Integrating Pharmacogenomics into Pharmaceutics: A New Horizon in Personalized Drug Delivery

Shashank Patel [1*], Ankur Awasthi[2], Vilas Baisane[3]

[1*,2,3] postgraduate student at IPS academy college of pharmacy, A.B Road, Rajendra Nagar, Indore (M.P) 452012

Abstract

Personalized medicine represents a transformative shift in healthcare, emphasizing tailored medical interventions based on an individual's genetic makeup, lifestyle, and environment. Central to this approach is pharmacogenomics, which explores how genetic variations influence drug metabolism, efficacy, and toxicity, offering the potential to optimize therapeutic outcomes and minimize adverse drug reactions. This review provides an in-depth analysis of key pharmacogenomic biomarkers, clinical applications across multiple medical domains including oncology, psychiatry, cardiology, and infectious diseases and the technological advancements enabling widespread genetic testing. It also examines the role of global databases and implementation guidelines (e.g., CPIC, PharmGKB), ethical and regulatory challenges, and future perspectives involving polygenic risk scores and artificial intelligence. Collectively, this paper underscores the pivotal role of pharmacogenomics in advancing precision medicine and shaping the future of individualized therapeutics.

Keywords : Pharmacogenomics**,** Precision Medicine, Personalized Therapeutics**,** Genomic Biomarkers**,** Drug Response Variability.

1.Introduction

Personalized medicine also known as precision medicine which refers to the customization of healthcare based on an individual's genetic content, environment, and lifestyle. This aims to move away from the "one-size-fits-all" model, tailoring prevention and treatment strategies to the unique characteristics of each patient [1,2]. Pharmacogenomics is a key pillar of this approach how an individual's genetic makeup influences their response to drugs, integrating genomics into drug development and clinical practice [3,4].

Historically, the concept of inter-individual variation in drug response can be traced back to ancient times, but it wasn't until the mid-20th century that the scientific foundations of pharmacogenetics later evolving into pharmacogenomics were formally established. The identification of inherited differences in drug metabolism, such as with isoniazid and succinylcholine, marked the beginning of the field [5]. With the sequencing of the human genome and the advent of high-throughput genotyping, pharmacogenomics has rapidly evolved, enabling the identification of single nucleotide polymorphisms (SNPs) and their association with drug efficacy and toxicity [6,7].

The rationale for personalized drug therapy is rooted in the significant inter-individual variability observed in drug response, which contributes to adverse drug reactions (ADRs) and therapeutic failures. ADRs are among the leading causes of morbidity and mortality globally, emphasizing the need for more individualized therapeutic strategies [8]. Incorporating pharmacogenomic data into clinical decision-making has the potential to enhance drug efficacy, minimize harmful side effects, and improve overall patient outcomes [9,10]. In oncology, psychiatry, and cardiology, for example, pharmacogenomic testing is already being utilized to inform drug selection and dosing [11].

2.Pharmacogenomic Biomarkers and Drug Response

2.1 Cytochrome P450 Enzymes (CYP450)

The cytochrome P450 (CYP450) enzyme superfamily is essential for the metabolism of nearly 75% of all prescribed drugs. Variants in CYP2D6 and CYP2C19 are well-characterized for their roles in altering drug metabolism phenotypes—ranging from ultra-rapid to poor metabolizers [12]. CYP2D6 polymorphisms significantly affect the metabolism of antidepressants, antipsychotics, and opioid analgesics such as codeine. Poor metabolizers may experience subtherapeutic effects or increased toxicity due to slower drug clearance [13].

CYP2C19 variants impact the bioactivation of prodrugs like clopidogrel. Individuals with loss-of-function alleles (e.g., CYP2C19 *2/*3) have an impaired ability to convert clopidogrel to its active form, which can lead to insufficient platelet inhibition and increased risk of thrombotic events [14]. Clinical pharmacogenetics implementation guidelines now recommend genotyping for CYP2C19 prior to antiplatelet therapy [15].

2.2 Drug Transporters

SLCO1B1 encodes the organic anion transporting polypeptide 1B1 (OATP1B1), which plays a crucial role in hepatic uptake of statins. A well-established variant, SLCO1B1 c.521T>C (rs4149056), is associated with reduced transporter function. Carriers of this variant are at increased risk of statin-induced myopathy, particularly with simvastatin [16]. Based on this risk, pharmacogenetic-based dosing guidelines have been issued, recommending dose reduction or alternative statins for individuals with the risk allele [17].

