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A Review on Role of Artificial Intelligence in Pharmaceutical Sciences

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Abstract

Artificial intelligence [AI] encompasses advanced computational system designed to execute functions that normally depend on human cognitive abilities, such as learning inference problem solving, and decision-making Therapeutic progress in information systems, the expansion of big data and the growth in computing resources have generally facilitated the incorporation of AI into pharmaceutical and health care sectors. This technological integration has promoted strong partnerships between pharma organizations and AI solution providers , learning to a transformation in technical drug development approaches.AI technologies are now applied across various phases pf pharmaceutical research and development, including identification of therapeutic targets, discovery of new drug molecules, formulation development, designing dosage forms, optimization of clinical manufacturing processes, quality management and quality control , and regulatory submissions . In addition, AI facilitates drug repositioning, accelerate research activities, and automates routine process which collectively enhances productivity, accuracy, and efficiency while reducing both time and operational costs. nevertheless, the practical adoption of AI is accompanied by several barriers, including concerns related to data integrity and availability, complex regulatory requirements, ethical and privacy issues, the limited explainability of AI algorithms, and the shortage of trained professionals with domain expertise. This review aims to explore the contribution of artificial intelligence, particularly artificial neural networks and other AI- based approaches, in pharmaceutical development. It also focuses on the key benefits, existing challenges, and future opportunities, providing insights into how AI can further drive innovation and efficiency in the pharmaceutical industry.

Keywords

AI, Pharmaceutical Sciences, learning inference problem solving, and decision-making Therapeutic progress.

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INTRODUCTION

Artificial intelligence (AI) is a specialised area of computer science concerned with developing systems that can perform activities generally associated with human intelligence. AI is able of doing complex activities and adapting to previously unseen situations [1]. In 1955, Herbert A. Simon and Allen Newell developed one of the earliest AI related programs, known as the “Logic Theorist.” The program was designed to generate mathematical proofs and successfully demonstrated proofs for 38 of the 52 theorems [2]. Drug discovery and in vitro

research are often time-consuming and expensive thus artificial intelligence (AI) has emerged as a powerful tool for improving research efficiency [3]. During the 1980s, mechanical learning (ML) emerged as a branch of artificial intelligence, that enables computer systems to learn patterns from data and apply this knowledge to various applications [4]. In recent years, artificial intelligence (AI) has become increasingly important in the pharmaceutical industry, particularly in drug discovery. where machine learning algorithms can rapidly analyse huge chemical database to identify potential drug candidates [5]. Traditional clinical trial approaches can be inefficient and have several limitations, resulting in increased costs longer development timelines, and uncertain outcomes. By using predictive analytics, AI can optimize patient selection, improve clinical trial performance, and support the advancement of innovative therapies through more personalized eligibility criteria and treatment strategies [6]. Artificial intelligence can process large and complex datasets, identify meaningful trends form data, and generate reliable estimates, thereby enhancing the speed and efficiency of pharmaceutical development. This review examines the major uses of AI in pharmaceutical research, with particular emphasis on drug discovery, therapeutic target identification, and preclinical studies [7]. By utilizing existing datasets, artificial intelligence can predict the potential effectiveness and safety of newly developed compounds with greater accuracy. This capability the drug discovery process while minimizing unsuccessful experiments, ultimately reducing both development time and cost [8].

ARTIFICIAL INTELLIGENCE IN PHARMACEUTICAL DEVELOPMENT:

AI has emerged as a transformative technology in healthcare and pharmaceutical sciences by improving diagnostic accuracy, accelerating drug discovery, optimizing treatment strategies, and supporting clinical decision-making. The rapid advancement of computational technologies, machine learning algorithms, and the availability of large biomedical datasets have enabled AI to play a significant role in modern medicine [9]. During global health emergencies such as the COVID-19 pandemic, AI demonstrated its potential by assisting in disease surveillance, drug repurposing, vaccine development, and patient management, thereby accelerating biomedical research and healthcare delivery.

