

Pharmaceutical Industry Driven by Artificial Intelligence and Machine Learning

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ABSTRACT

Artificial Intelligence (AI) and Machine Learning (ML) are transforming the pharmaceutical industry at all phases—drug research, development, regulatory compliance, quality assurance, and post-marketing monitoring. These technologies enhance data processing, precision, and timeliness through the utilisation of intricate algorithms and extensive healthcare datasets. Artificial intelligence aids in drug target identification, drug design, toxicity prediction, and pharmacokinetics modelling, while also enhancing regulatory processes and pharmacovigilance. Despite its advantages, difficulties persist, including data privacy, algorithmic bias, explainability, and accountability. Regulatory frameworks and ethical considerations must evolve to ensure the safe and equitable application of AI in pharmaceuticals. This article examines the current applications, benefits, hazards, and future potential of AI and ML in revolutionising medication development and healthcare outcomes.

Keywords: Artificial Intelligence, Machine Learning, Pharmacokinetics Modelling.

INTRODUCTION

Artificial intelligence and machine learning are transforming the pharmaceutical sector, encompassing drug development, design, marketing, and post-marketing surveillance. It has induced a paradigm change in the pharmaceutical and biotechnology industries. The application of AI and ML in various sectors enables the processing of extensive datasets in a

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

minimal timeframe, surpassing human capacity. Drug design, a crucial element in the drug delivery system, has conventionally depended on a trial-and-error approach. AI and ML technologies can significantly decrease time and costs by accurately predicting molecular behaviour and the toxicity of substances. Pharmacovigilance formerly depended on conventional data gathering and labour-intensive independent analysis, which included numerous possible flaws [1]. Artificial Intelligence and Machine Learning have emerged as potent tools in this market, evaluating substantial quantities of adverse events and discovering drug-drug interactions in patients. Artificial Intelligence and Machine Learning can assist in forecasting potential adverse events stemming from patient history, comorbidities, prescription interactions, and drugs. They can entirely revolutionise the domains of drug distribution and pharmacovigilance, enhancing accuracy, speed, and personalised care. Nevertheless, this necessitates additional advancement in AI and ML, heightened understanding of ethical considerations, and collaboration among regulators, healthcare providers, and technologists [2].

Drug discovery is a complex and arduous process that typically lasts 10 to 15 years. The initial phase of drug research entails the identification of novel targets to manage a certain disease. A high-throughput screening (HTS) of compound libraries is utilised to identify compounds that may interact with the pertinent targets. These compounds are subsequently altered to enhance their pharmacological characteristics. Thereafter, these systems undergo comprehensive preclinical and clinical designs, culminating in regulatory approval. Recently, artificial intelligence and machine learning methodologies have been employed across all facets of pharmaceutical and drug research, encompassing computer-aided drug discovery (CADD) through both structure- and ligand-based design strategies. Nevertheless, CADD, which is more closely associated with conventional drug development techniques, has limits and hurdles, including intricate biological systems, the ability to capture target flexibility, and the restricted analysis inherent in old procedures [3].

RESEARCH ELABORATIONS

The identification and confirmation of prospective therapeutic targets is a crucial phase in drug research. AI algorithms can examine various data sets, including genomes, proteomics,

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

and transcriptomics, to find potential therapeutic targets. AI improves accuracy in target identification and mitigates the danger of creating useless pharmaceuticals. Generation and optimisation of drug candidates: Following the identification of therapy targets, novel compounds are sought that can interact with the target proteins. In this procedure, AI improves accuracy, minimises errors, and accelerates the identification of new candidate molecules. De novo drug design involves the creation of novel chemical compounds that can bind to specific target molecules, in addition to selecting active molecules from the compound library, without relying on pre-existing templates. Generative Adversarial Networks (GANs) exemplify artificial intelligence utilised in de novo drug design and optimisation. Prediction of pharmacokinetics for drug candidates: AI techniques enhance the success rate of clinical trials through predictive modelling and simulations. AI algorithms can forecast the pharmacokinetics and pharmacodynamics of medication candidates and can detect probable negative effects [4]. Diverse AI tools are employed to ascertain the absorption, distribution, metabolism, excretion, and toxicity characteristics of pharmaceuticals. This diminishes the expenses and temporal demands in animal research. Prediction of drug candidate toxicity: AI algorithms are employed to forecast the toxicity of drug candidates. Machine learning algorithms are trained on data from toxicological studies, clinical trials, and chemical analyses to discern patterns and forecast the likelihood of a medicine inducing toxicity [5]. DeepTox exemplifies an AI model utilised for predicting medication toxicity.

