



Review

A Comprehensive Review on the Development of Nanotechnology by Artificial Intelligence

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ABSTRACT

Many sectors, including healthcare, energy, and materials research, stand to gain greatly from the combination of nanotechnology (NT) with artificial intelligence (AI). Through its examination of AI-driven NT development, this research emphasizes how AI has the ability to speed the discovery, design, and growth of nanomaterials and nanosystems, so revolutionizing their fabrication. Optimised nanosensors for biological monitoring, improved drug administration, and energy usage prediction based on material properties are just a few possible uses. Problems with existing AI systems include a lack of reliable datasets and a lack of mechanisms to connect theoretical models with real-world validation. Algorithmic prejudice, data privacy, and social repercussions are all important ethical factors to consider. To guarantee equitable and advantageous AI-driven NT integration, the research stresses the significance of responsible and ethical development, open legislation, and stakeholder engagement. If we want to make the most of this confluence, we need to work together across disciplines in academia, address ethical problems, and get the public involved. By using this route, we want to increase the beneficial effects of AI-NT synergy in a number of domains.

Keywords

Deep learning; Machine learning; Nanomaterials; Nanorobotics; Nanosensors.

INTRODUCTION

By bringing together experts from other fields, we can build on our history and prepare for the future via transdisciplinary dynamics, which will allow us to construct an inclusive vision of AI-NT in this rapidly evolving 21st century [1]. A study of AI that draws from several fields Artificial intelligence (AI) and nanotechnology (NT) have the potential to revolutionize several industries, which would have enormously positive impacts on global economies and society. The exceptional material management and atomic accuracy of NT are the foundations of its exceptional compatibility. Changing science of nanomaterials [2,3]. Methods for modifying a material's characteristics are classified according to the ways in which atoms and molecules interact with the surface or substrate of an item. The field of nanotechnology seeks to comprehend and manipulate matter on a scale ranging from around 1 to 100 nanometers. Both naturally existing compounds and those engineered specifically for nanoscale characteristics may do this [4]. Nanostructure manufacturing is primarily guided by two methods: "bottom-up" and "top-down." While top-down approaches re-

duce bigger materials to the nanoscale, bottom-up methods build structures from atomic or molecule components. Combining the two approaches, a hybrid method uses precision engineering methods to direct molecular arrangements (top-down augmenting bottom-up) and natural molecular assembly processes to build tiny systems (bottom-up informing top-down). By combining the best features of the two approaches, nanofabrication becomes more flexible and efficient [5].

Slow demand and an emphasis on empirical knowledge defined technical progress in antiquity. Macroscopic studies predominated in contemporary economics, urban planning, and warfare, whereas industrial chemistry, biology, medicine, and astronomy relied on the actual application of processes and forces rather than on precise theoretical frameworks [6](Fig. 1). Scales below 100 are used in nanotechnology, which involves controlled manipulation of atoms and molecules.

Micrometers, where phenomena are found to be substantially differ-



ent from what is seen in traditional materials. Quarks, galaxies, biological cells, electronics, polymers, diamonds, superconductors, and heat transport phenomena all come together in this discipline, which is sometimes characterized as a multidisciplinary playground [7–10]. In this research, we look at how artificial intelligence (AI) and neural networks (NT) may work together to change many different industries, such as healthcare, energy, biology, and materials science. Highlighting possible ethical and regulatory concerns, it investigates the present uses, constraints, and future paths of AI-driven NT development.

