Regulatory frameworks should be developed and updated to ensure safety and efficacy, while holding stakeholders accountable for ongoing evaluation and addressing emerging ethical concerns or risks associated with AI-enabled nanomedicine. While applying AI to clinical practice has great promise for enhancing healthcare, it also raises ethical concerns that must be resolved. Informed consent to use data, safety, justice and fairness, freedom and autonomy, privacy, openness, patient autonomy, and solidarity are some ethical issues that need to be addressed. There is also ongoing discussion on whether AI belongs in already established legal categories or whether a new category with its own characteristics and implications should be created.

ii. *Safety Considerations*: Integrating AI and nanorobotics for therapeutic purposes raises serious safety issues. Concerns concerning potential safety repercussions of utilizing unconfirmed or invalidated AISs in clinical settings are raised by the lack of accountability. To prevent patient injury, it is essential to mandate that both doctors and AI developers adhere to the "do no harm" principle and to include AI developers and engineers with a focus on system safety in moral accountability assessments [33].

iii. *Risk Assessment*: Using ethical check lists, AI can be used to evaluate the risks and potential advantages of goods that are currently being created that use AI. Before the product is published, this can assist detect any ethical concerns and address them. The use of AI in medical decision-making is a complex and multifaceted field. It involves assessing the risk of unauthorized access to sensitive health data, evaluating encryption methods, access controls, and data storage practices to mitigate privacy risks. Informed consent challenges are also a concern, with strategies to enhance patient understanding of AI applications and potential implications. The risk of biases in AI algorithms leading to unequal treatment among diverse patient populations is also a concern. Unexpected side effects or adverse reactions related to nanomaterials used in medical treatments are also a concern. The safety of nanomaterials is another critical aspect, with toxicity and safety profiles being evaluated. Transparency and explainability are also crucial, with measures to enhance transparency being implemented. Regulatory compliance is another concern, with AI-enabled nanomedicine solutions adhering to relevant frameworks and quality standards. Over-reliance on AI systems may diminish human involvement in medical decision-making, and safeguards must be implemented to maintain a balance between AI support and human expertise. Ethical oversight and accountability are also crucial, with clear lines of responsibility and accountability established for ethical considerations. Finally, the risk of exacerbating global health inequalities through unequal access to AI-enabled healthcare technologies is also a concern.

iv. *Monitoring and Guidelines*: AI-enabled nanomedicine involves several ethical considerations, including continuous algorithmic monitoring, patient outcome tracking, data security audits, transparency assessments, and ethical compliance checks. These measures aim to ensure the ethical use of AI in healthcare by identifying and mitigating biases, protecting patient privacy, and ensuring the explainability of AI algorithms in medical decision-making. Informed consent guidelines are essential for obtaining informed consent, while algorithmic bias mitigation guidelines help identify and mitigate biases in AI systems. Privacy protection frameworks outline the best practices for data storage, sharing, and access, while explanation standards provide guidelines for communicating AI-driven insights to patients. Safety and toxicity evaluation criteria define safety and toxicity criteria for nanomaterials used in medical treatments.Global health equity guidelines promote global health equity in the adoption and implementation of AI-enabled nanomedicine, addressing disparities in access to advanced medical technologies on a global scale. A regulatory adherence framework outlines steps for adherence to healthcare regulations and standards relevant to AI-enabled nanomedicine, providing clear guidelines for obtaining regulatory approvals and ensuring ongoing compliance. Continuous education and training of healthcare professionals on ethical considerations of AI-enabled nanomedicine are also crucial. These guidelines ensure that professionals stay updated on evolving ethical standards and the best practices. By implementing robust monitoring mechanisms and following comprehensive ethical guidelines, stakeholders can navigate the ethical challenges associated with AI-enabled nanomedicine, fostering responsible development and deployment in the healthcare sector. Nanotechnology research should be permitted to proceed, but with non-governmental advisory council to oversee the research and assist in developing ethical standards. To prevent the technology from becoming too potentially destructive, guidelines for responsible and trustworthy artificial intelligence should be devised. While nanotechnology is still in its early stages, it is crucial to investigate its ethical implications [34].

