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Polymer Nanocomposites As Emerging Platforms in Pharmaceutical Nanotechnology

Lakshman Kumar Dogiparthi[1,*], Balakrishna Talamanchi[2], Mynam Harika[3], Vannappagari Prabhash[4], Raichur Ruhinaz[5], Kora keerthi[6], A. Jayanth[7], P. Amitha[8], Bezawada Siva Nagaraju[9], Guggulotu Vishnu Tulasi Naik[10]

Abstract

Nanotechnology allows the handling of materials in the 1–100 nm range, where distinct physicochemical phenomena, including quantum effects and higher surface-to-volume ratio, enable disruptive uses in pharmaceuticals and biomedicine. Significant challenges in solubility, stability and targeted biodistribution of therapeutics can be overcome by incorporating nanostructured polymers and polymer-based composites into drug delivery systems. PLGA nanoparticle and other nanocarriers, such as PLGA micelles, dendrimers, and hydrogels, have revealed promising effects on enhanced bioavailability and reduced systemic toxicity of chemotherapeutics, proteins, and nucleic acids. The non-covalent modification or immobilisation at specific locations on a drug has been achieved through smart polymer platforms which respond to pH, redox state and temperature enabling site-specific drug release and theranostic functionalities. The incorporation of artificial intelligence and machine learning extends to the design, optimisation and predictive modelling of the performance of polymeric nanomedicines. The recent developments in the areas of high-throughput screening, nano-enabled microfluidics and polymer-based nanocomposites and nanoscience and nanotechnology applications have facilitated drug discovery and have extended applications in bioimaging, sensing and environmental remediation with polymer based nanocomposites containing graphene, carbon nanotubes or iron oxide nanoparticles. Although encouraging, challenges such as difficulties in large-scale production, quality control, long term safety and harmonised standards continue to limit the clinical translation of nanomedicines. Ethical aspects of patient safety, data confidentiality and equitable accessibility should be addressed as well. The future brings personalized nanomedicine, self-governing intelligent nanorobots, green bio-degradable polymers, and lives feedback nanoplatforms. This discussion highlights the key role of polymeric nanocomposites in pharmaceutical nanotechnology and emphasizes the need of the interdisciplinary research and ethical governance in advancing safe, effective and accessible to globally nanotherapeutic solutions.

***Author for Correspondence**
Lakshman Kumar Dogiparthi

[1]Associate Professor, Department of Pharmacognosy, MB School of Pharmaceutical Sciences, Mohan Babu University, Tirupati, Andhra Pradesh, India
[2]Professor and HOD, Department of Pharmaceutics, V. V. Institute of Pharmaceutical sciences, Gudlavalleru, Andhra Pradesh, India
[3]Assistant Professor, Department of Pharmaceutics, V. V. Institute of Pharmaceutical sciences, Gudlavalleru, Andhra Pradesh, India.
[4-8]Student, Department of Pharmacognosy, Sree Vidyanikethan College of Pharmacy, Tirupati, Andhra Pradesh, India
[9-10]Student, Department of Pharmaceutics, V. V. Institute of Pharmaceutical sciences, Gudlavalleru, Andhra Pradesh, India

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INTRODUCTION

Definition of Nanotechnology

Nanotechnology deals with handling matter at scales between one to one hundred nanometers, where materials often have unusual physical, chemical and biological properties when compared to their normal forms [1]. Nanotechnology becomes significant at this level since quantum mechanical impacts appear, bringing about fresh phenomena called quantum confinement, tunneling and increased reactivity [2]. Nanotechnology includes a range of methods, for example, lithography or making things from bottom to top with self-assembly and molecular engineering, to manufacture useful devices [3]. Nanotechnology helps to explore science and also encourages many kinds of innovations, mainly by contributing to improvements in healthcare and pharmaceuticals [4]. The Polymeric Nanocomposites in Pharmaceuticals were showed in figure 1.