Table 1 Compilation of frequently utilised AI models in the pharmaceutical sector

AI/Machine Learning Models	Specification/Application
Generative Adversarial Networks (GANs)	Generative Adversarial Networks (GANs) are extensively employed in pharmaceutical research to create innovative chemical compounds and enhance their characteristics. Generative Adversarial Networks (GANs) comprise a generator network that synthesises novel compounds and a discriminator network that assesses their quality, resulting in the production of structurally varied and functionally optimised therapeutic candidates.
Recurrent Neural Networks (RNNs)	Recurrent Neural Networks (RNNs) are frequently utilised for sequence-oriented tasks in pharmaceutical research, including the prediction of protein structures, genetic

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

	data analysis, and peptide sequence design. They capture sequential dependencies and can produce novel sequences based on acquired patterns.
Convolutional Neural Networks (CNNs)	Convolutional Neural Networks (CNNs) excel in image-centric tasks, such as analysing molecular architectures and suggesting prospective drug targets. They can extract pertinent information from molecular pictures and assist in drug design and target identification.
Long Short-Term Memory Networks (LSTMs)	LSTMs are a kind of RNNs that excel in modelling and forecasting temporal dependencies. They have been utilised in pharmacokinetics and pharmacodynamics research to forecast drug concentration-time profiles and assess drug efficacy.
Bayesian Models	Bayesian models, including Bayesian networks and Gaussian processes, are utilised for uncertainty quantification and decision-making in pharmaceutical development. They facilitate researchers in formulating probabilistic forecasts, evaluating risks, and refining experimental designs.
Deep Q-Networks (DQNs)	Deep Q-Networks (DQNs), integrating deep learning with reinforcement learning, have been employed to enhance drug discovery by forecasting compound activity and identifying promising candidates for further investigation.
Graph Neural Networks (GNNs)	Graph Neural Networks (GNNs) are engineered to analyse graph-structured data, rendering them appropriate for drug development endeavours that entail chemical configurations. They can simulate molecular graphs, forecast attributes, and assist in virtual screening and de novo drug development.

AI technology are utilised to regulate the quality of medicinal items. Guaranteeing the safety and efficacy of a medication is a crucial phase in the drug industry. Conventional quality control procedures may be labour-intensive and susceptible to inaccuracies and false positives. The implementation of AI and ML models has significantly transformed quality control. AI

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

systems can swiftly identify faults, inconsistencies, and departures from set standards. The integration of AI has expedited the inspection process and reduced errors.

Table 2 Illustrations of the benefits of employing AI systems for the quality control of pharmaceutical items

Advantages	Specification/Application
Artificial intelligence enhances quality control and decision-making processes within the pharmaceutical sector	AI-driven predictive analytics can foresee potential quality issues, facilitating preventative measures.
AI technologies improve real-time visual inspection and monitoring of products to guarantee quality control.	AI-driven systems consistently oversee production parameters through sensor data and machine learning algorithms, facilitating early issue detection and minimising disruptions.
Artificial intelligence increases manufacturing operations by optimising procedures, minimising waste, and boosting production results.	Extensive datasets are utilised by machine learning algorithms to predict demand, optimise production processes, and effectively manage inventories. AI-driven real-time monitoring systems facilitate early fault diagnosis, hence reducing waste and production downtime.
Artificial intelligence optimises tasks, reduces errors, and ensures adherence to regulatory standards.	AI optimises labour-intensive tasks like as regulatory reporting and compliance monitoring through the automation of intricate processes.
Artificial intelligence systems facilitate continuous improvements and optimisation.	These systems employ adaptive control and real-time analytics to dynamically optimise manufacturing, enhancing productivity and product quality.

