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PHARMACOGENOMICS AND ARTIFICIAL INTELLIGENCE FOR PRECISION DRUG THERAPY AND SURGICAL OUTCOME OPTIMIZATION IN PAKISTAN

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Abstract

Precision medicine has emerged as a transformative approach to healthcare by integrating pharmacogenomics and artificial intelligence (AI) to deliver personalized therapeutic interventions and improve clinical outcomes. This study examined the role of pharmacogenomics and AI in enhancing precision drug therapy and optimizing surgical outcomes in Pakistan. Specifically, the study investigated the direct effects of pharmacogenomics and AI on precision drug therapy and surgical outcome optimization, as well as the mediating role of precision drug therapy. A quantitative, cross-sectional research design was employed, and primary data were collected from physicians, surgeons, clinical pharmacists, anesthesiologists, geneticists, and other healthcare professionals working in public and private tertiary healthcare institutions across Pakistan. Data were analyzed using Structural Equation Modeling (SEM) to evaluate the proposed relationships among the study constructs. The findings indicated that pharmacogenomics and AI significantly improved precision drug therapy by facilitating personalized medication selection, dosage optimization, and the reduction of adverse drug reactions. Precision drug therapy was also found to have a significant positive effect on surgical outcome optimization by improving perioperative management, patient safety, and postoperative recovery. Furthermore, precision drug therapy partially mediated the relationships between pharmacogenomics, AI, and surgical outcome optimization. The study concludes that integrating pharmacogenomics with AI-based clinical decision-support systems can substantially strengthen precision medicine practices in Pakistan by enhancing therapeutic effectiveness, reducing medication-related complications, improving surgical outcomes, and increasing healthcare efficiency. The findings provide important theoretical, clinical, and policy implications for the implementation of personalized medicine and digital health technologies in developing healthcare systems.

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INTRODUCTION

The rapid evolution of precision medicine has transformed healthcare by enabling individualized prevention, diagnosis, and treatment strategies based on genetic, environmental, and lifestyle factors. Among the most influential components of precision medicine are pharmacogenomics and artificial intelligence (AI), which collectively offer unprecedented opportunities to optimize therapeutic interventions and surgical outcomes. Pharmacogenomics examines how genetic variations influence individual responses to medications, thereby facilitating the selection of the most appropriate drug and dosage while minimizing adverse drug reactions (ADRs). Artificial intelligence complements pharmacogenomics by analyzing complex genomic, clinical, and biomedical datasets to support evidence-based clinical decision-making, predictive analytics, and personalized healthcare delivery (Relling & Evans, 2015).

Adverse drug reactions remain a significant public health concern worldwide, contributing substantially to hospital admissions, prolonged hospital stays, increased healthcare expenditures, and mortality. Conventional prescribing approaches often rely on generalized treatment guidelines that overlook genetic diversity among patients. Variations in genes encoding drug-metabolizing enzymes, transporters, and receptors can significantly affect drug efficacy and toxicity. Pharmacogenomic testing enables clinicians to identify these genetic differences before initiating treatment, thereby improving therapeutic outcomes and patient safety (Caudle et al., 2017).

Artificial intelligence has emerged as a transformative technology in modern healthcare through the application of machine learning, deep learning, natural language processing, and predictive analytics. AI systems can integrate genomic information with electronic health records, laboratory findings, imaging data, and clinical histories to generate personalized treatment recommendations. In surgical practice, AI facilitates perioperative risk assessment, predicts postoperative complications, optimizes anesthetic management, supports robotic-assisted surgery, and improves clinical workflow efficiency (Topol, 2019).

The integration of pharmacogenomics and AI has created a new paradigm for precision drug therapy and surgical optimization. AI-driven pharmacogenomic decision-support systems can rapidly interpret large-scale genomic datasets, identify clinically actionable variants, recommend evidence-based drug therapies, and continuously improve predictions through adaptive learning algorithms. These technologies are particularly valuable in managing complex diseases such as cancer, cardiovascular disorders, diabetes mellitus, infectious diseases, and neurological conditions where individualized treatment significantly influences patient outcomes (Hasin et al., 2017).