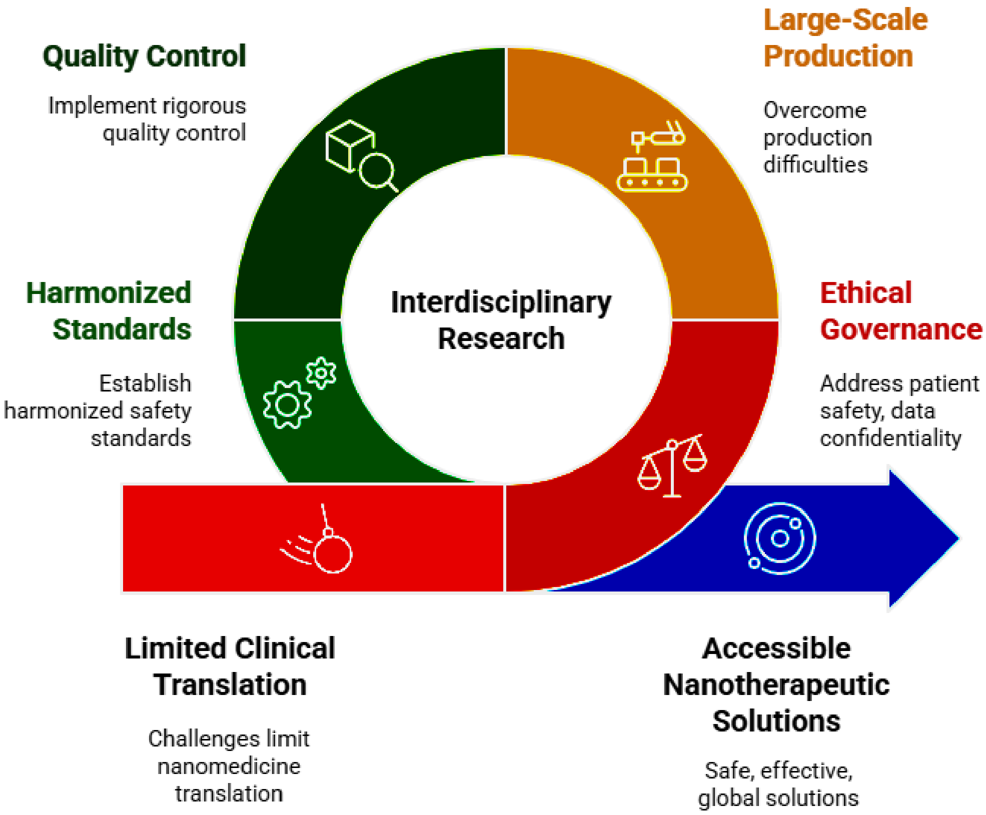

Figure1. Polymeric Nanocomposites in Pharmaceuticals

In pharmaceuticals, nanotechnology helps address problems with drugs that do not dissolve well, problems with reaching the blood and drugs that spread to parts they should not [5]. Many substances in medicine that are found naturally or chemically made, do not dissolve well in aqueous solutions which lowers their effect. This can be improved by using nanocarriers [6]. More therapies are using nanoparticles called liposomes, dendrimers, micelles and polymeric nanoparticles to treat diseases more effectively and experience fewer side effects [7]. When building vaccines and gene therapies, nanotechnology is necessary because nucleic acids such as mRNA and siRNAs need safeguarding during transportation into the cells as well as after delivery [8].

Recent developments in how nanoparticles are synthesized and modified have allowed scientists to make them fit for specific drug delivery and diagnosis roles [9]. Controlling the particle size, shape and surface chemistry which help to enhance the performance in the body which is possible with techniques like nanoprecipitation, microfluidics and electro spraying[10]. The adoption of artificial intelligence (AI) and machine learning (ML) in making nanoparticles helps set the best values for parameters such as particle size, electrical charge and coating molecules to improve their functions in biological processes [11]. Relying on AI algorithms, a large amount of data about nanoparticles and biology may be analyzed rapidly to predict how they interact, helping to improve the process of creating effective, rationally designed nanomedicines [12].

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This study aims to look closely at how nanotechnology is influencing pharmaceutical and biomedical research, including the latest findings, obstacles and digital technologies like AI and ML [13]. By blending information from nanoscience, pharmacology and biomedical engineering, this paper helps researchers and practitioners grasp the whole concept of the field [14]. A further goal is to assess the ethical and legal challenges involved in using nanomedicines, focusing on how they relate to safety, being open and having consent from patients [15]. The last goal of this paper is to support future research and teamwork between researchers, businesses and public authorities that focus on responsible progress in healthcare nanotechnology [16].

Purpose of the Study includes the following points:

- To look at the progress of nanotechnology in treating diseases by carrying drugs across the blood-brain barrier and other pathways [17].
- To point out that using AI and ML in nanoparticle development helps simulate and understand how drugs are carried, their effects on living cells and speeds up the process [18].
- To point out and discuss some of the main issues and dangers related to nanotechnology used in clinical practice, for example, differences in producing particles, difficult reproduction and missing long-term toxicity tests [19].
- To create future plans that involve smart robots, personalized drugs and containers that can be absorbed by the body which may lead to special care for each person, quick updates on health and completely safe delivery of drugs to patients [20].