Regulatory bodies grant marketing authorisation for pharmaceutical goods based on guidelines and the data and documentation presented throughout all phases, from medication research to product development. Artificial intelligence (AI) and machine learning technologies can expedite this procedure by diminishing the time required to collect, segregate, and standardise data from records, while also decreasing the necessity for human interaction in the documentation process [5]. Artificial Intelligence (AI) technology can enhance regulatory procedures, encompassing administrative tasks, dossier compilation, data acquisition, auditing, regulatory enforcement, and quality assurance. Moreover, while corporations are required to adhere to evolving laws and stay informed about legislation and industry standards, individual

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

compliance and regulatory engagements within the pharmaceutical sector could be enhanced by the application of artificial intelligence (AI) technology [4]. Artificial Intelligence can facilitate the collection of data regarding significant changes from various regulatory bodies.

Table 3 AI-Enhanced Functions in Pharmaceutical Regulatory Affairs

AI-assisted tasks	Details of AI application
Extraction of data from an unstructured document	AI-driven data extraction facilitates the identification of medical products from unstructured text files, enabling pharmaceutical companies and health authorities to efficiently assess documentation, identify chemical contamination, and automatically gather and input data into regulatory intelligence systems.
Automation of administrative tasks	Robotic processes and machine learning assist regulatory administrative bodies in managing intricate tasks, including the handling of regulatory letters, scheduling meetings, conducting audits, facilitating consultation processes, maintaining accounts, developing evaluation procedures, managing submission updates, and organising data.
Completion of the dossier	Amid evolving standards, automation is crucial for efficiently managing regulatory documents pertinent to a certain region. The International Council for Harmonization's establishment of the electronic common technical document for standardised dossier submissions emphasises data over story, driven by the expansion of small enterprises and the rising volume of submissions.
Data documentation	AI-enhanced software reduces errors and expenses, while tracking, monitoring, and analysing data to enhance regulatory compliance. Complete automated data mining collects and analyses data, reduces mistakes, and converts signals for discovery, whereas artificial intelligence (AI) analytics forecasts outcomes, identifies trends, provides recommendations, does correlation analysis, personalises products, and allocates budgets.

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

Artificial Intelligence is integral to post-marketing surveillance. Post-marketing surveillance denotes the ongoing assessment of the safety and efficacy of pharmaceutical products subsequent to their market authorisation. AI-driven solutions are transforming various aspects of pharmacovigilance, including the acquisition and analysis of real-world data, signal recognition, risk evaluation, and patient involvement. AI aggregates and analyses vast real-world data from sources including electronic health records, social media, and patient registries to reveal insights that enhance traditional clinical trials. Artificial Intelligence enhances signal identification and risk assessment by identifying potential safety concerns and adverse drug occurrences through the analysis of extensive datasets, including patient reports and social media references. AI-driven predictive analytics detects adverse reactions prior to their manifestation, informs treatment alternatives, and enables proactive interventions. AI-driven chatbots and virtual assistants that provide tailored information on medication safety promote patient engagement and personalised pharmacovigilance. Artificial intelligence assesses real-world evidence and benefit-risk analysis to ascertain the long-term safety and efficacy of medicinal treatments. AI is thereby profoundly transforming and enhancing PMS, ushering in a new epoch of advanced, patient-centric medication safety surveillance.

Pharmacovigilance, the discipline of identifying and evaluating adverse events, is crucial for monitoring drug safety and alleviating adverse effects. Underreporting in pharmacovigilance constitutes a significant issue that jeopardises patient safety by concealing adverse events. The capacity to identify adverse events and make educated judgements is compromised by a significant median underreporting rate of 94%. Artificial intelligence, machine learning, and natural language processing (NLP) have facilitated numerous breakthroughs in pharmacovigilance. These methods enhance the efficiency and precision of ADR detection by transforming unstructured data into structured data.