In the pharmaceutical industry, AI has become an essential tool across the entire drug development pipeline. Its applications include target identification, lead optimization, formulation development, pharmacokinetic and pharmacodynamic prediction, toxicity assessment, dosage optimization, and personalized medicine. AI-based in silico models reduce the need for extensive laboratory experiments, thereby lowering research costs, shortening development timelines, and improving the probability of successful drug candidates [10]. These technologies have transformed conventional drug development into a more efficient, data-driven process.

AI technologies can be broadly classified into different categories based on their capabilities and functional characteristics. According to capability, AI is divided into Artificial Narrow Intelligence (ANI), Artificial General Intelligence (AGI), and Artificial Super Intelligence (ASI). ANI performs specific tasks such as image recognition, language translation, and medical diagnosis. AGI represents a theoretical system capable of performing any intellectual task comparable to human intelligence, whereas ASI refers to a hypothetical stage where machine intelligence surpasses human cognitive abilities. Based on functionality, AI systems are categorized as Reactive Machines, Limited Memory systems, Theory of Mind, and Self-aware AI. Reactive machines operate without storing previous experiences and respond only to current inputs. Limited memory systems use historical information to improve decision-making and are widely employed in autonomous vehicles and predictive healthcare applications. Theory of Mind and Self-aware AI remain theoretical concepts that aim to replicate human emotions, social interactions, and self-consciousness [11].

OVER VIEW OF ARTIFICIAL INTELLIGENCE:

Healthcare systems around the world are facing unprecedented challenges due to rapidly increasing healthcare expenditures, which have grown at a much faster rate than global economic growth. These financial pressures have been further intensified by major global events such as the COVID-19 pandemic and the Russia–Ukraine conflict. In addition, aging populations, the increasing prevalence of chronic diseases, and limited healthcare resources have placed enormous strain on healthcare systems, leading to service disruptions in several countries, including India, Brazil, and Indonesia [12].

To ensure sustainable healthcare delivery, health systems increasingly rely on evidence-based clinical practices and structured disease management approaches. For example, in the United States, a significant proportion of adults live with one or more

chronic diseases, resulting in substantial healthcare expenditure [13].

The emergence of COVID-19 in late 2019 accelerated the digital transformation of healthcare worldwide. The pandemic exposed weaknesses in healthcare infrastructure, disrupted supply chains, and placed extraordinary demands on healthcare professionals. Consequently, healthcare providers rapidly adopted digital technologies, including telemedicine, electronic health records, remote patient monitoring, and other digital health solutions, to maintain continuity of care. This transition also increased patient participation in healthcare decision-making, as virtual healthcare services became more widely accepted and accessible.

In the post-pandemic era, healthcare delivery has become increasingly patient emphasizing personalized care and digitally enabled communication between patients and healthcare professionals. The adoption of advanced digital tools has enhanced patient monitoring, improved medication adherence, and facilitated continuous health assessment, particularly during post-discharge care. However, concerns regarding data privacy and cybersecurity remain significant challenges. Therefore, healthcare organizations must ensure transparency, reliability, and robust data protection measures to maintain patient trust and confidence [14].

Recent advances in biomedical sciences, including genomics, digital medicine, artificial intelligence (AI), and machine learning (ML), are transforming modern healthcare. These technologies are enabling significant improvements in disease diagnosis, drug discovery, treatment planning, regenerative medicine, and precision healthcare. In combination with innovations such as biometrics, tissue engineering, and advanced vaccine development, AI-driven technologies are reshaping healthcare delivery while creating the need for a digitally skilled workforce and updated clinical practices. These advancements are expected to play a central role in the future evolution of global healthcare systems [15].

HISTORICAL DEVELOPMENT OF ARTIFICIAL INTELLIGENCE:

Artificial intelligence refers to a broad field of computer science that focuses on developing systems capable of performing tasks that typically require human intelligence, such as learning, reasoning, problem-solving, and decision-making. The foundations of AI were established during the 1950s when Alan Turing introduced the concept now known as the Turing Test, proposing that a machine could be considered intelligent if its responses were indistinguishable from those of a human. This idea laid the conceptual groundwork for future AI research A major milestone occurred in 1956 during the Dartmouth Summer Research Project on Artificial Intelligence, where researchers formally introduced AI as an academic discipline. The conference brought together scientists from diverse fields who envisioned the possibility of developing machines capable of human-like intelligence, setting the stage for decades of AI innovation [16]. Industrial applications of AI also began during the 1950s with the development of machines designed to imitate human actions. In 1955, the first industrial robotic arm was introduced, demonstrating the potential of automation. Later, in 1964, Joseph Weizenbaum developed ELIZA, one of the earliest chatbot programs capable of simulating conversations using predefined language rules. Another landmark achievement of the 1960s was Shakey, the first mobile robot capable of interpreting commands and performing tasks autonomously, demonstrating the practical feasibility of intelligent machines. During the 1970s, AI began making significant contributions to healthcare. One of the earliest medical expert systems, INTERNIST-1, was developed to assist physicians in diagnosing diseases by analysing patient symptoms. Around the same period, the National Institutes of Health (NIH) supported the first conference dedicated to AI in medicine, encouraging collaboration autonomously, demonstrating the practical feasibility of intelligent machines. During the 1970s, AI began making significant contributions to healthcare. One of the earliest medical expert systems, INTERNIST-1, was developed to assist physicians in diagnosing diseases by analysing patient symptoms. Around the same period, the National Institutes of Health (NIH) supported the first conference dedicated to AI in medicine, encouraging collaboration between computer scientists and healthcare professionals Figure (1).

Subsequent developments included MYCIN, an expert system designed to recommend appropriate antibiotic therapies for infectious diseases, and developed in the 1980s to assist clinicians by generating differential diagnoses based on patient symptoms while providing relevant medical information. These systems demonstrated the growing potential of AI to support clinical decision-making and improve diagnostic accuracy. The modern era of AI began in the early 21st century with remarkable advances in machine learning, natural language processing, and computational power. IBM's Watson, introduced in 2007, demonstrated advanced question-answering capabilities by

processing vast amounts of information using natural language understanding. Watson later found applications in healthcare, including biomedical research and disease analysis. Additional AI-based systems such as were developed to educate patients about medications and treatment procedures, illustrating the expanding role of AI in patient education and healthcare delivery Figure1 [17].

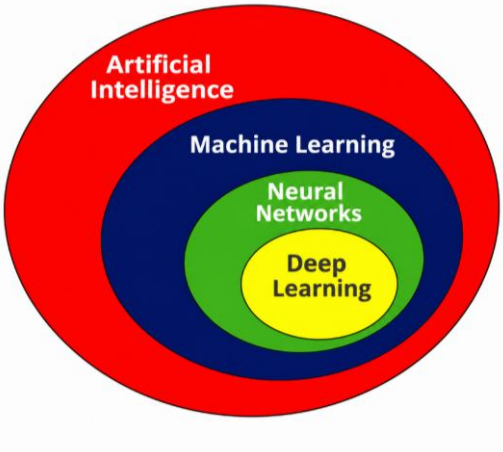


Fig 1: History and evolution of AI in healthcare and pharmaceuticals

HISTORY AND EVOLUTION OF AI IN HEALTH CARE AND PHARMACEUTICALS

Artificial intelligence (AI) has become one of the most influential technological innovations in modern healthcare. It is transforming the way diseases are diagnosed, treated, and monitored by improving the efficiency, accuracy, and quality of healthcare services. AI assists healthcare professionals in clinical decision-making, enhances patient care through personalized treatment approaches, and improves access to medical services using digital health technologies. Despite these significant advantages, the integration of AI into healthcare also presents several challenges including concerns related to accuracy, transparency, patient privacy, ethical issues, and regulatory compliance [18]. This review explores the historical evolution of AI, beginning with its early conceptual development in the 1950s and tracing its progress to current applications in precision medicine, telemedicine, drug discovery, public health, and medical education. In addition, the review discusses the ethical, legal, and social implications associated with AI adoption, particularly regarding healthcare equity, data security, and patient confidentiality. Finally, it highlights future directions and recommendations for developing trustworthy, inclusive, and patient AI technologies [19]. Figure: 2.