Nanotechnology and ai integration

An interdisciplinary field, nanotechnology encompasses a wide range of techniques for precisely determining and manipulating matter on an atomic and molecular scale [11]. When it comes to forecasting material qualities and phenomena and balancing the experimental effort needed, artificial intelligence (AI) has the potential to take nanotechnology to new heights [12]. In order to address pre-processing issues with AI used for cancer cell segmentation, which necessitates specific image contrast methods for optimal detection [14], researchers are using AI frameworks to study the shape of nanoparticles and the influence of biomolecules, leading to the development of more specific and efficient image contrast agents [13]. To create a new high-produced contrast within the theoretical limits, scanning transmission electron microscopy

(STEM) imaging primarily relies on phase contrast detection, which can be achieved by combining AI techniques from a deep learning framework with a classical physical model approach in a single AI simulation program [15]. By combining AI with electron microscopy, the interaction between nanoparticles and cells can be better understood. The intricacy of dynamic biological properties can be managed by using AI to anticipate surface- interface-environment interactions of any nanomaterial, according to recent work using hybrid techniques [16]. In addition, there are AI-powered methods for predicting the body's chaotic reaction to nanoparticles while keeping tabs on the residence time (a critical parameter for predicting how nanomaterials will behave in the human body) and the equilibrium binding constant, which is influenced by surface charge and encapsulation [17].

Nanorobotics

As pivotal components in local systems independent of external infrastructure, nanorobots show promise in intracellular medicine for combating diseases. For instance, self-organized drug administration could potentially reduce or eliminate chemotherapy doses, while minimizing off-target effects. These systems might utilize wireless energy supply and multi-level communication networks within the body [18]. This section explores crucial aspects such as localization, movement control, communication, and cooperation, which are essential for developing 3D nanorobot swarm operating techniques. These techniques envision the use of area-specific online robots and cell-swarm robots equipped with advanced technologies like machine intelligence [19]. Concurrently, numerous studies focus on nanorobotic applications involving single-axis motion [20–22]. Various nanorobot designs have emerged (Fig. 2), including the lens-shaped “cheetah” nanorobot, the kener parapheto nanorobot, and the lemniscate nanorobot, all utilizing bounce motion for propulsion [23]. This groundbreaking work has inspired subsequent research

aimed at exploring the potential of mesoporous “nanotube-based” structures as carriers for “short strand” media containing single or multiple tumor cells [24, 25].

These advancements in nanorobotics demonstrate the field's potential to revolutionize targeted drug delivery and cancer treatment (Fig. 3). By combining precise localization, controlled movement, and intelligent communication systems, nanorobots could offer unprecedented accuracy in navigating the complex cellular environment. Furthermore, the development of specialized nanorobot designs tailored to specific medical applications highlights the versatility and adaptability of this emerging technology [26–28].

As a commercial sector, nanorobotics—the use of nanotechnology to robotics—is still in its early stages. Advanced group-oriented nanorobots are planned for use in broader contexts, like industrial processes and environmental cleaning, while autotelic and localized nanorobots are anticipated to primarily operate in-vivo in the near future [30]. Heavy research is being conducted on high-level supervisory challenges for big groups of offline, networked robots in many prospective applications because to the lack of relevant practical experience at the idea level. Starting with nanorobot operating platforms in 3D environments, where practical problems do not greatly impact movement strategies, the next step is to realize these platforms in order to test critical clustered autonomous technologies.

This will guarantee that communication, energy collection, localization, and localized collaborations are all properly addressed for any specific formation type.

Nanosensors

As far as nano-sensors and AI are concerned, human health might be among the most dynamic areas where the fastest progress has been observed. Fabricating nano-sensors is now possible thanks to advancements in nanotechnology and manufacturing. The great sensitivity and selectivity of the point-of-care system are achieved by using nano-scale polymeric materials, metals, graphene, carbon nanotubes, and quantum dots [31]. Although systems based on nano-sensors have the potential to be useful, the use of big data and AI to achieve these goals raises ethical questions because they involve the collection of vast quantities of personal and in-vivo data. Their current uses are the Internet of Things technologies that people use. Once again, sensors integrated with nano-technological breakthroughs fall within the category of communication and networking. The future of bio-electronic devices will be determined by the extent of integration of nano-sensors, AI, and the Internet of Things [12]. The capabilities of nano-sensors (NS) have been enhanced through the integration of artificial intelligence (AI). Machine learning (ML) techniques and artificial intelligence (AI) have made it possible to accurately recognize and identify target molecules. Making sensors that are both smaller and more sensitive and repeatable has been the primary focus of most recent developments in nano-sensors. But there have been higher-level reports of applications where nano-sensors and AI have demonstrated the capacity to work on real-time data acquisition and accurate prescriptive solutions for cancer genetics [32], pathogen detection (Fig. 4), bio-marking [35], agriculture [36], etc. (Fig. 5). A low-cost sensing system that is secure, accurate, and made possible by the successful combination of two fast-growing technologies—nano-sensors and AI. There is almost limitless poten-