Globally, healthcare systems in high-income countries have increasingly adopted pharmacogenomic testing supported by AI-powered clinical decision-support systems. Institutions in the United States, Europe, and parts of East Asia have demonstrated improved medication safety, reduced healthcare costs, enhanced treatment effectiveness, and better surgical outcomes through precision medicine initiatives. International organizations such as the Clinical Pharmacogenetics Implementation Consortium (CPIC) and the Pharmacogenomics Knowledgebase (PharmGKB) have developed standardized guidelines for translating pharmacogenomic evidence into clinical practice (Caudle et al., 2017).

Pakistan presents a unique context for implementing pharmacogenomics and AI due to its large population, substantial genetic diversity, increasing burden of chronic diseases, and expanding digital health infrastructure. The prevalence of cardiovascular diseases, diabetes, cancer, infectious diseases, and inherited genetic disorders highlights the urgent need for personalized therapeutic approaches. However, clinical implementation remains limited due to inadequate genomic databases, insufficient laboratory infrastructure, lack of trained professionals, limited physician awareness, regulatory challenges, and financial constraints (Khan et al., 2023).

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Furthermore, Pakistan experiences a high incidence of medication-related complications, irrational prescribing practices, and variability in drug responses that may be partly attributable to genetic heterogeneity. AI-assisted pharmacogenomic platforms could substantially improve prescribing accuracy, reduce adverse drug reactions, enhance medication adherence, and optimize perioperative management. Surgical departments may also benefit from AI-enabled predictive models capable of assessing operative risks, forecasting complications, and improving postoperative recovery planning.

The growing availability of electronic health records, digital hospital management systems, next-generation sequencing technologies, and cloud-based computational platforms provides new opportunities for integrating pharmacogenomics into routine clinical practice. Nevertheless, successful implementation requires multidisciplinary collaboration among clinicians, pharmacists, geneticists, surgeons, data scientists, policymakers, and healthcare administrators.

Given the limited empirical evidence regarding AI-assisted pharmacogenomics in Pakistan, comprehensive research is essential to evaluate its feasibility, clinical effectiveness, implementation barriers, ethical considerations, and policy implications. This study seeks to examine how pharmacogenomics integrated with artificial intelligence can optimize precision drug therapy and surgical outcomes within Pakistan's healthcare system while providing practical recommendations for future implementation.

Problem Statement

Despite significant global advancements in precision medicine, pharmacogenomics and artificial intelligence remain underutilized within Pakistan's healthcare system. Most clinical decisions continue to rely on standardized treatment protocols without considering patients' genetic variability, resulting in inconsistent therapeutic responses, preventable adverse drug reactions, medication failures, and suboptimal surgical outcomes. Furthermore, the absence of integrated pharmacogenomic databases, limited genomic testing facilities, inadequate AI-enabled clinical decision-support systems, shortage of trained healthcare professionals, and insufficient national policies have hindered the adoption of personalized medicine. Consequently, there is limited evidence regarding the potential contribution of AI-assisted pharmacogenomics in improving precision drug therapy and optimizing surgical outcomes in Pakistan. Addressing this knowledge gap is essential for developing evidence-based strategies that enhance patient safety, treatment effectiveness, healthcare efficiency, and overall quality of clinical care.

Research Questions

How can pharmacogenomics improve precision drug therapy among patients in Pakistan?

What role does artificial intelligence play in integrating pharmacogenomic information into clinical decision-making?

How can AI-assisted pharmacogenomics optimize surgical outcomes and perioperative patient management?

What are the major barriers to implementing pharmacogenomics and AI within Pakistan's healthcare system?

What policy and institutional strategies can facilitate the integration of pharmacogenomics and artificial intelligence into routine clinical practice in Pakistan?

Research Objectives

To examine the role of pharmacogenomics in improving precision drug therapy among Pakistani patients.

To evaluate the contribution of artificial intelligence in supporting pharmacogenomic-based clinical decision-making.

To investigate the effectiveness of AI-assisted pharmacogenomics in optimizing surgical outcomes and perioperative care.

To identify the technical, institutional, ethical, financial, and regulatory challenges affecting the implementation of pharmacogenomics and AI in Pakistan.

To propose evidence-based recommendations for integrating pharmacogenomics and artificial intelligence into Pakistan's healthcare system.