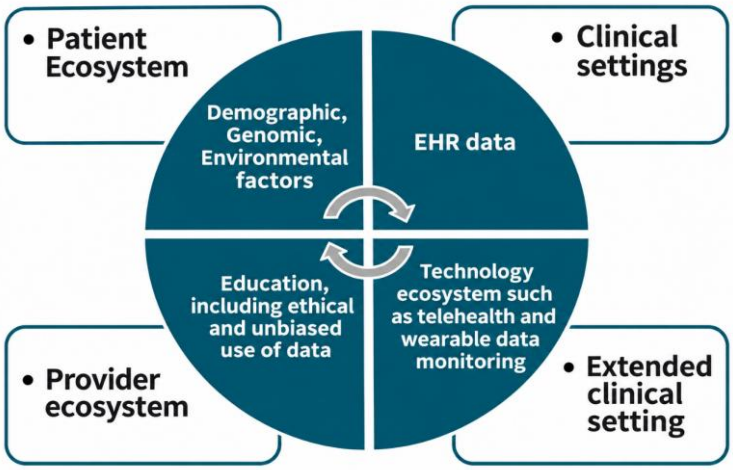


Fig 2: History and evolution of AI in healthcare and pharmaceuticals

TYPES OF AI TECHNOLOGIES USED IN PHARMACEUTICAL INDUSTRIES:

The pharmaceutical industry is continuously evolving to meet increasing healthcare demands through scientific innovation and technological advancement. It plays a crucial role in improving patient outcomes by developing safe, effective, and high-quality medicines.[20] Traditionally,

pharmaceutical innovation has relied on extensive research and development across drug discovery, formulation, manufacturing, packaging, and marketing. Modern drug development encompasses both small-molecule drugs and biologics, with emphasis on improving efficacy, stability, and safety while addressing unmet medical needs. However, ensuring the safety and minimizing the toxicity of newly developed drugs remain major challenges, requiring advanced research approaches and innovative technologies.

- The pharmaceutical sector also faces significant operational and workforce-related challenges. A shortage of skilled professionals, the need for continuous training, and rapidly changing technological requirements create substantial pressure on organizations. In addition, supply chain disruptions, intensified during the COVID-19 pandemic, exposed vulnerabilities in pharmaceutical manufacturing, distribution, and logistics. Factors such as transportation delays, geopolitical conflicts, fluctuating prices, cyberattacks, natural disasters, and shortages of raw materials continue to threaten supply chain resilience. These disruptions not only affect product availability but also reduce customer confidence and increase financial risks [21].
- During the COVID-19 pandemic, maintaining vaccine cold-chain logistics emerged as a major challenge, resulting in the wastage of large quantities of vaccines. Inaccurate demand forecasting and delayed decision-making further amplified supply chain problems. Consequently, pharmaceutical companies are increasingly adopting digital technologies to strengthen operational efficiency, improve forecasting, and enhance supply chain resilience.
- Artificial intelligence (AI) has emerged as a transformative technology capable of addressing many of these pharmaceutical challenges. AI integrates machine learning (ML), deep learning (DL), and natural language processing (NLP) techniques to optimize supply chain management, accelerate clinical trials, improve manufacturing efficiency, and support data-driven decision-making. AI-powered predictive analytics enable companies to anticipate supply chain disruptions, optimize inventory management, and improve resource allocation [22].
- The pandemic also accelerated the adoption of AI-enabled virtual clinical trials. Digital platforms, wearable sensors, and remote monitoring devices allow continuous collection of patient health data while minimizing physical visits to clinical sites. AI algorithms analyse these real-time data streams to improve patient recruitment, monitoring, treatment adherence, and overall trial efficiency. Furthermore, AI helps design patient-centric clinical trials by optimizing study protocols and reducing the manual workload associated with data collection and analysis.
- Cybersecurity has become another major concern within the pharmaceutical industry due to the increasing digitization of healthcare data. Patient records and confidential medical information are vulnerable to cyber threats and data breaches. AI-based cybersecurity systems can detect unusual network activities, identify security vulnerabilities, and support rapid responses to cyberattacks. Additionally, AI contributes to fraud detection by recognizing abnormal financial transactions and operational patterns [23].
- Despite its immense potential, AI has certain limitations. The accuracy of AI predictions depends heavily on the quality, diversity, and completeness of training datasets. Algorithmic bias, limited interpretability, and false-positive predictions remain important concerns. For example, computational drug screening may identify compounds that ultimately prove biologically inactive during laboratory testing. Therefore, expert human interpretation and validation remain essential to ensure reliable decision-making and minimize errors.
- AI methodologies in pharmaceutical research primarily involve supervised and unsupervised machine learning techniques. Supervised learning uses labelled datasets to predict predefined outcomes, whereas unsupervised learning identifies hidden structures and patterns within unlabelled datasets [24]. These approaches have significantly expanded the capabilities of pharmaceutical research and development

