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Review article

AI's role in revolutionizing personalized medicine by reshaping pharmacogenomics and drug therapy

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ABSTRACT

This paper examines the transformative impact of artificial intelligence (AI) on pharmacogenomics, signaling a paradigm shift in personalized medicine. With a focus on enhancing drug response prediction and treatment optimization, AI, particularly machine learning and deep learning algorithms, navigates the complexity of genomic data. By elucidating intricate relationships between genetic factors and drug responses, AI augments the identification of genetic markers and contributes to the development of comprehensive models. The review emphasizes AI's role in guiding treatment decisions, minimizing adverse reactions, and optimizing drug dosages in clinical settings. Ethical considerations, challenges, and future directions are also discussed. This work underscores the synergy of AI and pharmacogenomics, offering a more effective and patient-centric approach to drug therapy, marking a significant advancement in the field of personalized medicine.

1. Introduction

Personalized medicine, also known as precision medicine, is a rapidly evolving medical approach that seeks to personalize healthcare by taking into account a patient's unique characteristics at molecular, physiological, ecological, and behavioral levels.[1] The idea behind personalized medicine is to tailor interventions for the prevention and treatment of diseases to the individual, rather than using a one-size-fits-all approach. The complete sequencing of the human genome in 2003 facilitated the further evolution of personalized medicine, moving beyond the genome into the entire spectrum of molecular medicine. Advances in technology, such as DNA proteomics, imaging protocols, and wireless health monitoring devices, have contributed to significant improvements in personalized medicine. However, there are still challenges to overcome, such as the need for more relevant models based on human cell cultures and the personalization of therapy.[1,2] Despite these challenges, personalized medicine holds immense promise in revolutionizing the field of healthcare and transforming patient care by offering personalized and targeted therapies that improve health outcomes and enhance the quality of life.[2]

The integration of artificial intelligence (AI) into pharmacogenomics is motivated by the potential to enhance patient care and treatment outcomes. Personalized medicine, which considers an individual's unique molecular, physiological, ecological, and behavioral characteristics, forms the foundation of this integration. By leveraging AI and machine learning, healthcare professionals can analyze large and complex datasets generated by pharmacogenomics, enabling them to predict drug responses and tailor treatment plans to each patient's specific genetic makeup. This personalized approach has the potential to improve the effectiveness of medications, reduce adverse drug reactions, and optimize treatment outcomes. Furthermore, the application of AI in pharmacogenomics can contribute to the development of novel drugs and medical devices, as well as facilitate the clinical integration of pharmacogenomic data into healthcare decision-making processes.[1,3] Therefore,

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the integration of AI into pharmacogenomics represents a significant advancement in the field of personalized medicine, offering the promise of more effective, tailored treatments and improved patient care. The rationale for integrating AI into pharmacogenomics lies in the potential to improve patient outcomes, reduce healthcare costs, and advance drug development (Fig. 1).

Pharmacogenomics, the study of how an individual's genetic makeup influences their response to drugs, presents a significant opportunity for personalized medicine. However, the integration of pharmacogenomic data into clinical practice faces challenges related to data analysis, decision support, and implementation.[4] The complexity of gene–drug interactions further underscores the need for advanced tools to predict and understand individual responses to medications. In this context, the application of AI and machine learning can play a pivotal role in addressing these challenges and advancing the field of personalized medicine.[5] The research objectives of the article are multifaceted. Firstly, the article aims to explore the potential of AI in advancing pharmacogenomics and its application in drug development for personalized treatment and managed care. This involves leveraging AI algorithms to analyze genetic data and predict drug responses, ultimately leading to more effective and tailored treatment strategies. Secondly, the article seeks to develop a framework that integrates electronic health record (EHR) and genetic data, providing decision support for healthcare professionals to improve patient care through pharmacogenomics-driven approaches. This integration can enable personalized medication optimization and enhance the efficacy and safety of drug therapies. Lastly, the article aims to address the challenges of polypharmacy and drug interactions in chronic disease management by implementing AI tools for proactive medication management based on pharmacogenomic data. By doing so, the research aims to contribute to the development of AI-driven solutions that support healthcare providers in making informed decisions about medication selection and dosing, particularly in the context of complex, chronic conditions. By addressing these research objectives, the article endeavors to demonstrate how AI-powered pharmacogenomics can lead to a paradigm shift in personalized medicine, offering actionable insights and innovative solutions to improve patient outcomes and enhance the quality of care.