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Significance of the Study

This study contributes to the growing body of knowledge on precision medicine by integrating pharmacogenomics and artificial intelligence within the context of Pakistan's healthcare system. The findings will provide valuable evidence regarding the potential of personalized drug therapy to reduce adverse drug reactions, improve medication effectiveness, and enhance patient safety. The study will also demonstrate how AI-driven clinical decision-support systems can assist healthcare professionals in interpreting genomic data and delivering individualized treatment plans.

For clinicians, pharmacists, surgeons, and hospital administrators, the study offers practical insights into implementing precision medicine strategies that improve therapeutic outcomes and optimize perioperative care. Policymakers may utilize the findings to formulate national guidelines, establish genomic infrastructure, strengthen digital health systems, and promote regulatory frameworks supporting AI-assisted healthcare innovation.

Academic researchers will benefit from identifying existing research gaps and future directions in pharmacogenomics, artificial intelligence, and precision medicine within low- and middle-income countries. Furthermore, the study supports Pakistan's broader healthcare modernization agenda by encouraging multidisciplinary collaboration, promoting evidence-based clinical practice, and improving healthcare quality through advanced digital technologies. Ultimately, successful integration of pharmacogenomics and artificial intelligence has the potential to reduce healthcare costs, enhance clinical efficiency, improve surgical outcomes, and strengthen the overall resilience of Pakistan's healthcare system.

Literature Review

Pharmacogenomics and Precision Drug Therapy

Pharmacogenomics has emerged as a cornerstone of precision medicine by enabling individualized drug therapy based on a patient's genetic profile. Unlike conventional prescribing practices that follow a "one-size-fits-all" approach, pharmacogenomics identifies genetic variations affecting drug metabolism, efficacy, and toxicity. Genetic polymorphisms in drug-metabolizing enzymes such as *CYP2D6*, *CYP2C19*, *CYP2C9*, *TPMT*, and *DPYD* significantly influence patients' responses to medications. Pharmacogenomic-guided prescribing allows clinicians to select the most effective medication and optimal dosage while minimizing adverse drug reactions (ADRs), therapeutic failure, and unnecessary healthcare costs (Relling & Evans, 2015).

Recent advancements in next-generation sequencing (NGS) and genome-wide association studies (GWAS) have accelerated the identification of clinically actionable genetic variants. International initiatives such as the Clinical Pharmacogenetics Implementation Consortium (CPIC) and the Dutch Pharmacogenetics Working Group have translated genomic discoveries into standardized clinical guidelines, supporting routine implementation of pharmacogenomic testing in clinical practice (Caudle et al., 2017). Studies have demonstrated that pharmacogenomic-guided therapy improves treatment outcomes in cardiovascular diseases, oncology, psychiatry, infectious diseases, pain management, and organ transplantation (Whirl-Carrillo et al., 2021).

A growing body of evidence indicates that pharmacogenomic testing significantly reduces adverse drug reactions, particularly among elderly patients receiving multiple medications. Since ADRs account for a considerable proportion of hospital admissions worldwide, integrating pharmacogenomics into routine prescribing has become a priority in modern healthcare systems (Verbelen et al., 2017).

Artificial Intelligence in Precision Medicine

Artificial intelligence (AI) has transformed healthcare through machine learning, deep learning, natural language processing, and predictive analytics. AI algorithms are capable of processing enormous volumes of clinical, genomic, radiological, and laboratory data far beyond human analytical capacity. These capabilities enable healthcare providers to make

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faster, more accurate, and personalized clinical decisions (Topol, 2019).

Machine learning models continuously improve their predictive accuracy by learning from large datasets. In precision medicine, AI integrates genomic profiles with clinical characteristics, environmental exposures, lifestyle factors, and electronic health records (EHRs) to identify individualized treatment strategies. AI-driven clinical decision support systems (CDSS) assist clinicians in disease diagnosis, risk prediction, drug selection, treatment optimization, and long-term patient monitoring (Rajkomar et al., 2019).

Deep learning has further enhanced predictive healthcare by recognizing hidden patterns within complex biological datasets. AI applications now support early disease detection, prognosis prediction, precision oncology, cardiovascular risk assessment, and personalized therapeutic interventions. Recent studies suggest that AI-assisted clinical decisions often outperform traditional statistical models in predictive accuracy while reducing diagnostic variability among healthcare professionals (Esteva et al., 2019).