2.3 Drug Targets (

VKORC1 encodes the vitamin K epoxide reductase complex subunit 1, the molecular target of warfarin. Genetic polymorphisms in VKORC1 significantly affect warfarin sensitivity. The VKORC1 -1639G>A variant (rs9923231) is associated with reduced gene expression and increased sensitivity to warfarin, necessitating lower starting doses to avoid over-anticoagulation and bleeding risks [18]. When considered alongside CYP2C9 variants, VKORC1 genotyping enables more accurate warfarin dose predictions [19].

3. Clinical Applications of Pharmacogenomics

3.1 Oncology: EGFR and BRCA

In oncology, pharmacogenomics is instrumental in selecting targeted therapies based on tumor and germline mutations. Epidermal growth factor receptor (EGFR) mutations in non-small cell lung cancer (NSCLC) predict sensitivity to tyrosine kinase inhibitors (TKIs) such as gefitinib and erlotinib. Patients with activating EGFR mutations experience improved progression-free survival when treated with TKIs compared to chemotherapy [20]. Similarly, BRCA1 and BRCA2 mutations, commonly found in hereditary breast and ovarian cancers, influence treatment response to PARP inhibitors (e.g., olaparib) by exploiting synthetic lethality in DNA repair-deficient tumors [21].

3.2 Psychiatry: CYP2D6 and SSRIs

In psychiatry, genetic variation in drug-metabolizing enzymes, particularly CYP2D6, impacts the pharmacokinetics of selective serotonin reuptake inhibitors (SSRIs) like fluoxetine, paroxetine, and venlafaxine. CYP2D6 poor metabolizers are at increased risk of side effects

due to drug accumulation, while ultrarapid metabolizers may experience subtherapeutic effects [22]. Clinical guidelines now recommend CYP2D6 genotyping before initiating therapy with certain SSRIs to personalize dosage and avoid treatment failure [23].

3.3 Cardiology: CYP2C19 and Clopidogrel

Clopidogrel, a prodrug used in preventing thrombotic events, requires bioactivation by CYP2C19. Individuals carrying CYP2C19 loss-of-function alleles (e.g., *2 or *3) exhibit reduced platelet inhibition, leading to higher rates of cardiovascular events post-percutaneous coronary intervention (PCI) [24]. The FDA and CPIC recommend genotyping prior to clopidogrel administration to guide the use of alternative antiplatelet agents like prasugrel or ticagrelor in poor metabolizers [25].

3.4 Infectious Diseases: HLA-B*57:01 and Abacavir

Abacavir, a nucleoside reverse transcriptase inhibitor used in HIV treatment, is associated with life-threatening hypersensitivity reactions (HSRs) in patients carrying the HLA-B*57:01 allele. Screening for this allele before abacavir initiation has become a standard of care, virtually eliminating the risk of HSR [26]. This is one of the most successful examples of a pharmacogenomic test preventing adverse drug reactions in clinical practice [27].

4. Technological Advances in Genomic Testing

4.1 Next-Generation Sequencing (NGS), Microarrays, and WGS

NGS platforms have revolutionized pharmacogenomic testing by allowing rapid, cost-effective, and scalable analysis of entire genomes or specific pharmacogenes. Unlike traditional Sanger sequencing, NGS can detect rare variants, structural rearrangements, and copy number variations with high resolution [28]. WGS provides the most extensive genetic coverage by sequencing all 3 billion base pairs of the human genome, offering unparalleled insight into both coding and non-coding regions [29].

Microarrays, though more limited in scope than WGS, remain widely used for genotyping known variants associated with drug response. They are particularly useful for pharmacogenomic panels targeting well-established loci such as CYP2D6, SLCO1B1, and HLA alleles [30]. Platforms like Affymetrix and Illumina have developed disease-focused

microarrays that are integrated into clinical decision-making in fields such as oncology and psychiatry [31].

4.2 Direct-to-Consumer Genetic Testing

The democratization of genomic data through DTC testing companies such as 23andMe has introduced pharmacogenomic insights into everyday healthcare. These platforms utilize SNP microarrays to offer users information about their response to common drugs, including antidepressants, statins, and anticoagulants [32]. In 2018, the U.S. FDA approved 23andMe to provide pharmacogenetic reports directly to consumers, underscoring a regulatory shift toward increased public access to genetic information [33].