2. Literature review

Personalized medicine, also known as precision medicine, is a rapidly evolving field that aims to tailor medical treatments and interventions to individual patients based on their unique genetic, environmental, and behavioral factors.[6] However, the integration of personalized medicine into clinical practice faces several challenges. One of the major issues within the field of personalized medicine is the ethics surrounding patient confidentiality and privacy.[7]

Merging data from different sources and platforms is necessary for personalized medicine, but it requires significant effort and resources. The development and implementation of personalized medicine strategies require a skilled workforce with expertise in genomics, data analysis, and healthcare management. The time required for data analysis and decision-making in acute situations can be slow, which may hinder the effectiveness of personalized medicine. The presence of noise and inconsistencies in data can affect the accuracy and reliability of personalized medicine strategies. The validity of data used in personalized medicine is essential for making informed decisions, but it can be challenging to calculate and ensure.[7,8] Despite these challenges, personalized medicine holds great potential for improving patient outcomes, reducing healthcare costs, and advancing drug development.[6] By addressing these challenges and leveraging the power of AI and machine learning, we can develop more effective personalized medicine strategies and integrate them into clinical practice.

The traditional approaches to pharmacogenomics have long aimed to optimize drug therapy based on an individual's genetic makeup, with the ultimate goal of realizing the potential of personalized medicine. These approaches promise to revolutionize medical history by enabling personalized therapy, improving drug efficacy, reducing adverse reactions, correlating genotypes with clinical outcomes, identifying novel drug targets, and predicting disease susceptibility and drug response.[9] Furthermore, the integration of pharmacogenomics into primary care and psychiatric practice has been the subject of ongoing research, with the aim of tailoring pharmacotherapy to individual patients based on their genomic data.[10] However, the application of pharmacogenetics in routine patient care has been hindered by various challenges, including the slow integration of established guidelines, the need for more validation research, and the barriers associated with its implementation in family medicine and chronic disease management.[11] Despite these challenges, the study of pharmacogenomics, particularly single nucleotide polymorphisms (SNPs), continues to hold promise for individualizing treatments and studying diseases with complex inheritance pathways, such as inflammatory disorders, diabetes, and cancers.[12]

The literature also highlights the barriers to and strategies for implementing pharmacogenetic testing in healthcare settings. These include conflicting conclusions on the clinical utility and cost-effectiveness of pharmacogenetics, regulatory and reimbursement concerns, the need for informatics to support pharmacogenetics-informed prescribing decisions, and ethical, legal, and social implications surrounding its application.[5,11] Overcoming these barriers is seen as crucial for the widespread adoption of pharmacogenetics and the realization of its full potential in improving patient outcomes.

Clinical trials are essential to medical research, but patient matching and design are frequently problematic.[13] Pharmacogenomics uses genetic data relating to absorption, distribution, metabolism, and excretion (ADME) to anticipate medication responses and prevent adverse effects, hence personalizing treatment. But because phenotype-genotype concordance is frequently poor, researchers are investigating alternate phenotyping techniques to improve the prediction of metabolic and

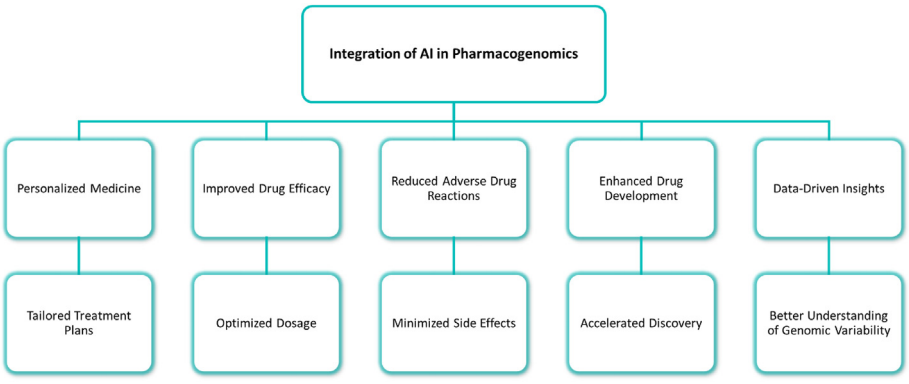

Fig. 1. The benefits of integrating AI into pharmacogenomics.

transport capacity. Examples of these techniques include drug combinations and liquid biopsies. Exosomes from the liver appear to be a promising tool for ADME phenotyping, and AI and pharmacometric modeling improve prediction accuracy even further. However, additional prospective research is required to confirm the therapeutic value of these strategies outside of genetics.[14] This work by Nageeta et al.[15] addresses implementation issues and ethical considerations as it examines the promise of precision medicine, including biomarkers, pharmacogenomics, and targeted medicines, in controlling diabetic kidney disease (DKD). Case studies demonstrate the efficacy of precision-based therapies; in the future, AI integration will be emphasized to further improve DKD care.