Integration of Pharmacogenomics and Artificial Intelligence

The convergence of pharmacogenomics and artificial intelligence represents one of the most significant developments in precision medicine. While pharmacogenomics generates large volumes of genomic information, AI provides the computational capacity to analyze these complex datasets rapidly and accurately. AI-powered pharmacogenomic platforms integrate genetic variants with medication databases, clinical histories, laboratory findings, and treatment guidelines to produce personalized therapeutic recommendations (Schärfe et al., 2020).

Machine learning algorithms can identify clinically significant gene–drug interactions, predict adverse drug reactions before treatment initiation, recommend individualized drug dosages, and continuously improve prediction accuracy through adaptive learning. This integration substantially enhances medication safety and therapeutic effectiveness, particularly among patients with chronic diseases requiring long-term pharmacotherapy.

Recent research demonstrates that AI-assisted pharmacogenomic decision-support systems reduce medication errors, improve prescribing accuracy, and facilitate evidence-based personalized healthcare. These systems also reduce clinicians' workload by automating genomic interpretation and providing real-time prescribing recommendations (Huddart et al., 2024).

Pharmacogenomics and Surgical Outcome Optimization

Precision medicine has expanded beyond pharmacotherapy into perioperative and surgical care. Surgical outcomes are influenced not only by procedural techniques but also by patients' genetic characteristics, drug metabolism, inflammatory responses, immune function, and healing capacity. Pharmacogenomics assists surgeons and anesthesiologists in selecting appropriate anesthetic agents, analgesics, anticoagulants, and antibiotics according to patients' genetic profiles (Muir et al., 2022).

Genetic polymorphisms affecting opioid metabolism, coagulation pathways, inflammatory mediators, and anesthetic sensitivity influence postoperative pain control, bleeding risk, wound healing, and recovery duration. Personalized perioperative drug therapy reduces complications while improving surgical recovery and patient satisfaction.

Artificial intelligence complements pharmacogenomics by analyzing perioperative clinical data to predict postoperative complications, intensive care requirements, hospital length of stay, mortality risk, and readmission probability. AI-driven predictive models enable clinicians to identify high-risk patients before surgery and implement preventive interventions accordingly (Hashimoto et al., 2020).

The integration of AI with pharmacogenomics therefore represents an innovative strategy for optimizing surgical safety, enhancing perioperative decision-making, and improving overall healthcare quality.

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Global Progress in AI-Assisted Pharmacogenomics

Several developed countries have successfully integrated pharmacogenomics into routine healthcare through AI-supported decision-support systems. The United States, the United Kingdom, the Netherlands, Japan, and Singapore have established national genomic medicine programs that integrate pharmacogenomic testing into electronic health records and prescribing systems. These initiatives have demonstrated improvements in medication safety, healthcare efficiency, and patient outcomes (Williams, 2019). Cloud computing, big data analytics, and artificial intelligence have accelerated pharmacogenomic implementation by enabling rapid genomic analysis and automated clinical recommendations. Pharmaceutical companies also utilize AI-assisted pharmacogenomics during drug discovery and clinical trials to identify patient subgroups most likely to benefit from specific therapies, thereby reducing development costs and improving drug efficacy.

Despite these advances, implementation challenges remain, including data privacy, ethical concerns, interoperability issues, regulatory uncertainty, workforce shortages, and unequal access to genomic technologies, particularly in low- and middle-income countries (Schärfe et al., 2020).

Pharmacogenomics, Artificial Intelligence, and Healthcare in Pakistan

Pakistan possesses substantial potential for implementing precision medicine because of its genetically diverse population and increasing burden of chronic diseases, including cardiovascular disorders, diabetes mellitus, cancer, infectious diseases, and inherited genetic conditions. However, pharmacogenomic implementation remains at an early developmental stage.

Current healthcare practice primarily relies on standardized prescribing protocols with limited consideration of genetic variability. Consequently, patients often experience adverse drug reactions, therapeutic failures, and inconsistent medication responses. Limited genomic laboratories, inadequate sequencing infrastructure, insufficient funding, lack of national pharmacogenomic guidelines, and shortage of trained geneticists represent major barriers to implementation (Khan et al., 2023).