Principal Applications of AI and ML in Pharmacovigilance: Early signal detection: AI and ML facilitate the rapid identification of adverse events, surpassing previous methodologies. Artificial intelligence gathers and analyses data from diverse sources and transforms it into organised information. Improved efficiency: By analysing substantial volumes of both structured and unstructured data, artificial intelligence diminishes time consumption and enhances productivity. This enhances the efficacy of the pharmacovigilance sector by concentrating on intricate data and decision-making processes. Enhanced precision: AI/ML

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

models exhibit superior accuracy in detecting patterns, trends, and safety issues that may be neglected by conventional methods. Moreover, these models exhibit reduced vulnerability to human error, leading to enhanced accuracy in safety signal and adverse drug response (ADR) recognition. Enhanced accuracy reduces the likelihood of neglected or erroneous safety concerns. Cost reduction: AI/ML models diminish expenses through the automation of data management, case triage, and adverse event reporting. AI/ML systems can do large-scale data analysis rapidly, hence substantially decreasing the costs associated with previous methods[3]. Predictive Modelling for Adverse Event Prediction: Predictive modelling employs patient data to discern trends and risk variables that may result in adverse drug reactions (ADRs). Extensive datasets, including patient demographics, pharmacological characteristics, comorbidities, and drug-drug interactions, can be evaluated by machine learning algorithms to predict the likelihood of specific adverse events. These predictive models can identify high-risk patient populations.

RESULTS AND DISCUSSIONS

Insilico Medicine developed a small molecular inhibitor drug candidate, designated INS018_055, which acts as a TRAF2- and NCK-interacting kinase (TNIK) inhibitor. It is utilised for the management of idiopathic pulmonary fibrosis. It became the inaugural AI-generated drug, spanning the full process directed by artificial intelligence, from target identification to the formulation of the therapeutic molecule. Unlike traditional drug development methods, which often exceed ten years, the AI-assisted approach from target identification to preclinical candidate nomination was completed in approximately eighteen months. INS018_055 has advanced to Phase II clinical trials to assess the safety, tolerability, pharmacokinetics, and preliminary efficacy of a 12-week oral treatment in patients with IPF following promising Phase I outcomes. Two. IBM Watson and Oncology: The renowned AI system IBM Watson has been deployed in oncology and various other sectors of healthcare. A notable use is the tailored distribution of medicine for cancer patients. IBM Watson has been utilised alongside the Memorial Sloan-Kettering Cancer Centre to assess patient data and deliver tailored treatment protocols. Watson evaluates extensive clinical trial data, medical literature, and patient information to suggest the most effective medicine combinations and

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dosages for specific individuals. It could analyse genetic data, patient history, and treatment outcomes to determine effective chemotherapy protocols for breast cancer treatment. This method has improved treatment outcomes and diminished the risk of side effects by tailoring drugs to the patient's distinct genetic profile. Three. Bayer and Inhaled therapeutics: The global pharmaceutical giant Bayer is employing artificial intelligence to optimise medication delivery systems, particularly in the development of inhaled therapeutics for respiratory ailments. Bayer enhanced the formulation and delivery of inhaled therapies for conditions such as asthma and chronic obstructive pulmonary disease through the application of artificial intelligence algorithms. The AI models forecast variables such as pulmonary deposition, absorption rates, and therapeutic efficacy by simulating the responses of different formulations upon inhalation. The AI system may also personalise inhaled medicine delivery by assessing environmental circumstances and patient information, adjusting dosages and formulations based on the patient's respiratory profile and sickness severity. This methodology has resulted in the advancement of more efficacious inhaled medicines, characterised by superior drug deposition in the lungs and augmented therapeutic results.

The FDA recognises the increasing utilisation of AI across multiple therapeutic areas and across the lifecycle of medical products. Recently, CDER has observed a significant increase in the number of drug application submissions using AI elements. These submissions encompass the nonclinical, clinical, post-marketing, and manufacturing phases of a drug product's life cycle. The Centre for Drug Evaluation and Research (CDER) is tasked with ensuring the safety and efficacy of medications while promoting advances in their development. The FDA released a draft guidance in 2025 entitled, "Considerations for the Use of Artificial Intelligence to Support Regulatory Decision Making for Drug and Biological Products." This guidance offers recommendations to the industry on employing AI to generate information or data aimed at supporting regulatory decisions concerning the safety, efficacy, or quality of drugs. This guidance establishes the foundation for evaluating the model risk associated with artificial intelligence. AI Model Risk encompasses two elements: a. Model influence refers to the extent of evidence provided by the AI model in relation to other evidence utilised to address the pertinent question, while decision consequence denotes the significance of an adverse outcome stemming from an erroneous decision concerning the question at hand.