However, DTC testing presents challenges. Limitations include restricted variant coverage, lack of clinical interpretation, and potential for misinterpretation without medical guidance [34]. Nonetheless, DTC pharmacogenomic platforms have proven useful for pre-emptive screening and enhancing patient engagement with personalized medicine [35].

5. Pharmacogenomic Databases and Guidelines

5.1 CPIC (Clinical Pharmacogenetics Implementation Consortium)

The CPIC was established in 2009 as a collaborative initiative between the NIH-funded PharmGKB and the Pharmacogenomics Research Network. Its mission is to develop and disseminate peer-reviewed, evidence-based guidelines that enable clinicians to interpret genetic test results for drug prescribing [36]. CPIC guidelines do not recommend whether a test should be ordered, but instead provide detailed dosing recommendations based on genotype when genetic information is already available. For example, CPIC offers actionable recommendations for drugs such as clopidogrel (CYP2C19), warfarin (VKORC1, CYP2C9), and thiopurines (TPMT, NUDT15) [37].

5.2 PharmGKB (Pharmacogenomics Knowledgebase)

PharmGKB is a comprehensive, NIH-funded database that curates information on the impact of genetic variation on drug response. It includes annotations of gene-drug relationships, variant-drug associations, clinical guidelines (including CPIC and Dutch Pharmacogenetics Working Group), FDA label information, and genotype-phenotype summaries [38].

PharmGKB plays a critical role in integrating pharmacogenomic data from the literature, helping researchers and clinicians understand the functional relevance of pharmacogenomic variants across populations [39].

5.3 FDA Labelling of Pharmacogenomic Drugs

The FDA maintains a list of drugs with pharmacogenomic information in their labelling, known as the **Table of Pharmacogenomic Biomarkers in Drug Labelling**. This resource provides essential information on how genetic variation can influence drug safety, efficacy, or metabolism [40]. As of 2024, over 400 drugs include pharmacogenomic information in their labels, including warnings, dose adjustments, or required testing [41].

6. Ethical, Legal, and Social Issues (ELSI)

6.1 Genetic Privacy and Discrimination

One of the central ethical concerns in pharmacogenomics is the protection of genetic privacy. Genetic information, if misused, may lead to discrimination by employers, insurers, or other institutions. Although legal protections such as the Genetic Information Non-discrimination Act (GINA) exist in countries like the United States, many regions lack robust safeguards [42]. Furthermore, concerns remain about unauthorized data sharing, especially with increasing integration of pharmacogenomics into electronic health records [43].

There is also a significant risk of stigmatization based on genetic risk profiles, particularly in communities with histories of discrimination. Informed consent procedures must clearly explain how genomic data will be used, stored, and protected. Ethical guidelines emphasize the importance of transparency and confidentiality in both research and clinical settings [44].

6.2 Access and Affordability

Pharmacogenomic testing is often expensive and not universally covered by health insurance, creating a divide between those who can benefit from personalized medicine and those who cannot. This disparity is especially pronounced in low- and middle-income countries, where access to genomic infrastructure is limited [45].

The development and clinical validation of pharmacogenomic markers have historically been biased toward populations of European ancestry, leading to reduced clinical utility for underrepresented groups [46]. Ensuring global equity in precision medicine requires increasing genomic research diversity and revising testing guidelines to reflect broader genetic variation [47].

7. Challenges and Limitations

7.1 Clinical Implementation Barriers

Implementing pharmacogenomic testing in routine clinical care is hindered by practical and systemic obstacles. These include the high cost of testing, lack of reimbursement policies, slow integration into electronic health records, and variable availability of certified testing laboratories [48]. Many healthcare systems also lack clear clinical pathways and infrastructure to support real-time pharmacogenomic decision-making, delaying the adoption of genotype-guided prescribing [49].

7.2 Data Interpretation and Healthcare Provider Training

Another critical challenge is the complexity of interpreting genetic data. The translation of raw genotypic information into actionable therapeutic recommendations requires sophisticated bioinformatics tools and decision-support systems. However, many clinicians report insufficient training in pharmacogenomics and a lack of confidence in applying genetic results to patient care [50]. Surveys consistently highlight knowledge gaps among physicians, pharmacists, and nurses, underscoring the need for specialized education programs [51].