tial in healthcare (Fig. 6), the food sector, mobile applications, energy conversion, and social life [39, 40,41], although most applications and research studies in these areas have been primarily concentrating on industrial and military uses now.

Smart Nanomaterials

Nanotechnology developments have necessitated multifunctional materials. Nanomaterials have excellent physio-chemical properties for their small size, including enhanced absorption and reactivity, surface area, molar extinction coefficients, tunable plasmonic capabilities, quantum effects, magnetic and optical properties. Non-biocompatible, poor photostabilities, low targeting capacity, rapid renal clearance, side effects on other organs, insufficient cellular uptake, and small blood retention make nanomaterials difficult to use for

better therapeutics in biomedicine, so “smart” nanomaterials must be developed (Fig. 7). Modern science developed a nanomaterial that changes its physical, chemical, or biological properties significantly in response to modest environmental changes [42].

Rapid microbial lysis was achieved by interacting with the bacterial cell membrane using nanoparticles of titania (nano-TiO₂) in conjunction with vancomycin or gramicidin S [42]. such as the production of ROS and the subsequent triggering of cell death in response to bacterial cell disruptions. By releasing oligodynamic ions, metallic silver inhibits microbial development by severely damaging microbial DNA and proteins as well as bacterial anions. The weakening of the influenza virus envelope and a decrease in the virus’s infectivity are the first two causes of antiviral activity in nanomaterials like TiO₂-Vanc or TiO₂-GS. The second cause is the development of huge Mont. By attaching to lipids on the influenza virus’s envelope, mont complexes establish robust HC contacts with the virus [43]. Zinc oxide and silver nanoparticles bound to acrylonitrile, sodium dodecyl sulfate, trisodium citrate, and citric acid, in varying proportions, may also possess antiviral properties[44]. Beyond their antimicrobial and antiviral effects, nanomaterials can also exhibit antioxidant properties[45], which are essential for human health. Antioxidants protect cells from the damaging effects of reactive oxygen species (ROS), which are implicated in a wide range of diseases, including cardiovascular disease, cancer, and neurodegenerative disorders[46]. Some nanomaterials, such as those containing selenium or zinc, have shown promise as antioxidants in preclinical studies. The ability to design nanomaterials with tailored antioxidant properties could lead to the development of novel therapies for these conditions. The fight against popular parasites such as Plasmodium lead to malaria [47], and biofilms [48] also benefits from nanotechnology. These microorganisms can cause severe complications. Nanomaterials have been investigated as potential anti-parasitic and anti- bacterial agents, targeting various stages of their life cycle. For example, nanoparticles can be designed to disrupt the cell membrane, inhibit metabolic processes, or even deliver drugs directly to the site of infection. This area of research holds immense promise for developing novel treatment strategies for many diseases caused by microbes[49]. Nanomaterials with biocompatibility, directed cell proliferation and destruction, resistance to macrophage recognition, immune response inhibition, and controlled release of therapeutic agents that interact with target cells specifically are ideal for nanosmart functionality [50].