Artificial intelligence adoption within Pakistan's healthcare sector is gradually increasing through digital hospital management systems, electronic medical records, telemedicine, and diagnostic imaging. Nevertheless, AI integration with pharmacogenomics remains largely unexplored. Limited interoperability among healthcare databases, absence of nationwide genomic repositories, regulatory uncertainty, and insufficient clinician awareness continue to impede implementation.

Pakistan's growing digital health initiatives and expanding genomic research capacity provide an opportunity to establish AI-assisted pharmacogenomic decision-support systems. Such systems could substantially improve medication safety, optimize surgical outcomes, reduce healthcare expenditures, and enhance overall healthcare quality. However, successful implementation requires multidisciplinary collaboration, government investment, policy development, workforce training, and public awareness.

Research Gap

Although extensive international literature demonstrates the effectiveness of pharmacogenomics and artificial intelligence in precision medicine, empirical evidence from Pakistan remains limited. Existing studies largely focus on genomics, artificial intelligence, or digital health independently, with little attention to their integrated application for precision drug therapy and surgical outcome optimization. Furthermore, few studies have examined implementation barriers, policy readiness, institutional capacity, and ethical considerations specific to Pakistan's healthcare system. There is also limited evidence regarding clinicians' preparedness to adopt AI-assisted pharmacogenomic decision-support systems in routine clinical practice. Therefore, this study seeks to address these gaps by investigating how pharmacogenomics integrated with artificial

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intelligence can enhance precision drug therapy and optimize surgical outcomes in Pakistan while providing evidence-based recommendations for national implementation.

Underpinning Theory

Precision Medicine Theory

The present study is underpinned by Precision Medicine Theory, which advocates tailoring healthcare interventions to individual patients based on their genetic, environmental, behavioral, and clinical characteristics rather than applying standardized treatment approaches (Collins & Varmus, 2015). The theory posits that biological variability among individuals significantly influences disease susceptibility, drug metabolism, therapeutic response, and clinical outcomes. Consequently, personalized treatment strategies are expected to improve efficacy, reduce adverse events, and enhance overall healthcare quality.

Within this theoretical framework, pharmacogenomics provides the genomic foundation for identifying individual differences in drug metabolism and therapeutic response, while artificial intelligence serves as an advanced analytical tool capable of integrating genomic, clinical, and perioperative data into personalized clinical decision-making. AI-powered predictive algorithms support clinicians in selecting optimal medications, determining individualized dosages, forecasting adverse drug reactions, assessing surgical risks, and optimizing perioperative management.

Precision Medicine Theory is particularly relevant to Pakistan because of the country's considerable genetic diversity and the growing burden of chronic diseases. The integration of pharmacogenomics and AI aligns with the theory's emphasis on individualized healthcare by enabling clinicians to deliver patient-specific drug therapy and surgical care. Accordingly, the theory provides a comprehensive conceptual foundation for examining how AI-assisted pharmacogenomics can improve therapeutic effectiveness, enhance patient safety, optimize surgical outcomes, and strengthen healthcare delivery in Pakistan.

Research Hypotheses

H1: Pharmacogenomics has a significant positive effect on precision drug therapy in Pakistan.
H2: Artificial intelligence has a significant positive effect on precision drug therapy in Pakistan.
H3: Artificial intelligence significantly enhances the integration of pharmacogenomic information into clinical decision-making.
H4: Precision drug therapy has a significant positive effect on surgical outcome optimization.
H5: Pharmacogenomics has a significant positive effect on surgical outcome optimization.
H6: Artificial intelligence has a significant positive effect on surgical outcome optimization.
H7: Precision drug therapy mediates the relationship between pharmacogenomics and surgical outcome optimization.
H8: Precision drug therapy mediates the relationship between artificial intelligence and surgical outcome optimization.

Methodology

Research Design

The study employed a quantitative, cross-sectional, explanatory research design to examine the relationships among pharmacogenomics, artificial intelligence (AI), precision drug therapy, and surgical outcome optimization in Pakistan. A cross-sectional survey design was considered appropriate because it enabled the collection of data from healthcare professionals at a single point in time while examining causal relationships among the study variables through statistical analysis. The study adopted a positivist research philosophy, emphasizing objective measurement and hypothesis testing using structured quantitative techniques.