AI tools need to undergo thorough and rigorous examination, just like any new treatment or medical technology, to guarantee that they improve clinical practice in a way that is fair and safe. This paper provides an overview of AI for clinical pharmacologists, emphasizing its present uses, model building processes, and deployment and assessment challenges.[16] Personalized medicine is about to change primary care, especially in the areas of precision molecular diagnosis, polygenic risk scores, and pharmacogenomics. Research should demonstrate that personalized medicine enhances health outcomes for all people without escalating health disparities or taking funds away from more comprehensive healthcare interventions to assure its implementation. To avoid becoming an exclusive and ineffective solution, personalized medicine needs to also be affordable and solve issues with data governance, transparency, and societal acceptance.[17]

Modern storage capacity, AI, and learning algorithms enable us to quickly decipher complicated systems like the human genome. Given that the majority of diseases have a genetic foundation, understanding the genome is essential for improving our understanding of how diseases occur, are prevented, and are treated. Given that an individual's genome is mostly unchanging throughout life and can offer important insights into future health risks, it may be beneficial to sequence their genome from birth.[18] In this field, AI incorporation into drug response trials has proved essential. Large-scale genomic datasets and patient histories are easily handled by these technologies, greatly enhancing drug discovery, disease prediction, and diagnostic accuracy. They work especially well on complicated illnesses like cancer and genetic abnormalities.[19] For example, pathologists now face a challenge to improve their appraisal of HER2 expression across a wider range as a result of the reevaluation of biomarker use in pathology brought about by the identification of HER2-low as a key marker in breast cancer. Strict quality control, well-defined evaluation protocols, and training are necessary to handle the subtleties of HER2 expression and apply cutting-edge methods like AI and molecular testing. The notion of HER2-low holds promise as a diagnostic approach for metastatic cancers; nevertheless, more investigation is required to establish the lowest clinically meaningful HER2 levels and comprehend the mechanisms underlying resistance or inadequate response to treatment.[20]

When machine learning and AI are integrated, clinical judgment, prognosis, and diagnostics are all improved.[21] The increased availability and exposure to machine learning necessitates education and a deeper comprehension of its principles. This obligation is shared by biomedical scientists and data scientists who want to use these techniques to extract insights from data and apply their analytical prowess in medical research, respectively.[22]

Over the past 20 years, sequencing technology have advanced to the point that broad research of human genome variations has been possible, revealing a multitude of pharmacogenomic variants. The majority of these variations, however, have not yet had their effects on medication toxicity and efficacy functionally evaluated. The review by Tremmel et al.[23] highlights the significance of iterative feedback between computational predictions and experimental validation to improve personalized drug response models. It covers recent advancements in sequencing techniques, bioinformatic pipelines, computational algorithms, and the integration of machine learning and omics techniques for better pharmacogenomic predictions. Personalized anesthesia is a new area of personalized medicine that is revolutionizing healthcare by combining a patient's clinical history and genetic profile. This method uses AI to expedite processes and lower risks, real-time monitoring to improve perioperative safety, genomics and biomarkers for more precise protocols, and anesthetic care tailored to the genetics, comorbidities, and unique variables of each individual. The work by Zeng et al.[24] examines how these technologies are being used in anesthesiology, considers how they might be used to advance individualized anesthesia, and promotes interdisciplinary cooperation across anesthesiology, AI, and genomics.

The scope, causes, detection techniques, and preventative measures of the global problem of duplication in these databases were all investigated in the scoping review by Kiguba et al..[25] The evaluation emphasizes that in order to guarantee accurate data for risk assessment and patient safety, effective deduplication techniques—such as the use of unique IDs and advances in AI—are required. The review by Zhou et al.[26] delves into the latest developments in customized medicine, mostly driven by high-throughput screening and gene sequencing. With an emphasis on molecular disease classification and global signaling networks, it discusses the integration of AI, multi-omics analysis, chemical proteomics, and computational drug design in the personalization of treatments. It also looks at natural and synthetic medications that are specific to genetic mutations, talks about difficulties in interpreting mutations and combining treatments, and provides fresh perspectives on pharmacogenomics and cancer research.

The review by Singh et al.[27] looks at how real-time data modeling, early diagnosis, and efficient treatment plans are being made possible by advances in genomics, epigenomics, proteomics, metabolomics, and nutrigenomics, in conjunction with AI and machine learning, to transform personalized medicine for metabolic disorders.