Challenges and opportunities

Artificial intelligence (AI) will be an integral part of the upcoming scientific and industrial revolution, both as a tool for cooperation and in practical industrial applications. The use of AI in conjunction with human supervision has the potential to greatly facilitate the processing of anatomical and functional images, the enhancement of human knowledge agents, and the acceleration of the exceedingly complicated processes involved in human cell and tissue cultures. In light of the worldwide demand for cutting-edge AI treatments and the present rate of AI medical device development, nanomaterials will play an essential role in AI interventions within the pharmaceutical and healthcare industries. In the future, AI can help in the design and development of smarter, more efficient, and more tailored nano-therapies for human disease [41,51].

Innovative nanomaterials, nanodevices, and nanosystems form the basis of the fast expanding field of nanotechnology. Nanotechnology has come a long way since its inception, with notable advancements in fields including electronics, biosensors, field effect transistors, and nanoparticles. There are several important challenges that need to be addressed when applying artificial intelligence (AI) to nanosciences. These include ensuring the reliability of methodologies and results, balancing physical and algorithmic models, adaptability of materials, and predicting the accuracy and uncertainty of generative models. One area of nanomedicine that is seeing fast growth is artificial intelligence (AI) in medication delivery. By combining AI with nanotechnology, researchers and pathologists can overcome medical challenges [52,53,54]. Indeed, models powered by AI can be employed to expedite the creation of medication delivery materials and to evaluate anomalies that are specific to both the system and individual tissues. Robust designs, guided by genetic and evolutionary algorithms, can produce new smart nanomaterials that overcome many biological obstacles and pathological causes, leading to successful targeted drug delivery in cancer treatment [17].

Ethical considerations

Ethical considerations surrounding artificial intelligence in nanotechnology extend far beyond the realm of employment and into every aspect of life on Earth. Additionally, AI now has several ramifications for development, privacy, security, and safety [51,55,56]. Structures are often amplified by AI. The historically oppressed in nano-tech may find themselves further excluded as a result. The medium of human understanding will be used by AI to support human meaning and culture infrastructures, and by scientists and doctors to consider the social and cultural impacts of AI-assisted systems [57]. AI also has plans for future formal moral agency.

The Anthropocene or Multitudeocene, a world that is becoming more algorithmically interfaced, has ethical issues that connect with

human knowledge and action. Within the more specific realm of unsocialized nano-AI evaluations, there are ethical considerations regarding operationalization and the handling of nano-AI mobile devices in a space-sharing setting [58].

Numerous moral concerns arise from the potential use of AI in the advancement of nanotechnology. Combining nanofabrication with molecular computation, for instance, has the ability to bring forth



new degrees of control and new physical systems (such synthetic molecular systems or biological cells). Elaborate analysis of the sociological, economic, and technical effects of this convergence is necessary. The purpose of this chapter is to analyze the potential ethical problems that might arise from using AI to advance nanotechnology. New methods of conducting ethical assessments are necessary in light of the emerging technology of global nano-transformations [59,60]. Given the abundance of other applications for artificial intelligence and nanotechnology, this raises concerns about how to balance the potential benefits of nano-AI systems on human health with the potential risks that unsocialized, worldwide nano-AI systems pose to human health [8,61].

The integration of AI and NT in medical applications must be approached with careful consideration of ethical and regulatory issues. These include ensuring patient data privacy, addressing algorithmic biases, and developing transparent regulatory frameworks to oversee the development and deployment of these technologies. Continuous stakeholder communication and collaboration are essential to address these concerns and ensure the responsible development of AI-driven NT in medicine [81].

Current applications and limitations

Nanomedicines improve cancer cell drug delivery compared to free pharmaceuticals in lab experiments. Nanoparticles with targeting components can take in more cancer cells. A successful target is the scavenger receptor class B type I (SR-B1), which is abundantly expressed in numerous malignant cancer cells and murine HSCs. SR-BI-functionalized nanoparticles improve cancer cell uptake and restore HSC function in gene therapy. Nanomedicines' uneven human performance is the main impediment to clinical translation, despite encouraging preclinical outcomes. Understanding how nanomedicine's key components—polymer, drug, and active tumor-target ligand (P, D, A)—interact in healthy and malignant tissues is essential to closing this gap. Here, AI is powerful. AI may improve nanomedicine clinical outcomes by analyzing nanomedicine properties and their interactions with target cancer cells across models [10, 62].