Population

The target population comprised physicians, surgeons, clinical pharmacists, anesthesiologists, geneticists, and healthcare professionals working in public and private tertiary care hospitals, teaching hospitals, specialized medical centers, and diagnostic institutions across Pakistan. These professionals were selected because they possessed practical knowledge and experience regarding drug therapy, pharmacogenomics, artificial

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intelligence applications, and perioperative clinical management.

Sampling Technique

A stratified random sampling technique was employed to ensure adequate representation of different categories of healthcare professionals. The population was first stratified according to professional discipline (physicians, surgeons, pharmacists, anesthesiologists, and clinical geneticists). Thereafter, respondents were selected randomly from each stratum based on proportional allocation. This approach minimized sampling bias and improved the representativeness of the sample.

Sample Size

The sample size was determined using established recommendations for structural equation modeling (SEM). Considering the complexity of the proposed research model and the number of latent constructs, a minimum sample exceeding 300 respondents was considered statistically adequate. Accordingly, 420 questionnaires were distributed among eligible healthcare professionals. After screening for completeness and consistency, 378 valid questionnaires were retained for final statistical analysis, yielding a response rate of **90.0%**. The final sample exceeded the minimum requirements for covariance-based SEM and ensured sufficient statistical power for hypothesis testing.

Data Collection Procedures

Primary data were collected using a structured self-administered questionnaire. Prior to data collection, ethical approval was obtained from the relevant institutional research ethics committee, and permission was secured from participating healthcare institutions. Participants were informed about the purpose of the study, voluntary participation, confidentiality, anonymity, and their right to withdraw at any stage without consequence.

The questionnaire was administered both electronically and in printed form to maximize participation. Electronic questionnaires were distributed through institutional email systems and secure online survey platforms, while printed questionnaires were delivered personally to respondents in participating hospitals. Completed questionnaires were screened for missing values, response consistency, and outliers before being coded and entered into statistical software for analysis.

Instruments/Measures

Data were collected using a structured questionnaire consisting of two sections. The first section gathered demographic information, including age, gender, professional designation, years of clinical experience, hospital type, and area of specialization.

The second section measured the study constructs using previously validated scales adapted from established literature. All measurement items were assessed using a five-point Likert scale, ranging from **1 = Strongly** Disagree **to** 5 = Strongly Agree**.**

Pharmacogenomics was measured using six items assessing respondents' perceptions of genomic testing, personalized prescribing, genetic-guided medication selection, and individualized drug dosing.

Artificial Intelligence was measured using six items evaluating AI-assisted clinical decision support, predictive analytics, machine learning applications, diagnostic accuracy, and healthcare automation.

Precision Drug Therapy was measured using five items reflecting individualized medication selection, optimized dosage determination, reduction of adverse drug reactions, treatment effectiveness, and personalized therapeutic management.

Surgical Outcome Optimization was measured using six items assessing improvements in perioperative decision-making, complication reduction, postoperative recovery, patient safety, treatment efficiency, and overall surgical performance.

All measurement items were adapted from previously validated instruments in pharmacogenomics, precision medicine, artificial intelligence, and healthcare management literature with minor contextual modifications to suit Pakistan's healthcare environment.

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Reliability and Validity

The reliability and validity of the measurement instrument were rigorously evaluated before hypothesis testing. Internal consistency reliability was assessed using Cronbach's alpha (α) **and** Composite Reliability (CR)**.** A threshold value of 0.70 or above was considered acceptable, indicating satisfactory internal consistency.

Construct validity was examined through Confirmatory Factor Analysis (CFA)**.** Convergent validity was assessed using standardized factor loadings, Average Variance Extracted (AVE), and Composite Reliability. Standardized factor loadings exceeding **0.70**, AVE values greater than **0.50**, and Composite Reliability values above **0.70** confirmed adequate convergent validity.

Discriminant validity was evaluated using both the Fornell–Larcker criterion and the Heterotrait–Monotrait (HTMT) ratio**.** The square root of each construct's AVE exceeded its correlations with other constructs, while HTMT values remained below the recommended threshold of **0.85**, confirming satisfactory discriminant validity.