Efforts such as CPIC and PharmGKB provide accessible guidelines and resources, but these are often underutilized in real-world settings due to workflow constraints and the absence of standardized protocols [52].

7.3 Limited Evidence in Diverse Populations

Pharmacogenomic research has historically focused on populations of European ancestry, which limits the applicability of many findings to other ethnic groups [53]. This lack of diversity reduces the predictive power of genotype-based treatment recommendations in non-European populations, exacerbating health disparities. For instance, certain variants affecting

drug metabolism may be underrepresented or entirely absent in reference databases for African, Asian, or Indigenous populations [54].

To ensure equitable benefit from pharmacogenomics, it is essential to conduct inclusive studies, expand biobanks, and develop population-specific allele frequency maps [55].

8. Future Perspectives

8.1 Polygenic Risk Scores (PRS)

Polygenic risk scores (PRS) aggregate the effects of numerous genetic variants to predict an individual's susceptibility to complex diseases. In pharmacogenomics, PRS is increasingly being explored for its potential to refine risk stratification and drug-response prediction, especially in multifactorial diseases like cardiovascular conditions, diabetes, and psychiatric disorders [56]. Unlike single-gene variants traditionally used in drug dosing, PRS enables a broader genomic landscape assessment, offering more nuanced insights into variability in drug efficacy and toxicity [57].

While promising, challenges remain in integrating PRS into clinical workflows due to variability in predictive accuracy across ancestries, limited standardization, and lack of clinical validation for many scores [58].

8.2 Integration with AI and Machine Learning

Artificial intelligence and machine learning (ML) are transforming the way pharmacogenomic data are analyzed and applied in clinical settings. These technologies enable high-dimensional data integration from genomics, EHRs, imaging, and lifestyle data to develop predictive models of drug response [59]. For example, deep learning algorithms are being trained to interpret genomic variants and generate individualized therapeutic recommendations [60].

Machine learning is also improving the predictive power of PRS by integrating gene-gene interactions, epigenetic factors, and environmental exposures [61]. Moreover, AI-driven clinical decision support systems (CDSS) are under development to assist clinicians in interpreting pharmacogenomic results in real-time, thereby reducing the cognitive burden and minimizing prescribing errors [62].

8.3 Global Pharmacogenomic Initiatives

Global initiatives such as the Global Alliance for Genomics and Health (GA4GH), the International HundredK+ Cohorts Consortium, and the Global Biobank Meta-analysis Initiative (GBMI) are actively expanding pharmacogenomic research across diverse populations [63

In many countries are investing in national precision medicine programs—for example, the UK's Genomics England, the U.S. All of Us Research Program, and Singapore's National Precision Medicine Strategy—offering large-scale infrastructure to embed pharmacogenomics into healthcare systems [64].

9. Conclusion

Pharmacogenomics stands at the forefront of precision medicine, offering unprecedented opportunities to individualize pharmacotherapy and enhance therapeutic outcomes. By integrating genetic information into clinical decision-making, healthcare providers can better predict drug efficacy, minimize adverse drug reactions, and optimize treatment regimens. Substantial progress has been made over the past two decades with the development of clinical guidelines (e.g., CPIC), regulatory advancements (e.g., FDA pharmacogenomic labeling), and large-scale genomic initiatives that promote data accessibility and population diversity [65,66].

The continuous refinement of genotyping technologies, such as next-generation sequencing and polygenic risk models, is accelerating the clinical relevance of pharmacogenomics. Coupled with advances in artificial intelligence and machine learning, the field is moving toward the development of real-time, data-driven decision-support systems capable of integrating complex genomic, clinical, and environmental datasets. This convergence promises to overcome current barriers in data interpretation and implementation while making pharmacogenomics more accessible at the point of care [67,68].

Looking ahead, the path toward fully personalized pharmacotherapy will require sustained investment in education, infrastructure, and equitable access. Future directions must also address the inclusion of underrepresented populations to ensure that pharmacogenomic benefits are universally distributed. Moreover, interdisciplinary collaboration between geneticists,

clinicians, data scientists, and policymakers will be essential to translating the promise of pharmacogenomics into routine clinical practice worldwide [69,70].