v. *Standards and Regulations*: The document outlines five standards for AI-enabled nanomedicine: Data Privacy Standards, Algorithmic Fairness Standards, Explainability and Transparency Standards, Informed Consent Guidelines, and Safety and Toxicity Evaluation Criteria. These standards aim to ensure secure patient data handling, algorithmic fairness, explainability and transparency, informed consent guidelines, and safety and toxicity evaluation. Data Privacy Standards ensure compliance with data protection laws and establish protocols for anonymization and encryption. Algorithmic Fairness Standards evaluate and mitigate bias in AI algorithms, ensuring fair treatment across diverse patient populations. Explainability and Transparency Standards set standards for AI algorithms' explainability in medical decision-making, while informed consent guidelines ensure clear information about AI and nanotechnology's role in healthcare interventions. The text outlines the regulations and standards for the ethical development and deployment of AI-enabled nanomedicine in healthcare. It outlines the Data Protection Regulations, which mandate the protection of patient data and penalties for unauthorized access or privacy breaches. The Ethical Oversight Framework establishes regulatory frameworks for ethical oversight in AI development and deployment, defining the responsibilities of regulatory bodies. The Global Health Equity Regulations address global health disparities in AI-enabled nanomedicine adoption and promote equitable access to advanced medical technologies. The Compliance with Existing Healthcare Regulations ensures AI-enabled nanomedicine complies with existing standards and develops specific regulatory pathways for the approval and monitoring of AI-driven medical interventions. The Continuous Monitoring and Reporting Requirements mandate regular audits to assess algorithmic performance and address ethical concerns. The Professional Standards for Healthcare Providers define professional standards for AI-enabled nanomedicine, ensuring they are trained to ethically integrate and interpret AI-driven insights in patient care. Intellectual Property Regulations address intellectual property rights in AI-enabled nanomedicine, balancing innovation with accessibility, and affordability. Public Engagement and Consultation Requirements ensure diverse perspectives are considered in ethical decision-making processes. To keep up with the rapid speed of technological breakthroughs in AI-enabled nanomedicine, governments and regulatory authorities must adapt. To guarantee safety and effectiveness, it is crucial to establish precise norms and standards.

vi. *Interoperability*: The ethical aspects of AI-enabled nanomedicine include patient-centric interoperability, data exchange standards, consent management across systems, cross-institutional collaboration, transparent data usage policies, the potential impact on vulnerable populations, continuity of care, interoperability standards for AI models, cybersecurity in interoperability, and education and training for healthcare professionals. Patient-centric interoperability aims to empower patients to access and share their health data seamlessly, aligning with ethical principles of autonomy and informed consent. Data exchange standards promote transparency, reduce data silos, and facilitate collaboration. Consent management across systems ensures patient consent preferences are respected and upheld, maintaining ethical integrity. Cross-institutional collaboration enhances collective knowledge and promotes ethical best practices, contributing to improved healthcare outcomes. Transparent data usage policies ensure patient trust and ethical data practices within AI-enabled nanomedicine. The potential impact on vulnerable populations requires special attention to ensure equitable access and benefits across diverse patient groups. Continuity of care is an ethical imperative, and interoperability supports the seamless exchange of patient information. Standards for AI models facilitate interoperability, ensuring consistent and reliable performance. Cybersecurity measures are prioritized to protect patient data during interoperability, aligning with ethical principles of privacy and security in AI-enabled nanomedicine. Education and training on interoperability are essential for healthcare professionals to understand the ethical implications of interoperability in AI-enabled nanomedicine. By addressing these ethical considerations, stakeholders in AI-enabled nanomedicine can promote interoperability that respects patient autonomy, enhances collaboration, and prioritizes equitable healthcare outcomes. To prevent potential issues and guarantee efficient healthcare delivery, it is crucial to make sure those AI systems and nanorobots from various manufacturers can collaborate easily [35].