BACKGROUND OF NANOTECHNOLOGY

The term nanotechnology was coined by Japanese researcher Norio Taniguchi in 1974 to indicate manufacturing where items are built using parts less than a nanometer, mainly for thin film coating and ion beam cutting [21]. Still, the origins of the field go back to Richard Feynman's 1959 presentation where he imagined controlling individual atoms and molecules to build miniature, advanced machines [22]. In the 1980s, K. Eric Drexler wrote the book Engines of Creation, describing atomically precise manufacturing and nanobots in a well-structured way [23]. The progress of this field increased when scanning tunneling microscopy became available in 1981 which made it possible for the first time to observe and manipulate single atoms. This accomplishment, together with the later introduction of atomic force microscopy (AFM), formed the fundamental basis for nanoscale research and fabrication [24]. By 2010, Japan, China, Germany and South Korea introduced national strategies for nanotechnology which resulted in more worldwide patents, startups and new academic programs [25]. Due to worldwide interest in nanotechnology, there were major advances in medicine, electronics, energy production and environmental science [26], proving that nanotechnology was no longer just a research subject but actual work applied in industries.

In nanoscale materials, the typical physical and chemical features often change such as more surface area, effects related to quantum physics and altered reactivity, solubility and strength [27]. When materials become nanoparticles, like quantum dots, quantum confinement occurs and changes their electronic and optical behavior so that fluorescence and bandgap energies can be controlled by adjusting the size of the nanoparticle [28].

A good example is gold nanoparticles which display optical properties and can look red or purple in colloidal form because conduction electrons on the surface resonate with incoming light [29]. A similar case is iron oxide (Fe_3O_4), as magnetic nanoparticles, that become superparamagnetic at the nanoscale and are used for MRI and drug targeting, since they no longer exhibit magnetism when the external field is removed.

Physics, chemistry, materials science and biology are some of the many science areas related to nanotechnology. This union makes it possible to construct systems such as nanocomposites, drug-delivery nanoparticles and nanoelectromechanical systems (NEMS) [28]. Due to its interdisciplinary character, it is possible to join chemical functionalisation of carriers with targeting by biological moieties, producing stimuli-responsive drug delivery systems that respond to changes in pH or temperature [29]. Nanocomposites have been invented in materials science by using nanotechnology to make materials that are strong and light, used in industries such as aerospace, automotive and implants [30]. Nanosensors, quantum dots and NEMS have been developed in physics and electronics and are now vital for applications like monitoring our environment and making better diagnostics [31].

Investment in nanotechnology across the globe is large, as markets are expected to top $125 billion by 2025 based mainly on opportunities in healthcare, electronics and energy [32]. The substantial investment from public and private sources, complemented by the U.S. Nanotechnology Initiative (NNI), has pushed for more research and commercialization in this field, totaling to over $29 billion invested since 2000 [33]. In addition, Horizon 2020 within the European Union has spent enormous funds to develop nanotechnology solutions for industry and a more sustainable future [34].

NANOTECHNOLOGY IN DRUG DISCOVERY

Using nanotechnology in drug discovery has made research more accurate and efficient and produces better results in less time [35]. With screening, researchers can handle more molecules at the same time, see results faster and use this data to optimize choices, all of which make drug design more efficient [36]. The joining of nanotechnology with AI and ML speeds up finding new drugs by identifying molecular connections, improving how nanocarriers function and saving time and money during preclinical work [37]. All in all, nanotechnology helps drugs get created more accurately, efficiently and in new ways by working together with standard drug development processes. Nanotechnology in Drug Discovery outline was shown in figure 2 as given below.