MACHINE LEARNING AND NEURAL NETWORKS IN HEALTHCARE

Machine learning (ML) is a specialized branch of artificial intelligence that enables computer systems to learn from data and improve their performance without explicit programming. Instead of relying solely on predefined instructions, ML algorithms identify patterns within large datasets and use these patterns to make predictions, classifications, or decisions. Several statistical learning techniques form the foundation of machine learning, including linear regression, logistic regression, random forests, and k-nearest neighbour (KNN) algorithms. These methods are widely used for disease prediction, risk

assessment, image analysis, and clinical decision support [25]. Among the most advanced forms of AI are neural networks and deep learning, which are designed to mimic the structure and function of the human models consist of multiple interconnected layers capable of extracting complex features from large datasets. These technologies have significantly improved medical image interpretation, disease diagnosis, drug discovery, genomics, and personalized medicine, making them integral

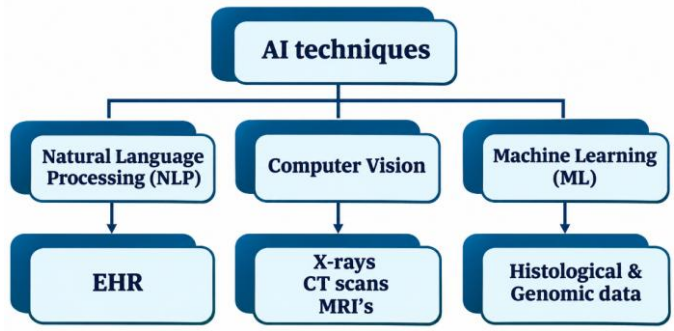


Fig 3: Machine learning and neural networks in health care

ROLE OF AI IN PHARMACEUTICAL DEVELOPMENT:

Artificial intelligence has the potential to identify or repurpose drugs that are more effective either as single agents or in combination therapies. It also supports the advancement of personalized medicine by analysing genetic markers and patient-specific data to optimize treatment strategies. One of the most important branches of AI is machine learning (ML), which enables computers to learn from data and improve predictions without explicit programming. The flexibility of ML is largely attributed to the architecture of artificial neural networks (ANNs).

Several ML algorithms are commonly employed in pharmaceutical research, including logistic regression, support vector machines (SVMs), random forests (RFs), and artificial neural networks (ANNs). Among these, ANNs have gained significant attention because they imitate the learning and decision-making processes of the human brain.[26] ANNs consist of interconnected processing units called neurons, which communicate in a unidirectional manner to analyse complex datasets and solve sophisticated problems. These networks integrate information from multiple prediction pathways, resulting in greater predictive accuracy and lower error rates than individual models, that enabling them to process large volumes of data and accurately predict physicochemical properties, pharmacokinetic characteristics, and toxicological profiles of drug candidates [27].

CNNs are a specialized type of ANN designed to automatically learn important features from extensive datasets. They are primarily used in image analysis and pattern recognition, where they process input images through supervised learning to generate accurate predictions. In pharmaceutical research, CNNs are particularly useful for medical imaging, molecular structure analysis, and disease diagnosis (Figure: 4) RNNs are designed to process sequential data, making them highly effective in natural language processing and chemical sequence analysis. They have been successfully applied to convert chemical structures into Simplified Molecular Input Line Entry System (SMILES) representations and are also used in the design and prediction of peptide and protein sequences [28], because of these capabilities, an increasing number of pharmaceutical companies are incorporating AI technologies into various stages of drug discovery and development to improve efficiency, accuracy, and innovation.