Drug research and discovery depend heavily on the assessment of pharmacokinetic characteristics, yet difficulties still arise from a lack of training data. The lack of data makes it difficult to forecast the pharmacokinetic features of drug candidates accurately, even with advances in machine learning and *in-silico* predictions.[28] The review by Mohamad et al.[29] emphasizes the value of tailored therapy to maximize effectiveness and minimize side effects, stressing the significance of genetic testing, risk assessment, and platelet function tests. It addresses the issues of cost, accessibility to tests, and patient compliance. It also looks at how big data analytics, AI, and omics developments are influencing the nature of personalized care in the future, with the ultimate goal of improving patient outcomes and quality of life in cardiovascular care.

One study discusses the impact and integration of AI, healthcare, clinical genomics, and pharmacogenomics in the scope of precision medicine.[30] The study highlights the advantages and current challenges associated with these different fields, including the need for a standardized model linking and translating all these different variables. The application of clinical genomics, pharmacogenomics, AI algorithms, and big data analytics in precision medicine across different types of patient data (multi-omics) is seen as crucial for the widespread adoption of personalized medicine. Another study explores the impact of AI and precision medicine on personalizing care in five ways: therapy planning using clinical, genomic, and environmental data; identifying patterns in gene sequences or molecular signatures; predicting treatment outcomes; environmental considerations in therapy planning; and providing additional risk information to clinicians caring for at-risk patients.[31] The study highlights the need for more prospective and retrospective clinical research and clinical studies to be conducted to further advance the field.

Advancements in AI software and hardware, especially deep learning algorithms and the graphics processing units (GPUs) that power them, have led to a recent and rapidly increasing interest in medical AI applications.[32] The study focuses on emerging methods for specific tasks in clinical genomics, including variant calling, genome annotation and variant classification, and phenotype-to-genotype correspondence. Recent advancements in AI applications in healthcare and genomics have led to significant progress in precision medicine, enabling personalized

treatment and improved patient outcomes. The integration of AI in healthcare and genomics has the potential to revolutionize medical practice by enabling more accurate diagnoses, more effective treatments, and more efficient healthcare delivery. The provided search results offer valuable insights into the impact and integration of AI, healthcare, clinical genomics, and pharmacogenomics in the scope of precision medicine, as well as the challenges, limitations, and biases that need to be addressed for the successful deployment of AI in medical applications. Table 1 is summarizing the outcomes of various articles related to AI-powered pharmacogenomics.

3. Methodological innovations in AI-enhanced pharmacogenomic studies

The methodologies employed in harnessing AI for pharmacogenomic research encompass a range of approaches, including deep learning, machine learning, and big data analytics. These methodologies have the potential to revolutionize pharmacogenomics and personalized medicine by enabling the analysis of large amounts of data and the extraction of useful information from biomedical genomic datasets. Some of the key methodologies and challenges are explored in this section.

3.1. Machine learning and deep learning

The use of machine learning and deep learning in pharmacogenomic research has shown promising developments. These approaches enable the analysis of large amounts of data, making them well-suited for drug discovery by merging genomics with pharmacokinetics.[34] Deep learning, a subset of machine learning, has the advantage of representation learning, which eliminates the feature extraction step and has improved the state-of-the-art in many machine learning tasks, including genomics and drug discovery.[37] The use of AI methodologies, including machine learning, deep learning, and probabilistic graphs, extends beyond traditional single-variable and multivariable statistical methods, providing a timely synergy for pharmacogenomics.[38]

The literature emphasizes that machine learning and deep learning techniques can serve as valuable tools in pharmacogenomics research, particularly in the context of antidepressant treatments. These approaches have the potential to provide novel therapeutic and diagnostic approaches for antidepressant treatments, and there is a growing demand for establishing bioinformatics frameworks in machine learning and deep learning to address the pressing issues in the field of pharmacogenomics.[39]

3.2. Big data analytics

The application of big data analytics in pharmacogenomics research has been identified as a transformative approach, enabling the efficient management and analysis of the substantial volume of data generated in this field. The large influx of data in pharmacogenomics presents a challenge, as traditional means of analysis, such as visual analysis or statistical correlation, are not sufficient to handle such large datasets. However, the use of AI and machine learning techniques, including big data analytics, alleviates this issue by allowing for the efficient management of the data and the independent detection and analysis of patterns within the data. These techniques provide the ability to predict pharmaceutical properties of drug targets, which is especially beneficial in clinical settings, where they can be implemented to improve patient care and drug development.[30]