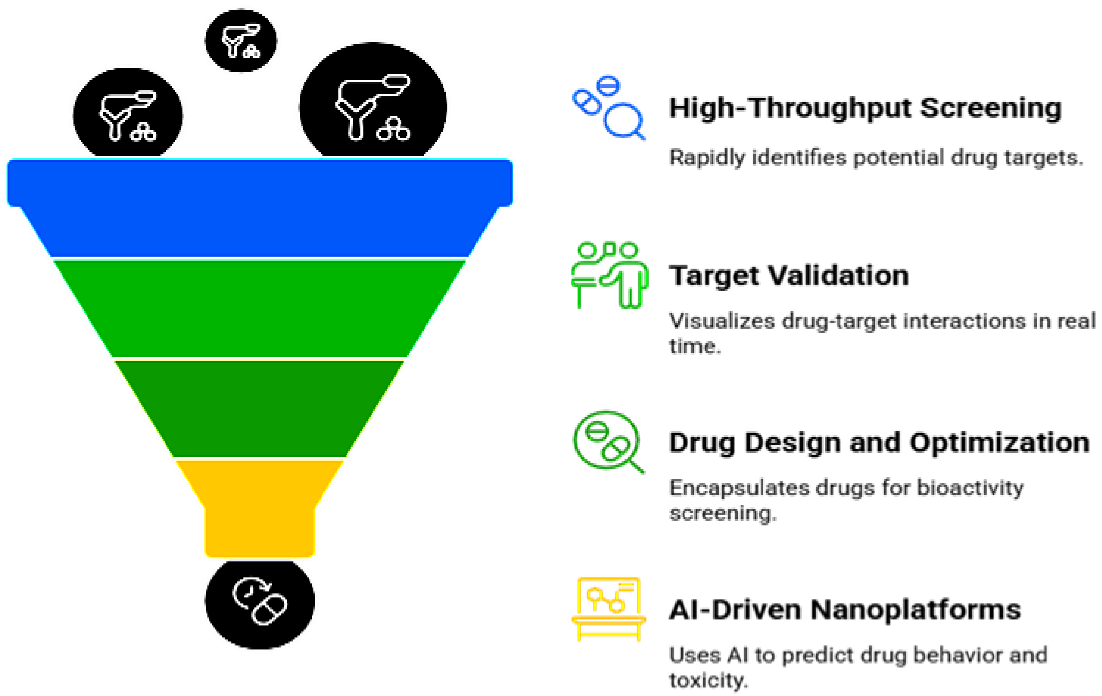

Figure 2. Nanotechnology in Drug Discovery

HTS (High-Throughput Screening)

Checking many candidate compounds, antibodies or genes at once with high-throughput screening is essential for finding ones that control a certain biomolecular pathway [38]. To make HTS platforms more sensitive and quick, scientists are using nanoparticles coated with ligands or antibodies [39]. Some technologies blend nanotechnology and AI to automatically identify the most promising compounds in HTS, improving its productivity [40]. In essence, HTS with nanotechnology brings faster results, higher precision and greater outcomes in exploring new drugs. The steps of HTS (High-Throughput Screening) are described in the figure 3.