AI also aids in the design of nanoformulations for specific therapeutic targets. A key premise of nanotechnology is its ability to design formulations that overcome biological barriers and enhance the efficacy of therapeutic drugs. For these formulations to effectively reach cells responsible for the pathology, they must be recognized by these target cells. Cell-based screens have proven valuable in providing critical information about the cellular uptake of nanomedicines. However, these screens are time-consuming, involving numerous low- and high-throughput experiments. To address this challenge and identify optimal nanocarriers more efficiently, researchers have developed new computational approaches utilizing AI. These AI-driven methods can predict nanocarrier uptake by specific cells, streamlining the design process and potentially accelerating the development of effective nanomedicines [12]. Multimodality therapy utilizing nanomedicines and conventional pharmaceuticals can be better planned and executed with the use of artificial intelligence.

Traditionally, trials that take a very long time to find formulations or dosages exhibiting certain behavior have been used to evaluate the

synergistic or antagonistic effect of various medications. Consistent with these limitations, AI has demonstrated the ability to foretell drug- nanoparticle interactions, which may pave the way for the development of nanomedicines with fewer side effects for patients [63].

Machine Learning

Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) have changed the field of sophisticated robotics in recent years. AI,

ML, and DL are changing the field of advanced robotics, making robots more intelligent, efficient, and adaptive to complicated jobs and situations. Some of the applications of AI, ML, and DL (Figs. 8 and 9) in advanced robotics include autonomous navigation, object recognition and manipulation, natural language processing, and predictive maintenance. These technologies are also being employed in the development of collaborative robots (cobots) that can work alongside humans and adapt to changing environments and tasks. The AI, ML, and DL can be applied in sophisticated transportation systems in order to bring safety, efficiency, and convenience to the passengers and transportation businesses. Also, the AI, ML, and DL are playing a crucial role in the evolution of manufacturing assembly robots, enabling them to work more efficiently, safely, and intelligently. Furthermore, they have a wide range of applications in aviation management, helping airlines to enhance efficiency, cut costs, and improve customer happiness. Moreover, the AI, ML, and DL can enable taxi firms in order to give better, more efficient, and safer services to clients [64].

Natural Language Processing

A significant link between carbon material structure and qualities is scientifically intriguing and promising for practical applications, according to [67]. Pressure coatings, sensors, fuel cells, catalysts, supercapacitors. Systematic research in this field are difficult because they require a diversity of carbon materials and physical- chemical characteristics. Thermogravimetric analysis provides crucial structural transformation

data [68]. Many articles have examined carbonized pitches and syn-carbons' supercapacitor characteristics. The quantity of affordable carbon materials and the ability to alter their properties are driving interest in their application in electrodes. Recent applications like controlling cytochrome c aggregation, manipulating iron- sulfur protein structural differences, and precisely decorating proteins with small molecules show great promise in this area. While it is still difficult to link structural changes to functionality in catalytic cycles, this research can help rationally design next-generation biomimetic systems that retain the redox and reactivity properties of natural metal centers while rationally incorporating protein- derived structural and dynamic features. The genotype/phenotype inconsistencies discovered during viral shedding indicate that the chemo- enzymatic synthesis of glycoproteins is still poorly understood. Assembly and modulation of signaling complexes can occur quicker than enumerating all conceivable interactions, and relative free energy calculation outperforms explicit thermodynamics. Kinases and multi-domain targets give a model for promiscuity and molecular recognition in networks using non-random, organized excitations [69].