In the context of personalized treatment and drug development, big data analytics, combined with AI, has the potential to create actionable insights from the patterns identified in pharmacogenomics data. This includes the application of algorithms using machine learning, deep learning constructs, and related technologies to predict drug efficacy, develop drugs, and introduce medical devices and treatment policies. The integration of big data analytics and AI in pharmacogenomics is seen as a paradigm shift in health interventions, with the potential to provide information ahead of time, test life-saving drugs, and target the community-level impact of pharmacogenomics implications, even on a population level.[40]

The use of big data in health care, including pharmacogenomics, is a fast-growing field that is transforming case-based studies to large-scale, data-driven research. This approach has the potential to directly affect personalized and precision medical care, reduce the costs of treatment, and improve patient outcomes. The integration of big data analytics and AI in pharmacogenomics research is expected to play a significant role in

Table 1
Outcomes of the articles with the focus of AI-powered pharmacogenomics.

Article title	Main findings	Reference
Artificial intelligence, healthcare, clinical genomics, and pharmacogenomics approaches in precision medicine	- AI and machine learning methods are promising for managing the increasing volume of pharmacogenomics and clinical genomics data. - AI and machine learning techniques can predict pharmaceutical properties of drug targets. - Pharmacogenomics information is increasingly included in the labels of new drugs, allowing for better testing and utilization in clinical practices.	30
Implementation of pharmacogenomics and artificial intelligence tools for chronic disease management in primary care setting	- The implementation of AI tools for chronic disease management involves the use of electronic health records and commercial-grade software. - Proactive medication management using AI tools is seen as a potential solution for the challenges associated with polypharmacy and drug interactions.	33
A literature review of current and emerging capabilities of ai powered genomics	- AI enables the analysis of large amounts of data, making it well-suited to drug discovery by merging genomics with pharmacokinetics. - AI allows for big data analytics by extracting useful information from enormous biomedical genomic datasets. - *In silico* drug repositioning is an excellent application of AI to drug discovery.	34
Technologies for pharmacogenomics: a review	- The article provides a review of the performance and applicability of available genotyping methods used for pharmacogenomics.	35
Pharmacogenomics driven decision support prototype with machine learning: a framework for improving patient care	- The study utilizes informatics methods with predictive modeling to create and validate algorithms for informed pharmacogenomic decision support. - The framework is aimed at improving patient care through the use of machine learning in pharmacogenomics.	36
Deep learning in pharmacogenomics: from gene regulation to patient stratification	- The article provides examples of current and future applications of deep learning in pharmacogenomics, including the identification of novel regulatory markers and drug targets based on information extracted from multimodal omics data. - Machine learning and AI-based systems have the potential to revolutionize pharmacogenomics and pharmaceuticals, providing recommendations for further action. - Pharmacogenomics offers promise for applications such as medication optimization for patients and drug discovery and development.	37

advancing personalized medicine and health care.[41,42]

The application of big data analytics in pharmacogenomics research has been identified as a transformative approach, enabling the efficient management and analysis of the substantial volume of data generated in this field. However, the implementation of big data analytics in pharmacogenomics research faces several challenges. One of the primary challenges is the availability of sufficient pharmacogenomics data for analysis. Obtaining an adequate amount of pharmacogenomics data, particularly labeled cases and controls, is difficult due to the limited use of pharmacogenomics in clinical practice. Advanced machine learning models often require large training datasets, including labeled cases and controls, which can be a challenge in the context of pharmacogenomics where the availability of such data is limited. The most successful applications of big data analytics and machine learning in pharmacogenomics require expertise in both the methodology and the domain, presenting a challenge in terms of the specialized knowledge and skills needed to effectively apply these techniques.[30,43]

Another challenge in implementing big data analytics in pharmacogenomics research is the limitations of conventional machine learning algorithms in processing raw data. Deep learning, while advantageous in representation learning, often requires relatively large training sets, which can be a challenge in the context of pharmacogenomics. The literature highlights that few studies focus exclusively on pharmacogenomics data, indicating a potential lack of dedicated research in this specific domain, which can impact the development and application of big data analytics and machine learning models in pharmacogenomics.[41,44]

4. AI applications in pharmacogenomics

AI and machine learning have significantly impacted pharmacogenomics, offering promising solutions to the challenges posed by the rapidly increasing volume of high-throughput data. These technologies enable the independent detection and analysis of patterns within the data, providing the ability to predict pharmaceutical properties of drug targets, which is especially beneficial in clinical settings. AI and machine learning approaches are well-suited to drug discovery by merging genomics with pharmacokinetics, allowing for big data analytics and the extraction of useful information from enormous biomedical genomic datasets. For instance, AI and machine learning techniques enable virtual screening of compounds, *in silico* drug repositioning, and the identification of risk genes for specific mutations that lead to disease, ultimately contributing to the advancement of personalized medicine and drug discovery.[30,45]