vii. *Transparency and Comprehensibility*: AI-enabled nanomedicine is a rapidly evolving field that requires a multifaceted approach to ensure its ethical and responsible integration. This involves several key aspects, including algorithmic transparency, explanation of AI decisions, patient-facing explanations, user-friendly interfaces, access to algorithmic insights, documentation of AI models, education on AI for healthcare professionals, handling uncertainties and limitations, public awareness campaigns, and ethical considerations in design and development. Transparent algorithms foster trust by allowing healthcare professionals and patients to understand how decisions are made. Clear explanations of AI decisions are essential for informed decision-making and gaining patient consent. Patient-facing explanations communicate AI-driven insights to patients in a comprehensible manner, promoting transparency and trust. User-friendly interfaces enhance the adoption of AI technologies while ensuring ethical and accurate usage. Access to detailed insights generated by AI algorithms aids clinicians in making well-informed decisions, aligning with ethical principles. Comprehensive documentation supports accountability and ethical oversight. Education on AI for healthcare professionals enhances their understanding of AI technologies, enabling them to navigate ethical considerations and integrate AI into healthcare responsibly. Public awareness campaigns help educate the general population about the role of AI in healthcare, fostering a sense of autonomy and trust. Ethical considerations are integrated into the design and development phases of AI-enabled nanomedicine, mitigating potential issues and ensuring transparency and comprehensibility. Continuous improvement mechanisms based on feedback from healthcare professionals and patients allow for the correction of ethical concerns and ongoing alignment with ethical principles. Patients and healthcare professionals need to have access to information about the inner workings of AI algorithms and the capabilities of nanorobots. This openness promotes confidence in the technology. Medical treatment decisions made by AI need to be comprehensible, especially for healthcare practitioners. For efficient cooperation between human specialists and AI, it is essential to comprehend the reasoning behind AI recommendations [36].

Future Directions and Opportunities in AI-based Nanomedicine Research

By enabling the acquisition and analysis of massive amounts of data, enhancing the precision of molecular profiling, early patient diagnosis, and optimizing the design pipeline of nanomedicines, the integration of artificial intelligence (AI) and nanotechnology has the potential to revolutionize the healthcare industry. Remote science and AI have a bright future in nanotechnology automation because they can tailor therapeutic nanoparticles to specific cell types and patients [37]. Future directions and prospects in AI-based nanomedicine research include the ones listed below:

i. Future directions in AI in nanomedicine research include predicting novel molecules with therapeutic potential, enhancing AI algorithms for hit and lead compound identification, using deep learning for Structure-Activity Relationship (SAR) prediction, implementing generative models for molecular design, developing multi-objective optimization in drug design, integrating quantum computing, building AI-driven virtual screening platforms, applying transfer learning techniques to accelerate progress in drug discovery, emphasizing explainable AI models in drug design, combining AI methods with de novo drug design approaches, and creating collaborative AI platforms for drug discovery. These advancements aim to accelerate drug discovery by generating hypotheses for previously unexplored chemical structures, expediting the identification of potential drug candidates. Deep learning can be used to predict complex SAR patterns and optimize molecular structures, improving the understanding of how changes in molecular structure impact biological activity. Generative AI models can create novel molecular structures with desired therapeutic properties, expanding chemical space exploration and offering innovative compounds that may not have been considered through traditional approaches. Integration of quantum computing could significantly speed up computations, allowing for more accurate and efficient predictions in nanomedicine research. AI-driven virtual screening platforms can increase the efficiency of lead compound identification, saving time and resources in the drug discovery pipeline. Transfer learning techniques can leverage knowledge from one drug discovery project to accelerate progress in another, fostering a more collaborative approach to drug development.