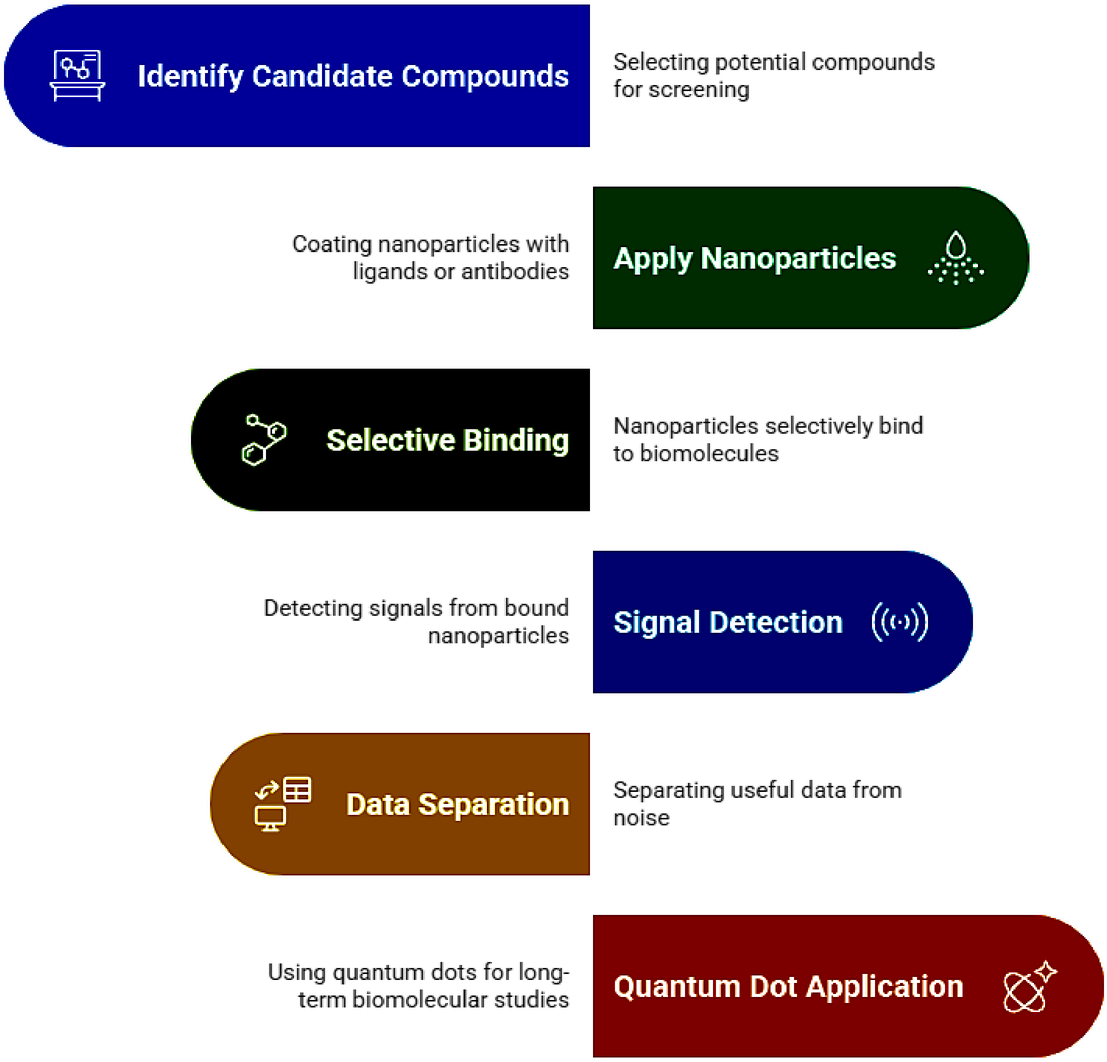

Figure 3. High Throughput Screening Process

Target Validation

Due to their stable and clear emissions, quantum dots (QDs) can help us to watch in real time as drugs interact with their targets, [41]. They confirm that a target is important and specific in the body and they are used for live imaging of cellular activities and receptor binding [42]. Targeted imaging and measuring the expression of receptors and cells can be done with QDs that have been combined with ligands, antibodies or aptamers and this is essential for validating potential drug targets [43]. By using carbon nanotube-based field-effect transistors (CNT-FETs), scientists can observe protein–protein and protein–DNA interactions directly and with a sensitivity of at least 1×10-12 molar. The flow of Biomarker Detection was described in the figure 4.

It is possible to detect events of targets binding to molecules through shifts in the resonance wavelength in localized surface plasmon resonance (LSPR) sensors that use gold or silver nanoparticles. Also with nanoparticle assays, it is possible to find and confirm several important biomarkers at one time which improves our understanding of when and why the targets are known to play a role. Combining nanotechnology and machine learning helps in examining data from biosensors to electronically detect genuine targets, asking for less help from people.

Drug Design and Optimization

In the process of developing new drugs, dendrimers, liposomes and polymeric nanoparticles help nanocarriers to solubilize poorly dissolving medicines by increasing their absorption. Because of this, researchers are now able to test more compounds, including some that were rejected before because of their solubility or stability issues. Screening many different types of nanoparticles quickly speeds up formulation discovery and assists with learning about the in vivo behavior of the nanoparticles. Because of their improvement on drug loading, stability and controlled release, NLCs and SLNs are now used more frequently in early drug development. Functionalizing nanoparticles with polyethylene glycol (PEG) or specialist molecular stuff makes it possible to send drug candidates only to needed tissues or cells and avoid affecting others. In addition, models based on AI are now being applied to nanoparticle design, helping to improve predictions about how nanoparticles interact with drugs which supports better drug development [44]. The sequence of Drug Design and Optimization was highlighted in figure 5.