AI methodologies, ranging from machine learning to deep learning and probabilistic graphs, extend beyond traditional single-variable and multivariable statistical methods, providing a timely synergy for pharmacogenomics. These methodologies have the potential to revolutionize pharmacogenomics and pharmaceuticals, offering insights and recommendations for further action.[38] AI is now used throughout the entire continuum of pharmacology research and clinical practice, from early drug discovery to real-world applications. It allows for the study of pharmacogenomic-based interactions, such as the interactions between disease and gene, gene and drug, and drug and disease, at a larger scale, contributing to a deeper understanding of personalized medicine and patient-specific outcomes.[46]

4.1. Machine learning models for drug response prediction

Machine learning models have been widely employed in predicting drug responses, particularly in the context of cancer therapy. These models use various drug response representations to train regression, classification, and ranking models. For instance, a deep learning model called DrugCell was designed to predict drug response in human cancer cells, achieving high predictive capability by capturing the determinants of drug response in an interpretable manner. The model utilized a neural network with two branches to maintain a high level of predictive capability while capturing the hierarchical organization of molecular subsystems in human cells. The model's predictive performance was characterized by its ability to separate cells into binary categories based on drug response, reflecting the area under the dose–response curve (AUC).[47]

In the field of cancer therapy, machine learning approaches have been applied to predict the efficacy of multiple drugs without prior knowledge of their effectiveness. These approaches typically involve the quantification of drug response, molecular feature selection or dimensionality reduction of cellular measurements, fitting machine learning models to predict drug response, and evaluating the models. High-throughput drug screenings with cell lines have provided a rich resource of response data, and machine learning models have been developed to predict drug responses based on these datasets. The use of deep learning and autoencoders has been proposed to address the large feature space of cancer and drug representations, as well as the size of drug response datasets, to improve the accuracy of drug response prediction models.[48,49]

A study evaluated the performance of machine learning and deep learning models for predicting drug responses in cancer. The study constructed two datasets, a gene expression dataset, and a mutation dataset, to establish drug response prediction models for individual drugs. The prediction performance of deep learning and machine learning models was compared, and the study identified the major genomic features affecting drug sensitivity. The results confirmed the applicability of drug response prediction models for individual drugs, highlighting the potential of these models in personalized medicine for cancer therapy.[50]

Machine learning models, including deep learning and traditional machine learning approaches, have been extensively utilized to predict drug responses in the context of cancer therapy. These models have shown promise in capturing the determinants of drug response, addressing the challenges of large feature spaces and datasets, and providing valuable insights for personalized medicine in cancer therapy. Table 2 is summarizing some successful applications of machine learning in pharmacogenomics research and their impact on treatment outcomes.

4.2. Deep learning in genomic analysis

Deep learning has emerged as a powerful tool for genomic analysis, offering the ability to capture complex structures within the data and learn intricate features from genomic data. It has been effectively applied in fields such as image recognition, audio classification, and natural language processing, and is increasingly being used in genomic research to analyze the sophisticated and complex nature of genomic data. Deep learning has the potential to transform the field of genomics by enabling the extraction of new insights from the exponentially increasing volume of genomics data, and by providing a method to capture dependencies in data and derive novel biological hypotheses.[52–55]

The application of deep learning in genomics has enabled the functional annotation of genomes, the determination of sequence determinants of genome functions, and the writing of synthetic genomic sequences. It has also been used to predict virus integration, identify binding sites, and provide an overview of studies applying deep learning in genomics. Deep learning models have the ability to deal with multimodal data effectively, and genomics, in particular, offers extremely heterogeneous data, making it a suitable domain for the application of deep learning models.[54]

4.3. Natural language processing (NLP) in literature mining

Natural Language Processing (NLP) has been increasingly used in identifying novel drug–gene interactions. NLP techniques are employed to extract and analyze information from unstructured data, such as scientific literature and medical records, to predict and understand drug–gene interactions. For instance, a review discusses the use of NLP in

Table 2
Successful applications of machine learning in pharmacogenomics.