9. REFERENCING

1. Scott SA. Personalizing medicine with clinical pharmacogenetics. Genet Med. 2011;13(12):987–995.
2. Dickmann LJ, Ware JA. Pharmacogenomics in the age of personalized medicine. Drug Discov Today Technol. 2016;21-22:11–16.
3. Evans WE, Relling MV. Moving towards individualized medicine with pharmacogenomics. Nature. 2004;429(6990):464–468.
4. Weinshilboum RM, Wang L. Pharmacogenomics: precision medicine and drug response. Mayo Clin Proc. 2017;92(11):1711–1722.
5. Kalow W. Pharmacogenetics and pharmacogenomics: origin, status, and the hope for personalized medicine. Pharmacogenomics J. 2006;6(3):162–165.
6. Tarantino P, D'Amico P, Morganti S, et al. Next generation sequencing (NGS): a revolutionary technology in pharmacogenomics and personalized medicine in cancer. In: Cancer Personal Medicine. Springer; 2019.
7. Zhou SF, Di YM, Chan E, et al. Clinical pharmacogenetics and potential application in personalized medicine. Curr Drug Metab. 2008;9(8):738–784.
8. Shah RR, Shah DR. Personalized medicine: is it a pharmacogenetic mirage? Br J Clin Pharmacol. 2012;74(4):698–721.
9. Mancinelli L, Cronin M, Sadée W. Pharmacogenomics: the promise of personalized medicine. AAPS PharmSci. 2000;2(1):E4.
10. Roman YM. Pharmacogenomics and rare diseases: optimizing drug development and personalized therapeutics. Pharmacogenomics. 2025.
11. Mini E, Nobili S. Pharmacogenetics: implementing personalized medicine. Clin Cases Miner Bone Metab. 2009;6(1):17–24.
12. Ji Y, Skierka JM, Blommel JH, et al. Preemptive pharmacogenomic testing for precision medicine: a comprehensive analysis of five actionable pharmacogenomic genes using next-generation sequencing data. J Mol Diagn. 2016;18(3):395–404.
13. Zhou S, Skaar D, Jacobson P, et al. Pharmacogenomics of medications commonly used in the intensive care unit. Front Pharmacol. 2018;9:1436.
14. Cacabelos R, Naidoo V, Corzo L, et al. Genophenotypic factors and pharmacogenomics in adverse drug reactions. Int J Mol Sci. 2021;22(24):13302.
15. Swen JJ, Nijenhuis M, de Boer A, et al. Pharmacogenetics: from bench to byte—an update of guidelines. Clin Pharmacol Ther. 2011;89(5):662–673.

16. Wilke RA, Ramsey LB, Johnson SG, et al. The clinical pharmacogenomics implementation consortium guideline for SLCO1B1 and simvastatin-induced myopathy. Clin Pharmacol Ther. 2012;92(1):112–117.
17. Ingelman-Sundberg M. Precision medicine in cardiovascular therapeutics: Evaluating the role of pharmacogenetic analysis prior to drug treatment. J Intern Med. 2024;295(5):571–585.
18. Wei CY, Lee MTM, Chen YT. Pharmacogenomics of adverse drug reactions: implementing personalized medicine. Hum Mol Genet. 2012;21(R1):R58–R65.
19. Stankov K, Sabo A, Mikov M. Pharmacogenetic biomarkers as tools for pharmacoepidemiology of severe adverse drug reactions. Drug Dev Res.2013;74(7):520–531.
20. Mok TS, Wu YL, Thongprasert S, et al. Gefitinib or carboplatin–paclitaxel in pulmonary adenocarcinoma. N Engl J Med. 2009;361(10):947–957.
21. Lord CJ, Ashworth A. PARP inhibitors: Synthetic lethality in the clinic. Science. 2017;355(6330):1152–1158.
22. Hicks JK, Bishop JR, Sangkuhl K, et al. Clinical Pharmacogenetics Implementation Consortium guideline for CYP2D6 and CYP2C19 genotypes and dosing of selective serotonin reuptake inhibitors. Clin Pharmacol Ther. 2015;98(2):127–134.
23. Greden JF, Parikh SV, Rothschild AJ, et al. Impact of pharmacogenomics on clinical outcomes in major depressive disorder in the GUIDED trial. J Psychiatr Res. 2019;111:59–67.
24. Mega JL, Simon T, Collet JP, et al. Reduced-function CYP2C19 genotype and risk of adverse clinical outcomes among patients treated with clopidogrel predominantly for PCI: a meta-analysis. JAMA. 2010;304(16):1821–1830.
25. Scott SA, Sangkuhl K, Gardner EE, et al. Clinical Pharmacogenetics Implementation Consortium guidelines for CYP2C19 genotype and clopidogrel therapy. Clin Pharmacol Ther. 2011;90(2):328–332.
26. Mallal S, Phillips E, Carosi G, et al. HLA-B*5701 screening for hypersensitivity to abacavir. N Engl J Med. 2008;358(6):568–579.
27. Saag M, Balu R, Phillips E, et al. High sensitivity of human leukocyte antigen-B*5701 as a marker for immunologically confirmed abacavir hypersensitivity in white and black patients. Clin Infect Dis. 2008;46(7):1111–1118.
28. van der Lee M, Kriek M, Guchelaar HJ, Swen JJ. Technologies for pharmacogenomics: a review. Genes (Basel). 2020;11(12):1456.