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

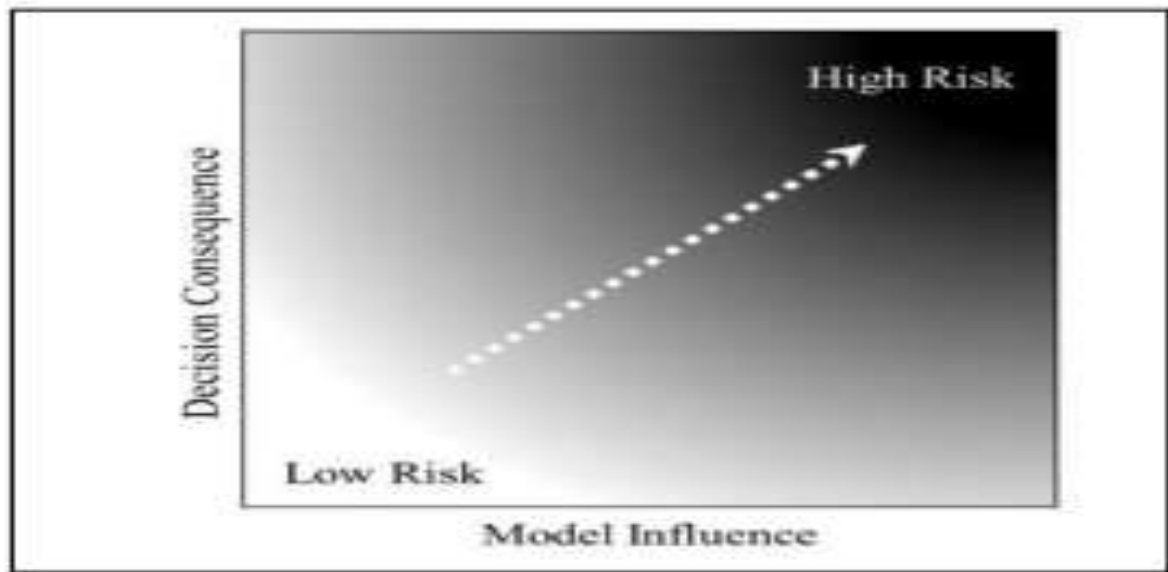


Fig.1 : Model risk matrix

Model risk escalates from low to high as the consequences of decisions or the influence of the model intensifies. The evaluations of choice consequences and model influence are assessed independently. Model risk refers to the potential for the AI model's output to result in an erroneous decision that may lead to negative outcomes, rather than risks inherent to the model itself. Evaluating model risk necessitates specialised knowledge and discernment among sponsors, stakeholders, and the FDA.

Artificial intelligence technologies in the healthcare sector consistently perpetuate prejudices and inequality. Biases manifest in three principal domains: the datasets utilised for training AI systems, the identities of the individuals who develop these systems, and those responsible for deploying the technology. Consequently, biases may exist in datasets utilised for training algorithms in therapies, as certain groups may be under-represented or excluded due to uneven or limited access to healthcare. These may be seen in biobanks, genetic databases, and electronic health records, and also encompass women, socioeconomically disadvantaged populations, and ethnic minorities. Utilising these datasets for algorithm development or validation integrates inherent biases into the algorithms, rendering them unrepresentative and hindering the models' generalisability, which may result in suboptimal outcomes or detriment to socioeconomically disadvantaged groups. Alongside human biases and discriminatory practices in clinical care, electronic health records and various forms of

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

health data also encapsulate disparities in healthcare access and quality. The distinguishing properties of such data will permeate the AI models generated from it.