Study	Method	Impact
Kidwai-Khan et al (2022)[36]	Pharmacogenomics driven decision support prototype with machine learning	Improved patient care through the development of a decision support prototype that utilizes machine learning algorithms to create and validate algorithms to enable informed pharmacogenomic decision-making.
Zhang (2021)[51]	Systematic review of pharmacogenetic interventions to improve outcomes in patients with multimorbidity or prescribed polypharmacy	Identified the potential of pharmacogenetics to improve outcomes in patients with multimorbidity or prescribed polypharmacy, but highlighted the need to overcome barriers such as regulatory and reimbursement concerns, informatics to support pharmacogenetics-informed prescribing decisions, and ethical, legal, and social implications surrounding pharmacogenetics.
Nam et al (2023)[50]	Performance evaluation of drug response prediction models for individual drugs	Confirmed the applicability of drug response prediction models for individual drugs, highlighting the potential of these models in personalized medicine for cancer therapy.

predicting drug–drug interactions and the extraction of drug interactions from unstructured data.[56] Another article highlights the application of NLP in gene-disease mapping and biomarker discovery, which are crucial steps for identifying drug–gene interactions.[57] An AI tool called PARMESAN has been developed to predict drug–gene interactions for genetic disorders, utilizing NLP for parsing modifiers via article annotations. Furthermore, text mining and automated reasoning are used to identify drug–drug interactions by aggregating gene–drug interactions, demonstrating the potential of NLP in this domain 58.

5. Challenges and limitations

AI-powered pharmacogenomics faces several challenges (Fig. 2), including the difficulty of obtaining sufficient pharmacogenomic data for model development, the integration of heterogeneous data, the need for transparent and explainable models, the lack of standardized evaluation metrics, the need for data security, the challenge of connecting different layers of the drug, and the need for accurate predictions. These challenges are discussed in various articles.[37,40,43,59,60] Despite these challenges, AI-powered pharmacogenomics has the potential to revolutionize pharmacogenomics and pharmaceutical research, providing insights and recommendations for further action.

Potential biases, interpretability issues, and ethical considerations are significant in the context of AI applications in healthcare, including pharmacogenomics. Algorithmic bias is a significant concern, and it can lead to systematically wrong outcomes. Bias can stem from various sources, including the data used to train the models. Addressing and mitigating bias in AI models is crucial for their ethical and fair deployment in healthcare. The interpretability of AI models, particularly in genomics, is essential for building trust among healthcare professionals and ensuring that the rationale behind the model's predictions is understood. Explainable AI (XAI) aims to establish transparency by explaining the decisions leading to the creation of the algorithm. However, achieving interpretability in complex AI models remains a challenge. The integration of AI in healthcare, including pharmacogenomics, raises ethical concerns related to data quality, privacy, bias, and the potential for disparate impact on underrepresented groups. Proactive embedding of ethics in research and implementation processes is advocated to address these concerns and ensure that AI-driven healthcare benefits society while upholding ethical standards. Governance models and bias evaluation checklists have been proposed to guide the ethical deployment of AI in healthcare settings. These efforts are essential to foster trust, mitigate potential harms, and ensure the equitable and ethical use of AI in healthcare.[61–63]

Pharmacogenomics is a promising field in personalized medicine, but it faces several challenges. One proposed strategy for addressing these challenges is the use of AI and machine learning algorithms to analyze large amounts of data from various sources, including genomic and clinical data. AI can help identify potential pharmacogenomic markers, drug targets, and drug–gene interactions, as well as provide recommendations for further action. However, one of the challenges is the need for large labeled datasets, which until recently were limited in biological and clinical datasets. Another challenge is the need for effective tools to address polypharmacy and drug interactions in chronic disease management. AI-powered algorithms can be used to test any life-saving drug, targeting the community-level impact of pharmacogenomics implication, even on a population. AI can also be used to develop drugs, predict their efficacy, and introduce medical devices and treatment policies. The crucial themes shaping the next generation of biomedical sciences include pharmacogenomics, big data, analytics, and AI.[37]

6. Future directions

Emerging trends and technologies in AI and pharmacogenomics are revolutionizing the way drugs are used to treat individual patients. Pharmacogenomics investigates how changes in genes affect how people respond to medications, allowing scientists to predict a drug's efficacy, guide dosage, and improve patient safety. AI is being used to develop

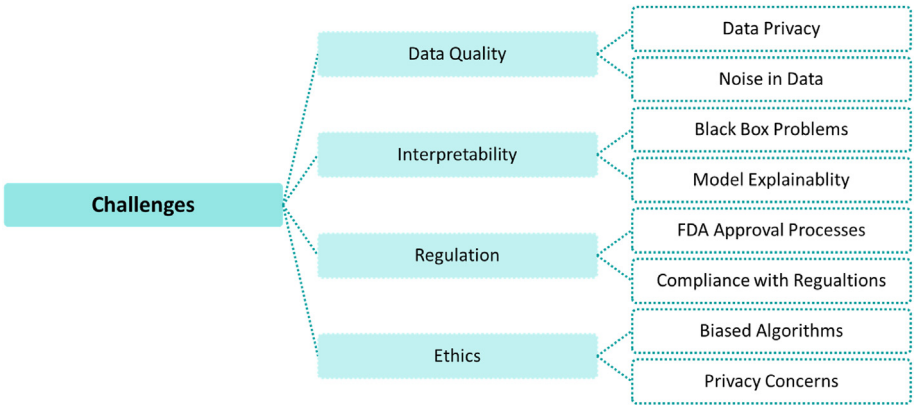

Fig. 2. Challenges and limitations in AI-powered pharmacogenomics.