ii. Personalized treatment plans can improve efficacy while minimizing adverse effects, enhancing overall patient outcomes. Real-time adaptive dosing algorithms can adapt nanomedicine doses in real-time based on dynamic patient responses, allowing precise adjustments to treatment regimens. Integrating AI predictions with comprehensive patient health data, including genetics, lifestyle, and biomarkers, enhances the accuracy of dose predictions by considering a broad range of factors influencing treatment response. Continuous monitoring for response prediction allows for early identification of response patterns, allowing for timely adjustments to treatment strategies. AI-driven biomarker identification enhances the ability to tailor nanomedicine treatments to patients with specific characteristics, improving overall efficacy. Adaptive clinical trial designs apply AI to design dynamically adjust dosing based on ongoing efficacy predictions, accelerating drug development and ensuring efficient and responsive clinical trials. Combination therapy optimization extends AI predictions to optimize nanomedicines, leading to more effective and personalized therapeutic approaches. Ethical considerations related to AI-assisted dosing, including patient autonomy, consent, and transparency, are also addressed. Establishing ethical guidelines to ensure responsible and patient-centred use of AI in treatment planning is crucial for future advancements in AI-based predictions for nanomedicine dose and treatment efficacy.

iii. AI-based nanoparticle medication delivery systems have the potential to significantly advance the field of nanomedicine by offering more precise, adaptable, and patient-specific therapeutic interventions. AI algorithms can also enable nanoparticles to adapt their behaviour in response to changes in the patient's physiological conditions, ensuring consistent therapeutic efficacy. Patient-specific drug delivery optimization can be achieved by analysing patient-specific data and optimizing drug delivery strategies based on patient characteristics. Real-time imaging and monitoring can be enabled by integrating AI with imaging technologies to enable real-time monitoring of nanoparticle distribution and drug release. AI-enhanced nanoparticle formulation design can be optimized using AI algorithms considering factors like stability, biocompatibility, and drug-loading capacity. Drug resistance prediction and adaptation can be achieved by developing AI models to predict the likelihood of drug resistance and enable adaptive nanoparticle delivery strategies. Regulatory compliance and safety assurance can be ensured through AI-driven systems for monitoring and ensuring regulatory compliance and safety in nanoparticle medication delivery. Global accessibility of nanomedicine can be enhanced by investigating AI-based strategies to enhance the accessibility and affordability of nanoparticle medication delivery systems [38].

iv. AI-driven design of targeting ligands and patient-specific biomarker analysis are also areas of focus. Automated nanoparticle synthesis and characterization will be developed using AI algorithms, streamlining the manufacturing process and ensuring consistency in nanoparticle production. AI-driven adaptive surface modifications will enhance targeting efficiency by dynamically responding to changes in the cellular microenvironment. Robotics integration in nanoparticle assembly will expedite the production of advanced nanoparticles with diverse functionalities for targeted therapies. AI-Assisted drug loading optimization will improve the efficiency of drug encapsulation, ensuring optimal therapeutic payload in each nanoparticle. Automated *in vitro* and *in vivo* testing platforms will be developed with AI-driven analytics for tailored nanoparticle testing. Real-time imaging feedback systems will be integrated with AI algorithms to monitor the distribution and behaviour of tailored nanoparticles *in vivo*, providing immediate feedback for adapting nanoparticle formulations and treatment strategies based on *in vivo* observations. Automated data analysis for clinical decision-making will be developed using AI to interpret complex data from clinical trials involving tailored nanoparticles. Automated quality control and assurance will be implemented to ensure the safety and efficacy of tailored nanoparticles, maintaining consistent quality standards and expediting the regulatory approval process. Global collaborative platforms will be established where researchers can share data, AI models, and automation protocols for tailoring nanoparticles. This integration of automation and AI in the tailoring of therapeutic nanoparticles will unlock new possibilities for precision medicine, optimize treatment strategies, and pave the way for personalized and efficient nanomedicine interventions.