29. Tarantino P, D'Amico P, Morganti S, et al. Next-generation sequencing (NGS): a revolutionary technology in pharmacogenomics and personalized medicine in cancer. In: Cancer Personalized Medicine. Springer; 2019.
30. Medwid S, Kim RB. Implementation of pharmacogenomics: Where are we now? Br J Clin Pharmacol. 2024.
31. Kanegusuku ALG, Chan CW, Thoburn CA, et al. Implementation of pharmacogenomics testing for precision medicine. Crit Rev Food Sci Nutr. 2024. https://www.tandfonline.com/doi/full/10.1080/10408363.2023.2255279
32. Tafazoli A, Guggilla RK, Kamel-Koleti Z, Miltyk W. Strategies to improve the clinical outcomes for direct-to-consumer pharmacogenomic tests. Genes (Basel). 2021;12(3):361.
33. Kanegusuku AG, Chan CW, Thoburn CA, et al. Challenges and considerations in implementing clinical pharmacogenomics. J Lab Precis Med. 2025.
34. Cacabelos R. Problems and prospects of the direct-to-consumer genetic testing for pharmacogenomics. Curr Pharm Biotechnol. 2023;24(1):22–29.
35. Clark T. Genomic innovation: Technologies for personalised medicine. AHSN Network Report. 2020.
36. Caudle KE, Dunnenberger HM, Freimuth RR, et al. Standardizing terms for clinical pharmacogenetic test results: consensus terms from the CPIC. Genet Med. 2017;19(2):215–223.
37. Relling MV, Klein TE. CPIC: Clinical Pharmacogenetics Implementation Consortium of the Pharmacogenomics Research Network. Clin Pharmacol Ther. 2011;89(3):464–467.
38. Whirl-Carrillo M, McDonagh EM, Hebert JM, et al. Pharmacogenomics knowledge for personalized medicine. Clin Pharmacol Ther. 2012;92(4):414–417.
39. Thorn CF, Klein TE, Altman RB. PharmGKB: the pharmacogenomics knowledge base. Methods Mol Biol. 2013;1015:311–320.
40. U.S. Food and Drug Administration. Table of pharmacogenomic biomarkers in drug labeling. 2024.
41. Fedorytenko R. The role of pharmacogenetics in the treatment of cardiovascular diseases. Coll Sci Pap SCIENTIA. 2024;3(1):45–53.
42. Brothers KB, Rothstein MA. Ethical, legal and social implications of incorporating personalized medicine into healthcare. Pers Med. 2015;12(4):435–444.