Diagnostic Applications and Data Analysis

AI-enhanced nanosensors represent a groundbreaking advancement in medical technology, combining the sensitivity and specificity of nanotechnology with the data processing and predictive capabilities of artificial intelligence. These sensors are capable of detecting minute biological and chemical changes within the body, enabling early diagnosis and precise monitoring of diseases. AI algorithms process the vast amounts of data generated by these nanosensors, identifying patterns and providing actionable insights for medical professionals. Nanosensors are devices that operate at the nanoscale (1 to 100 nanometers) and can detect physical, chemical, or biological signals. They typically consist of a sensing element and a transducer that converts the detected signal into a measurable response. In medical applications, nanosensors can be designed to detect specific biomarkers—molecules that indicate the presence or progression of a disease[70].

AI algorithms, particularly machine learning and deep learning models, can analyze the data generated by nanosensors. These models are trained on large datasets to recognize patterns and anomalies that may be indicative of disease. For instance, in cancer detection, AI can analyze the concentration and behavior of specific biomarkers detected by nanosensors, distinguishing between benign and malignant cells with high accuracy. AI can optimize the sensitivity and specificity of nanosensors by fine-tuning their design and functionality. This involves adjusting parameters such as the type of sensing material used, the configuration of the sensor, and the signal processing methods. In detecting viral infections, AI can enhance nanosensors to differentiate between various strains of a virus, providing precise diagnostics and aiding in timely treatment decisions[52].

PRACTICAL APPLICATIONS

Cancer Diagnosis

AI-enhanced nanosensors can detect cancer biomarkers at very low concentrations, enabling early diagnosis when the disease is more treatable. For example, they can identify circulating tumor DNA or specific proteins associated with cancer. Conduct clinical trials with patients at high risk of cancer to validate the efficacy of AI-enhanced nanosensors in early detection. These trials can compare the performance of traditional diagnostic methods with AI-enhanced nanosensor technology. The steps of nanotechnology test the sensitivity and specificity of AI-enhanced nanosensors in detecting various biomarkers associated with diseases such as cancer, cardiovascular diseases, and infectious diseases. Develop nanosensors with different sensing materials and configurations. Use AI algorithms to process the data and compare the results with traditional diagnostic methods [71,72].

Infectious Disease Detection

Nanosensors can be used to detect pathogens such as bacteria and viruses. AI can analyze the sensor data to quickly identify the type of pathogen and its concentration. During an outbreak of a novel virus, AI-enhanced nanosensors can be deployed in hospitals and clinics to rapidly identify infected individuals, enabling swift isolation and treatment [73,74].

CONCLUSION

Nanotechnology powered by artificial intelligence can only progress with models that combine quantum and classical system descriptions. Chemistry and solid-state physics usually distinguish between numerous model levels when attempting to explain characteristics at sizes ranging from the microscopic to the macroscopic. Due of the exponential rise in computing cost as these systems get bigger and more complex, it is necessary to develop and improve efficient methods and software to handle the remaining unaddressed concerns. All sorts of systems, from tiny biomolecules to large proteins, their properties, open interaction chains, and phase transitions in condensed matter fall under this umbrella. Systematic research conducted with specialized computer programs may provide new answers in many scientific and technical sectors. Emerging nanostructures with potential applications in fields like molecular electronics and electrochemical detection in healthcare, as well as previously unknown or confirmed theories about environmental and quantum system interactions, techniques for filtration of power and communication at scales comparable to those of emerging nanostructures, and much more will be within reach. Interest in creating intelligent software systems has grown in recent years across many industries. Countless articles explore the possible applications of new software development methodologies and cutting-edge technology (like deep learning) in fields as diverse as medical diagnosis, weather prediction, structural analysis, and the creation of high-tech materials. They also debunk myths and provide explanations of how intelligent algorithm software operates. In a number of our publications, we show that AI opens up a world of new, unexpected possibilities for the design of new modern materials, especially those based on nanotechnology. To achieve improvements in fine-grained optimization, it is essential to use the right software and hardware. Modeling, synthesis, optimization, and materials science play crucial roles in nanotechnology, which is why AI is finding more and more uses in this field.

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