v. AI-based nanomedicine research will involve employing advanced computational algorithms to analyse large-scale omics data for biomarker identification relevant to nanomedicine. This will enable the discovery of novel biomarkers for patient stratification, treatment monitoring, and personalized interventions. Integrated Multi-Omics Data Analysis: It will involve developing computational frameworks to integrate multi-omics data (genomics, proteomics, and metabolomics) for a holistic understanding of nanomedicine responses. This will enable comprehensive insights into the complex interactions between nanoparticles and biological systems, informing tailored therapeutic strategies. AI-Enhanced Image Analysis for Nanoparticle Tracking. It will also involve implementing AI algorithms for precise analysis of imaging data to track the distribution and behaviour of nanoparticles *in vivo*. This will enhance our understanding of nanoparticle pharmacokinetics, aiding in the optimization of drug delivery strategies. Developing computational models using AI to predict nanoparticle-cell interactions, guiding the design of nanoparticles for enhanced efficacy. This will also help in the development of safe and effective nanomedicine interventions.

vi. AI-driven data analysis and processing paving the way for faster, more cost-efficient drug discovery, screening, and application [39]. High-throughput screening automation will be integrated to analyse large datasets, accelerating the process and reducing time and cost associated with screening. AI-driven predictive models will be developed to analyse and predict drug-target interactions, enhancing lead identification efficiency. Virtual screening platforms will be implemented to analyse molecular interactions and design potential drug candidates, saving time and resources in the drug design phase. AI will also optimize nanoparticle formulation design, considering factors such as stability, drug loading, and release kinetics. Data-driven patient stratification will be utilized to analyse patient data for stratification in clinical trials, enabling more targeted and efficient clinical trials. Incorporating real-world evidence (RWE) will enhance understanding of nanomedicine effectiveness in real-world scenarios, guiding decision-making and reducing development risks. Automated literature mining for target identification will be implemented to expedite target identification and provide valuable insights for drug discovery. AI-Assisted biomarker discovery will be utilized to analyse complex biomarker data for disease profiling and therapeutic target identification. Continuous learning systems will be developed to ensure drug discovery processes remain agile and responsive to emerging knowledge, reducing the risk of costly setbacks. AI-driven quality control in manufacturing will improve manufacturing efficiency and reduce errors. Robotic automation in laboratory workflows will be integrated to increase efficiency and reproducibility, making drug discovery processes faster and more cost-effective. Cloud-based collaborative platforms will facilitate knowledge exchange, accelerate drug discovery efforts, and foster a collaborative ecosystem in nanomedicine research.

Conclusion

An important development in the nexus of cutting-edge technology and healthcare is the incorporation of artificial intelligence in nanomedicine. The intersection of AI and nanomedicine holds enormous promise as we embark on a journey into a time of previously unimaginable medical challenges and opportunity. Diagnostics, drug delivery, treatment customisation, and our comprehension of intricate biological systems could all be revolutionized by this combination. With the help of AI-driven algorithms, large datasets may be quickly analysed to provide insights into disease mechanisms, find potential new medication candidates, and create treatment plans specifically for each patient. On the other hand, nanomedicine develops various cutting-edge materials and techniques at the nanoscale that can accurately target disease areas, improve drug delivery, and reduce side effects. The fusion of artificial intelligence (AI) and nanotechnology is poised to revolutionize the field of nanomedicine. AI can address challenges in fabrication and targeted drug delivery for cancer therapy, as it quickly mines data and makes judgments. The integration of biology, AI, and nanotechnology is fostering a scientific and technological revolution. AI algorithms can improve the design of nanotechnologies for diagnostics and treatment, optimizing material properties based on interactions with target medications, biological fluids, immune systems, and cell membranes. Fostering multidisciplinary collaboration, upholding ethical standards, and remaining watchful in addressing potential difficulties are crucial as we move forward. Artificial intelligence's incorporation into nanomedicine is not merely a technological accomplishment; it also demonstrates our dedication to promoting human health and wellbeing. We are on the verge of a brighter, healthier future thanks to careful management and the ongoing commitment of researchers and healthcare professionals.

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Authors' contributions

All authors contributed toward data analysis, drafting, and revising the paper and agreed to responsible for all the aspects of this work.

Conflict of interest

The authors declare that they have no conflicts of interest in this article.

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