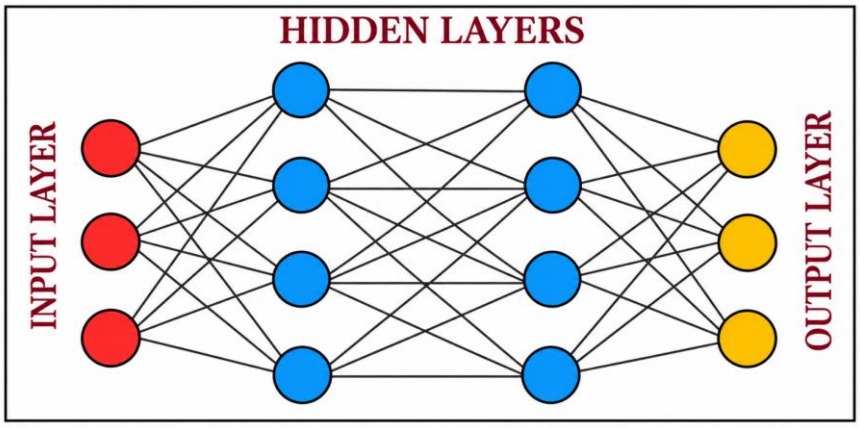


Fig 4: Role of AI in pharmaceutical development

AI THROUGH OUT THE PHARMACEUTICAL PRODUCT LIFE CYCLE:

Artificial intelligence supports nearly every stage of pharmaceutical product development, beginning with target identification and ending with post-marketing surveillance. AI assists researchers in rational drug design, candidate selection, optimization of formulations, personalized medicine, clinical decision-making, regulatory documentation, and lifecycle management. It also enables pharmaceutical companies to analyse market trends, predict product performance, and optimize commercial strategies using advanced predictive analytics Figure 5 [28].

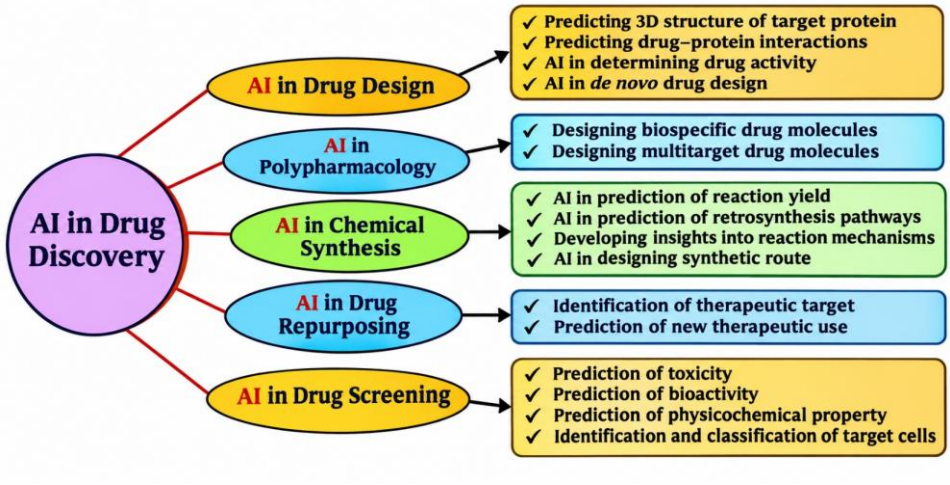


Fig 5: AI In Drug Discovery

AI in Drug Discovery:

Drug discovery traditionally requires enormous investments of time and financial resources because researchers must screen millions of chemical compounds before identifying suitable drug candidates. AI accelerates this process by rapidly identifying promising molecules, validating biological targets optimizing lead compounds, and predicting therapeutic effectiveness Machine learning and deep learning models analyse chemical structures, biological activity, and molecular interactions to prioritize compounds with the highest probability of success. AI-based computational techniques significantly reduce laboratory experiments, enabling researchers to identify lead compounds more efficiently while lowering development costs [30].