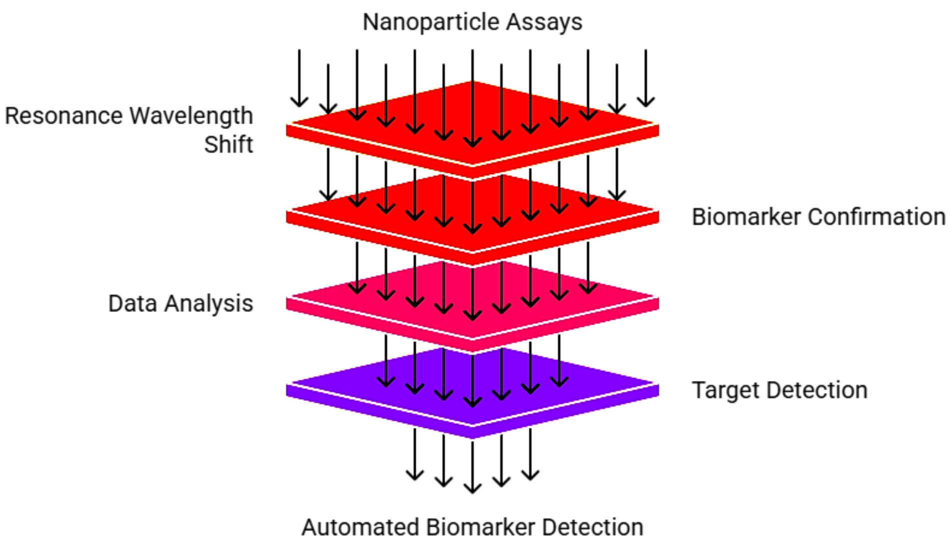

Figure 4. Biomarker Detection

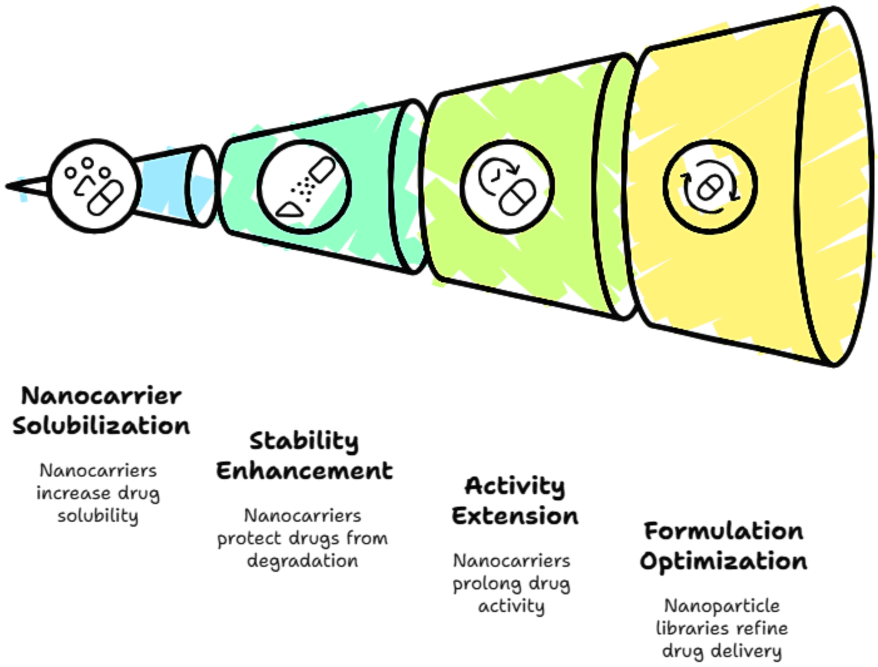

Figure 5. Drug Design and Optimization

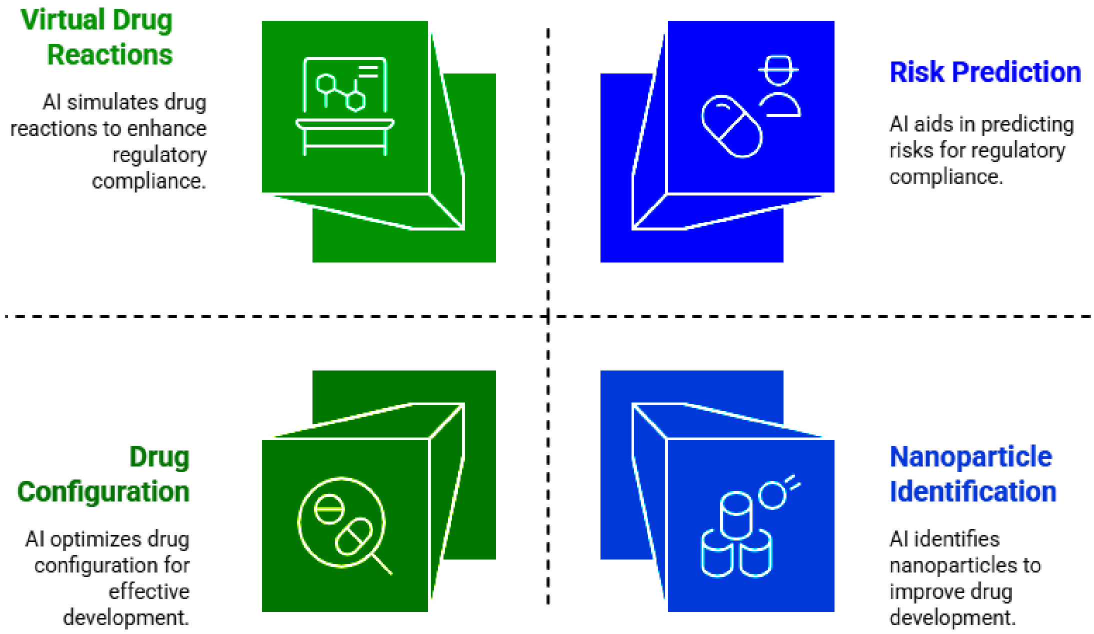

Figure 6. AI-Driven Nanoplatforms

AI-Driven Nanoplatforms

AI and ML play a major role in the predictive modeling used in nanotechnology today. By using artificial intelligence, tools can create virtual drug reactions with nanoparticles, improve therapy outcomes, estimate levels of drugs in the body and predict what side effects might occur.. In general, nanoplatforms based on AI are playing a huge role in shaping nanomedicines by simplifying the process, making it more effective and cost-friendly [45]. The key role of AI-Driven Nanoplatforms was shown in figure 6.

FUTURE DIRECTIONS

New developments in nanotechnology for medicine are set to greatly improve how drugs are developed, how they are used and how our health is monitored through diagnostics.

Personalized nanomedicine is developing at a very fast pace through the integration of molecular diagnostics and nanoscale therapeutics to develop personalized therapies. Nanoparticles can be genetically modified with special ligands or aptamers to bind to patient-specific biomarkers selectively to enhance efficacy and minimize side effects. Liposomal doxorubicin is an example that has been modified to suit patients with breast cancer that expresses the HER2 protein [46]. New methods combine CRISPR-Cas9 and nanocarriers to treat genetic faults in diseases like cystic fibrosis and sickle cell anemia. Nanoparticles based on exosomes that can be produced using patient cells are also in preclinical development to allow the administration of therapies with minimal immune response, and artificial intelligence is being used to design tailored nanosystems on the basis of patient data. Smart nanorobots are another direction, being capable of independently monitoring signs of disease, reaching diseased tissues, and administering drugs. DNA-based nanorobots are under investigation to release clotting factors to tumor vessels in particular, whereas enzyme-powered nanomachines can move without external energy and specifically deliver drugs or detect biomolecules. Iron oxide-based nanorobots alleviated with magnets have the potential in gastrointestinal applications and targeted drug delivery. Nanotechnology is aided by the artificial intelligence to predict physicochemical properties, optimize nanoparticles design, and