drugs, predict their efficacy, and introduce medical devices and treatment policies. Some key emerging trends and technologies in AI and pharmacogenomics include machine learning and deep learning, big data and analytics, explainable AI platforms, collaboration between AI researchers and healthcare professionals, and research collaborations. Machine learning and deep learning are used to create artificial neural networks that can analyze large datasets and identify patterns in patient outcomes. The use of big data and analytics in pharmacogenomics helps identify genetic and clinical factors responsible for patient drug response and biomarker levels. Explainable AI platforms provide a unique and explainable precision medicine AI system that can quickly identify the features driving variation in patient outcomes. Partnerships between AI researchers and healthcare professionals, such as the Northwest-Alaska Pharmacogenomics Research Network (NWA-PGRN), are essential for developing constructive approaches to the inclusion of AI/AN populations in community and academic partnerships. Companies like Tempus and Bristol Myers Squibb are collaborating to apply multimodal AI approaches to identify new drug targets and validate them faster, accelerating discoveries and innovating therapies.

Recommendations for further research and development in AI and pharmacogenomics include expanding the inclusion of AI/AN populations in pharmacogenomics research to define the array of variants relevant to drug response, developing more accurate and efficient AI algorithms for predicting drug response and identifying biomarkers linked to response, and enhancing collaboration between AI researchers and healthcare professionals to accelerate the development of personalized treatment and managed care.

7. Implications for clinical practice

AI-powered pharmacogenomics is reshaping clinical decision-making by providing personalized treatment and managed care. AI algorithms can predict drug efficacy, identify biomarkers linked to response, and reveal optimal patient profiles for drug therapies. AI-derived insights can be integrated into routine patient care to improve drug selection, dosage, and safety. For instance, AI can optimize the dosage and selection of drugs based on data regarding the effects of nucleotide changes. AI can also be used to predict the pharmaceutical properties of drug targets, which is especially beneficial in clinical settings.[30]

The integration of AI-derived insights into routine patient care has implications for healthcare providers, pharmaceutical companies, and regulatory bodies. Healthcare providers can use AI to improve patient outcomes, reduce healthcare costs, and enhance patient safety. Pharmaceutical companies can use AI to accelerate drug discovery, validate drug targets faster, and innovate therapies. Regulatory bodies can use AI to evaluate drug safety and efficacy, streamline drug approval processes, and ensure patient safety.[46]

AI-powered pharmacogenomics is transforming clinical decision-making by providing personalized treatment and managed care. AI-derived insights can be integrated into routine patient care to improve drug selection, dosage, and safety. The integration of AI-derived insights into routine patient care has implications for healthcare providers, pharmaceutical companies, and regulatory bodies.

8. Conclusion

The integration of AI and pharmacogenomics is significantly reshaping clinical decision-making and personalized medicine. AI-powered pharmacogenomics enables the identification of genetic markers associated with specific diseases, prediction of treatment outcomes, and customization of medication dosages, leading to more accurate diagnoses, targeted therapies, and improved patient outcomes. This transformative impact is evident in the convergence of AI and precision medicine, which promises to revolutionize healthcare by personalizing care for every individual. The use of AI in the development of personalized medicines, from finding appropriate intervention targets to testing them for their utility, is a clear indication of its potential to advance personalized medicine.

The transformative impact of AI on personalized medicine calls for continued research and collaboration in this rapidly evolving field. As AI is now used throughout the entire continuum of pharmacology research and clinical practice, further research is essential to address the limitations of AI techniques and to advance the integration of AI-derived insights into routine patient care. Collaboration between AI researchers, healthcare providers, pharmaceutical companies, and regulatory bodies is crucial to ensure the responsible and effective implementation of AI-powered pharmacogenomics in clinical practice.

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Conflicts of interest

The authors declare no conflicts of interest.

CRediT authorship contribution statement

Hamed Taherdoost: Writing – review & editing, Validation, Supervision, Conceptualization. **Alireza Ghofrani:** Writing – original draft, Software, Resources, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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