If algorithms utilised in drug research are not scrutinised for potential weaknesses or if they yield false-positive or false-negative results, patient safety may be compromised. Research has shown that within a span of six hours, an algorithm can identify or generate innovative therapeutic molecules, as well as detect dangerous chemical substances that could be utilised as biological weapons. While such studies may be conducted by humans independently of AI, concerns are amplified by the swift and precise dissemination of this technology. The WHO has released guidelines to govern dual-use research, having recognised it as a major bio-risk domain. Governments must implement rules and regulations to mitigate these hazards. Analogous to several applications of AI in healthcare and medicine, the reliance on "black-box" algorithms for decision-making may present ethical challenges for researchers, regulators, and healthcare providers in the development of novel pharmaceuticals. Literature characterises numerous algorithms, particularly those founded on artificial neural networks or other intricate models, as "black boxes" that render conclusions and inferences that their developers inadequately comprehend. A trade-off may exist between an algorithm's total explainability (sacrificing accuracy and efficacy) and its accuracy and efficacy (sacrificing explainability). To ensure that all algorithms meet safety and efficacy standards, the WHO recommends comprehensive evaluation in the contexts where the technology will be implemented. All assumptions, operational processes, data features, and output selections of the AI technology must be evaluated. The degree of transparency exhibited by developers, encompassing the revelation of source code, algorithm training data, and AI performance, constitutes another concern. Ultimately, authorities must determine the reliability of utilising AI technologies in the design, discovery, development, and post-marketing surveillance of new pharmaceuticals, along with the data required to validate the application of specific AI technologies in drug development or the administration of novel medications.

Accountability ensures that individuals and organisations are held responsible for the adverse outcomes of their actions. Moreover, accountability is essential to maintain human rights and sustain confidence. Certain characteristics of AI systems, like their opacity, reliance on human input, interactivity, discretion, scalability, capacity to uncover insights, and software complexity, influence concepts of responsibility and accountability. A significant challenge in

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

assigning culpability is the "control problem," which posits that AI designers and developers may evade responsibility as AI-driven systems function autonomously and may evolve in unforeseen manners, as claimed by the developers. Consequently, a responsibility gap exists. At any phase of the medication development process, employing ineffective AI could impose an undue burden on the individual adversely affected. - The second challenge is to the "many hands" or "traceability" of harm issue, which complicates health care decision-making procedures and may also affect an advanced system for the development of new pharmaceuticals. The involvement of numerous parties in AI and medicine research may complicate the assignment of accountability, as it is collectively shared both morally and legally. Furthermore, several entities engaged in the creation or usage of AI may not currently be governed by existing laws or regulations.

The efficacy of AI-driven drug discovery, development, and commercialisation is contingent upon the health data gathered, particularly from clinical trials. Nonetheless, disseminating this data to pharmaceutical corporations has significant privacy issues. The misuse and dissemination of private information can adversely affect individuals through discrimination, exploitation, or breaches of personal dignity, rendering privacy protection a vital concern in AI-driven pharmaceutical research. - Another concern is that researchers utilising AI in clinical studies may solicit external parties to analyse the data or utilise proprietary algorithms. Concerns arise around the management of sensitive health data, the compliance of third parties with the professional and business standards of healthcare organisations, the subsequent utilisation of the data, and the individuals granted access to it.

Artificial intelligence possesses significant potential to revolutionise pharmacovigilance, industry administration, regulatory compliance, medication discovery, and the creation of pharmaceutical products. AI systems can evaluate extensive biological data to identify potential therapeutic targets and expedite the drug discovery process. Pharmaceutical research can employ AI-driven simulations to predict the interactions between chemicals and biological systems, facilitating more efficient and cost-effective clinical trials. Artificial intelligence (AI) solutions can enhance supply chain management, bolster regulatory compliance, and expedite manufacturing and formulation development. AI algorithms require extensive repositories of data and information. The integration of AI technology into the pharmaceutical sector will

Received: 2024-07-09 Revised: 2024-10-19 Accepted: 2024-11-21 Published: 2025-01-28

foster breakthroughs, enhance patient outcomes, and eventually transform healthcare in an always evolving technological landscape.

CONCLUSIONS

The pharmaceutical industry's implementation of artificial intelligence and machine learning has ushered in a new era of opportunities. AI exerts a revolutionary influence across all sectors, including medication discovery, drug design, clinical trials, marketing, and post-marketing surveillance. AI-based methodologies have transformed the landscape of pharmacokinetics and pharmacodynamics. They have numerous benefits compared to conventional approaches. AI is capable of forecasting bad reactions prior to their manifestation, based on patient attributes. Nevertheless, some challenges, such as patient data protection and the necessity for an enhanced management system, must be resolved to fully harness the promise of artificial intelligence. The use of AI technology significantly enhances medication research, optimises patient outcomes, and transforms the pharmaceutical sector, facilitating its transition from era 4.0 to era 5.0.

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