study interactions between the drug and carrier. It also facilitates the imaging analysis, literature mining and establishing patient-specific nanomedicines. In conjunction with technological advancement, sustainability is the new buzzword and biodegradable carriers like chitosan, gelatin, PLGA and silk fibroin are becoming popular because of their biocompatibility and safe biodegradation. Innovation is being in line with environmental responsibility by using green synthesis methods based on plants and microbes to substitute damaging chemistry with nanoparticle synthesis [47]. The other significant development is the real-time monitoring systems which integrate therapeutic and diagnostic capabilities. Smart nanocarriers may also be programmed to respond to biological signals like pH or enzyme activity, and bring drugs out only in diseased tissue. Nanoparticles based on imaging can also be used to monitor drug release and distribution, and biosensors-containing carriers can adjust dosing in dynamic chronic disease settings, such as cancer and diabetes. These systems are likely to be improved with the introduction of AI and should allow autonomous adaptations in terms of therapy. With the development of nanomedicine, harmonization of regulations is necessary. FDA, EMA and ICH are advancing toward common principles of safety testing, characterization, and quality assurance of nanomaterials. International cooperation is focused on decreasing redundancy, enhancing disclosure, and consistent testing of innovative treatments. Digital solutions may include AI-based modeling and global registries as a means to enhance supervision and enhance equitable and safe global access to nanomedicines [48].

APPLICATIONS OF POLYMERS IN NANOTECHNOLOGY

Nanotechnology has seen the polymers become essential materials due to their universality in design, processability and interface with the biological, electronic and environmental systems. Polymer drug delivery is one of the greatest applications of polymers in nanotechnology whereby polymers like the polylactic-co-glycolic acid (PLGA) have been constructed into nanoparticles in which they encapsulate the therapeutic agents that can be effectively used to release drugs in the conditions like cancer and diabetes under controlled and prolonged release process [49]. Such as the case of when the PLGA nanoparticles loaded with paclitaxel has been found to lower the toxicity and enhance bioavailability within the tumor site.