Virtual Screening and Lead Optimization

Virtual screening employs AI algorithms to examine extensive chemical libraries and identify compounds that are most likely to bind with specific biological targets. Public databases such as PubChem, and provide valuable chemical information that AI systems analyse during screening. AI also facilitates lead optimization by evaluating molecular similarity, predicting physicochemical characteristics, estimating toxicity, and improving pharmacological properties. Advanced computational models consider molecular fingerprints, structural descriptors, and three-dimensional molecular

information to optimize drug candidates before laboratory validation [31].

QSAR Modelling and AI

Quantitative Structure–Activity Relationship (QSAR) models establish relationships between chemical structures and biological activities. Modern AI-based QSAR approaches utilize algorithms such as Support Vector Machines (SVM), Random Forest (RF), Decision Trees, Artificial Neural Networks, and Deep Learning to achieve greater predictive accuracy than conventional statistical methods. These models accelerate candidate selection by predicting biological activity, pharmacokinetic behaviour, and toxicity before experimental testing [32].

Prediction of Physicochemical Properties

AI accurately predicts essential physicochemical characteristics that influence drug performance, including aqueous solubility, partition coefficient permeability, ionization constant molecular stability, and lipophilicity. These predictions enable researchers to optimize compounds early in development and improve pharmacokinetic properties before synthesis.

Deep learning models using molecular descriptors, SMILES representations, graph neural networks, and quantitative structure–property relationship (QSPR) models have demonstrated high accuracy in predicting these parameters [33].

Prediction of Drug Bioactivity

The therapeutic effectiveness of a medicine depends largely on its interaction with the intended biological target. AI predicts drug–target binding affinity by analysing both molecular features and structural similarities between drugs and proteins. Numerous machine learning and deep learning models, including estimate drug–target interactions with high accuracy. These computational approaches improve target selection, reduce experimental workload, and increase the probability of discovering effective therapeutic agents [34].

Prediction of ADME Properties

AI also predicts pharmacokinetic parameters associated with absorption, distribution, metabolism, and excretion (ADME). Specialized computational tools estimate intestinal absorption, metabolic pathways, cytochrome P450 interactions, drug clearance, and bioavailability. Accurate ADME prediction minimizes late-stage failures and supports the selection of compounds with favourable pharmacokinetic profiles [35].

Toxicity Prediction. Evaluating drug toxicity is one of the most critical stages of pharmaceutical research. AI-based toxicity prediction models molecular descriptors and toxicological databases to identify potential adverse effects before animal or clinical studies. Advanced systems such as predict hepatotoxicity, cardiotoxicity, mutagenicity, carcinogenicity, and organ-specific toxicity with high accuracy. Early toxicity assessment reduces development costs, minimizes experimental failures.

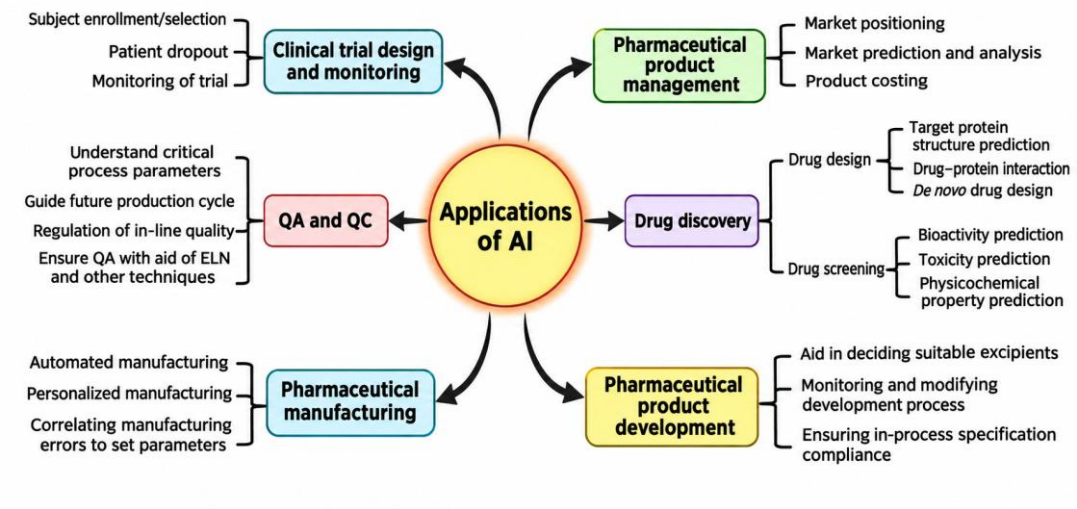


Fig 6: Applications of artificial intelligence

ADVANTAGES OF AI IN PHARMACEUTICAL MANUFACTURING:

- Improves manufacturing efficiency and productivity.
- Enhances product quality and consistency.
- Reduces production costs and material waste.
- Enables predictive maintenance and minimizes equipment downtime.
- Strengthens quality assurance through automated inspection.

- Supports real-time process monitoring and control.
- Optimizes inventory and supply chain management.
- Improves regulatory compliance and documentation accuracy.
- Increases worker safety by automating hazardous tasks.
- Facilitates continuous manufacturing and digital transformation [36].

APPLICATIONS OF AI IN PHARMACEUTICAL RESEARCH:

Artificial intelligence (AI) has become an integral part of pharmaceutical research by improving the speed, accuracy, and efficiency of drug development. AI technologies such as machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision enable researchers to analyse large datasets, identify hidden patterns, and make data-driven decisions throughout the pharmaceutical research process [37].

1. **Drug Discovery and Target Identification**
   AI analyses genomic, proteomic, and clinical data to identify novel drug targets and predict disease-associated biomarkers. Machine learning algorithms help researchers understand disease mechanisms and prioritize promising therapeutic targets, reducing the time required for early-stage drug discovery.
2. **Virtual Screening of Drug Candidates**
   AI rapidly screens millions of chemical compounds using predictive models to identify molecules with the highest probability of biological activity. This significantly reduces the need for expensive laboratory screening and accelerates lead identification [38].
3. **Lead Optimization**
   AI predicts the physicochemical, pharmacokinetic, and pharmacodynamic properties of lead compounds. It assists in optimizing molecular structures to improve efficacy, selectivity, and safety while minimizing toxicity.
4. **De Novo Drug Design**
   Generative AI models can design entirely new chemical structures with desired therapeutic properties. These models optimize compounds based on target binding affinity, drug-likeness, and synthetic feasibility, accelerating the development of novel medicines [39].
5. **Drug Repurposing**
   AI identifies new therapeutic applications for approved or discontinued drugs by analysing molecular interactions, disease pathways, and clinical data. Drug repurposing reduces development costs and shortens the time needed to bring treatments to patients.
6. **Toxicity and Safety Prediction**
   AI predicts potential toxic effects, adverse drug reactions, and organ toxicity before animal and human studies. Early toxicity prediction improves candidate selection and reduces drug failures during clinical development.
7. **Clinical Trial Design and Management**
   AI helps identify eligible patients, optimize trial protocols, predict patient recruitment, monitor trial progress, and analyse clinical data. These applications improve trial efficiency, reduce costs, and increase the likelihood of successful outcomes [40].
8. **Formulation Development**
   AI supports the selection of excipients, optimization of formulation variables, prediction of drug stability, and development of advanced drug delivery systems, resulting in improved product quality and reduced formulation development time.
9. **Pharmacovigilance**
   AI continuously analyses electronic health records, scientific literature, adverse event databases, and social media to detect adverse drug reactions (ADRs). This enables faster safety signal detection and enhances post-marketing surveillance.
10. **Pharmaceutical Manufacturing and Quality Control**
    AI improves manufacturing by enabling process optimization, predictive maintenance, automated inspection, real-time quality monitoring, and compliance with Good Manufacturing Practices (GMP), resulting in consistent product quality [41].
11. **Personalized Medicine**
    AI integrates genomic, clinical, and lifestyle data to recommend individualized treatment strategies. Personalized medicine improves therapeutic outcomes while minimizing adverse effects.
12. **Regulatory Affairs**
    AI assists in preparing regulatory documents, managing submissions, reviewing scientific literature, ensuring compliance with international guidelines, and supporting regulatory decision-making, thereby reducing the workload associated with drug approval [42].

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