43. Joly Y, Avard D. Pharmacogenomics: Ethical, social, and public policy issues. In: The Road from Nanomedicine to Precision Medicine. CRC Press; 2020.
44. Longo C, Rahimzadeh V, O'Doherty KC. Addressing ethical challenges at the intersection of pharmacogenomics and primary care using deliberative consultations. Pers Med. 2016;13(6):575–586.
45. Ashraf M, Mubarak S. Ethics considerations for precision medicine research and genetic testing in low-and middle-income countries. East Mediterr Health J. 2024;30(6):395–463.
46. Miao L, Zhang J, Yi L, Huang S. Ethical, legal, and regulatory issues associated with pharmacogenomics. In: Pharmacogenomics in Precision Medicine. Springer; 2020.
47. Pieters T, Vijverberg SJH. Ethical and social issues in pharmacogenomics testing. Curr Pharm Des. 2010;16(2):206–213.
48. Dunnenberger HM, Crews KR, Hoffman JM, et al. Preemptive clinical pharmacogenetics implementation: current programs in five US medical centers. Annu Rev Pharmacol Toxicol. 2015;55:89–106. https://doi.org/10.1146/annurev-pharmtox-010814-124835
49. Stanek EJ, Sanders CL, Taber KA, et al. Adoption of pharmacogenomic testing by US physicians: results of a nationwide survey. Clin Pharmacol Ther. 2012;91(3):450–458.
50. Just KS, Steffens M, Swen JJ, Patrinos GP, Stingl JC. Medical education in pharmacogenomics—results of a global survey. Eur J Clin Pharmacol. 2017;73(7): 855–861.
51. Haga SB, Burke W, Ginsburg GS, Mills R, Agans R. Primary care physicians' knowledge of and experience with pharmacogenetic testing. Clin Genet. 2012;82(4):388–394.
52. Luzum JA, Luzum MJ. Clinician readiness to adopt pharmacogenomics for patient care. Per Med. 2016;13(4):331–337.
53. Bentley AR, Callier SL, Rotimi CN. Diversity and inclusion in genomic research: why the uneven progress? J Community Genet. 2017;8(4):255–266.
54. Popejoy AB, Fullerton SM. Genomics is failing on diversity. Nature. 2016;538(7624):161–164.
55. Shuja N. Pharmacogenomics and Asia: Bridging scientific potential with access equity. Dev Med Life Sci. 2025;7(1):45–52.
56. Krittanawong C, Johnson KW, Choi E, et al. Artificial intelligence and cardiovascular genetics: A glimpse of the future. Life (Basel). 2022;12(2):279.

57. Siemens A, Anderson SJ, Rassekh SR, et al. A systematic review of polygenic models for predicting drug outcomes. J Pers Med. 2022;12(9):1394.
58. Fatumo S, Sathan D, Samtal C, et al. Polygenic risk scores for disease risk prediction in Africa: current challenges and future directions. Genome Med. 2023;15(1):44.
59. Lin E, Lin CH, Lane HY. Precision psychiatry applications with pharmacogenomics: Artificial intelligence and machine learning approaches. Int J Mol Sci. 2020;21(3):969.
60. Kalinin AA, Higgins GA, Reamaroon N, et al. Deep learning in pharmacogenomics: from gene regulation to patient stratification. Pharmacogenomics. 2018;19(8):629–640.
61. Srivastav AK, Mishra MK, Lillard JW Jr, et al. Transforming pharmacogenomics and CRISPR gene editing with the power of artificial intelligence for precision medicine. Pharmaceutics. 2025;17(5):555.
62. Alsaedi S, Ogasawara M, Alarawi M, et al. AI-powered precision medicine: Utilizing genetic risk factor optimization to revolutionize healthcare. NAR Genomics Bioinform. 2025;7(2):lqaf038. https://academic.oup.com/nargab/article/7/2/lqaf038/8124945
63. Pirmohamed M. Pharmacogenomics: Current status and future perspectives. Nat Rev Genet. 2023;24(6):365–377.
64. Fritzsche MC, Akyüz K, Cano Abadía M, et al. Ethical layering in AI-driven polygenic risk scores—New complexities, new challenges. Front Genet. 2023;14:1098439.
65. Cecchin E, Stocco G. Pharmacogenomics and personalized medicine: Present and future. Genes (Basel). 2020;11(6):679.
66. Shaman JA. The future of pharmacogenomics: Integrating epigenetics, nutrigenomics, and beyond. J Pers Med. 2024;14(12):1121.
67. Taherdoost H, Ghofrani A. AI and the evolution of personalized medicine in pharmacogenomics. Intelligent Pharmacy. 2024.
68. Weinshilboum RM, Wang L. Pharmacogenomics: Precision medicine and drug response. Mayo Clin Proc. 2017;92(11):1711–1722.
69. Pirmohamed M. Pharmacogenomics: Current status and future perspectives. Nat Rev Genet. 2023;24(6):365–377.
70. Wang Q, Sun S, Zhang W, et al. Pharmacogenomics education in China and the United States: Advancing personalized medicine. Pers Med. 2025.