Polymers of natural origins such as chitosan and alginate are also common in gene and protein delivery because they are biocompatible due to mucoadhesion and pH responsiveness [50]. Chitosan nanoparticles have been used in delivering insulin orally before it gets degraded in the gastric pathway. Self-assembled polymers Amphiphilic block copolymers form polymeric micelles in aqueous solution and are commonly investigated as a drug delivery system to increase the circulation lifetime and tumor uptake of poorly water-soluble anticancer agents like doxorubicin [51]. Studies on tissue engineering have revealed that electrospun nanofibers composed of poly (e-caprolactone) (PCL), gelatin or collagen can reproduce the extracellular matrix and provide a cell scaffold to attach, proliferate and regenerate tissues such as bone, skin and nerve. As an example, collagen/PCL nanofiber mats have demonstrated some interesting potential in wound dressing chronic wounds. Cartilage repair and stem-cell encapsulation use polymeric hydrogels, self-positioning water-swollen interlocked mesh-like networks.

Where polymers in nanocomposites, an inorganic nanofiller in the form of carbon nanotubes, graphene, silica nanoparticles are interpolated into the polymer in order to form a reinforced mechanical strength, conductive and thermal resistant material. Epoxy / graphene nanocomposites find application in aerospace and auto parts due to their low weights and high performance structures. The conductive polymers like polyaniline (PANI) and polypyrrole (PPy) are used in nanoelectronics, in sensors and in actuators due to the special electrical attributes that they possess. Such polymers are employed in producing the flexible biosensors that measure glucose and DNA biomarkers over minimal concentration levels.

Polymer-supported silver or iron oxide nanoparticles are also effective adsorbents and catalysts to remove dyes, pesticides and heavy metals, in contaminated water [52]. In another example, removal of arsenic using Fe o_3O_4 nanoparticles and polyacrylamide are coated to attain a superparamagnetic behavior. Smart polymers, termed stimuli-responsive, change in shape or solubility upon temperature, pH or enzyme before being employed in a nanocarrier with on-demand delivery to disease regions [53].

Also, the polymer-coated magnetic nanoparticles have high applications as contrast agents in magnetic resonance imaging (MRI) in the form of enhancing diagnostic resolution in the areas that bind them and via enhancing circulation time and diminishing aggregation. In general, polymers supply the fundamental material structures to a large number of nanoscale devices and systems, and it seems that future innovation on polymer design and nanofabrication approaches will broaden their applications even more in the fields of Medicine, Energy, Electronics, and Environmental Remediation.

CONCLUSION

With nanotechnology, medicine is undergoing a major change by offering higher levels of accuracy in designing, diagnosing and delivering drugs. By altering materials at the nanoscale, scientists have found new tools that face some of the common problems with drugs including bad solubility, quick metabolism and missing the right target. These innovations make it possible to treat patients with fewer negative effects which generally leads to improved outcomes.

Drugs like liposomal chemotherapeutics and siRNA drugs based on nanotechnology prove that nanomedicine really makes a difference in medicine today. They allow for better protection of drugs, better placement in specific body tissues and more convenient transport to difficult areas including the brain or inside tumors. Also, nanotechnology is an important part of research into gene therapy, immunotherapy and vaccines.

Combining nanotechnology with artificial intelligence (AI), biotechnology and precision medicine is likely to increase future health care. Such intelligent nanoparticles are being designed that can monitor the body timely, deliver drugs when needed and reach their target in patients. Through design algorithms, nanostructures are being improved before being actually manufactured.

However, a number of issues still need to be handled. large-scale production, regulation of quality and stability in nanoparticles are all major problems. Also, scientists must continue to look into the long-term safety, biodegradation and effects of nanomaterials on the environment. Various regulatory bodies are contributing to the effort to build consistent ways to make certain that nanomedicines are safe, effective and the same all over the world.

Thinking about ethics plays an equal part in the decision. Related issues are making sure that advanced nanotherapies are accessible, that patients agree to take part in challenging trials, securing data from theranostic devices and the effects nanoparticle waste might have on the environment. It will be important to make sure these innovations help the whole society by working together inclusively, involving the public and cooperating internationally.

All in all, nanotechnology is transforming medicine both by predicting its future and by affecting its present. If existing difficulties are handled and responsible changes are encouraged, the power of nanomedicine will help develop safe, effective and equal healthcare solutions for everyone.

DECLARATION

With a Conflict of Interest

The author(s) claim that there is no real or potential conflict of interest connected to publishing this work. They are outcomes of objectively reviewing the science, meaning no conflicts with companies have influenced these conclusions.

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Ethical Approval

All studies have been previously published and no new experiments were done with human or animal subjects in this work. For these reasons, ethical review by a review board or committee is not required beforehand. The studies reviewed here were assumed to have been given ethical approval in their original papers.

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