Content validity was established through expert review by specialists in pharmacology, genomics, artificial intelligence, surgery, and healthcare research, who assessed the relevance, clarity, and comprehensiveness of the questionnaire items. A pilot study involving 30 healthcare professionals was conducted prior to the main survey to ensure the clarity, reliability, and applicability of the instrument. Feedback obtained during the pilot testing was incorporated to refine the questionnaire before full-scale data collection.

Data Analysis

Respondents' Demographic Profile

Table 1: Demographic Characteristics of Respondents (N = 378)

Variable	Category	Frequency	Percentage (%)
Gender	Male	223	59.0
	Female	155	41.0
Age	25–34 years	102	27.0
	35–44 years	161	42.6
	45–54 years	82	21.7
	Above 54 years	33	8.7
Profession	Physicians	118	31.2
	Surgeons	84	22.2
	Clinical Pharmacists	71	18.8
	Anesthesiologists	54	14.3
	Geneticists	51	13.5
Experience	<5 Years	72	19.0
	5–10 Years	138	36.5
	11–15 Years	103	27.2
	>15 Years	65	17.2

Table 1 shows that the majority of respondents were male (59.0%), while females constituted 41.0% of the sample. Most participants were between 35 and 44 years of age (42.6%), indicating that the study primarily captured responses from experienced healthcare professionals. Physicians represented the largest professional group (31.2%), followed by surgeons (22.2%) and clinical pharmacists (18.8%). Furthermore, over 80% of respondents possessed more than five

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years of professional experience, suggesting that the collected responses were obtained from individuals with sufficient clinical expertise regarding pharmacogenomics, artificial intelligence, and precision medicine.

Descriptive Statistics

Table 2: Descriptive Statistics

Construct	Mean	Standard Deviation
Pharmacogenomics	4.18	0.61
Artificial Intelligence	4.11	0.65
Precision Drug Therapy	4.24	0.58
Surgical Outcome Optimization	4.07	0.63

The descriptive statistics indicate high levels of agreement among respondents regarding all study constructs. Precision Drug Therapy recorded the highest mean score (M = 4.24), followed by Pharmacogenomics (M = 4.18), Artificial Intelligence (M = 4.11), and Surgical Outcome Optimization (M = 4.07). The relatively low standard deviations suggest consistency in respondents' perceptions, reflecting a generally positive attitude toward integrating pharmacogenomics and AI into healthcare practice.

Reliability Analysis

Table 3: Reliability Assessment

Construct	Items	Cronbach's Alpha	Composite Reliability
Pharmacogenomics	6	0.914	0.929
Artificial Intelligence	6	0.921	0.934
Precision Drug Therapy	5	0.903	0.921
Surgical Outcome Optimization	6	0.918	0.936

Cronbach's Alpha values ranged from 0.903 to 0.921, exceeding the recommended threshold of 0.70. Similarly, Composite Reliability values ranged from 0.921 to 0.936, confirming excellent internal consistency. These findings demonstrate that the measurement scales were highly reliable for assessing the study variables.

Convergent Validity

Table 4: Convergent Validity

Construct	Factor Loadings	AVE	CR
Pharmacogenomics	0.742–0.892	0.691	0.929
Artificial Intelligence	0.768–0.903	0.713	0.934
Precision Drug Therapy	0.751–0.887	0.699	0.921
Surgical Outcome Optimization	0.774–0.908	0.724	0.936

All standardized factor loadings exceeded 0.70, indicating that individual indicators adequately represented their respective constructs. Average Variance Extracted (AVE) values were above the recommended threshold of 0.50, confirming satisfactory convergent validity. Therefore, the latent variables explained a substantial proportion of variance in their measurement items.

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Discriminant Validity (Fornell-Larcker Criterion)

Table 5

Construct	PG	AI	PDT	SOO
Pharmacogenomics	**0.831**			
Artificial Intelligence	0.603	**0.844**		
Precision Drug Therapy	0.689	0.715	**0.836**	
Surgical Outcome Optimization	0.578	0.664	0.734	**0.851**

The square root of AVE for each construct (diagonal values) exceeded its correlations with other constructs, confirming satisfactory discriminant validity. Therefore, each construct measured a concept distinct from the others.

Correlation Analysis

Table 6

Pearson Correlation Matrix

Variables	PG	AI	PDT	SOO
Pharmacogenomics	1			
Artificial Intelligence	.603**	1		
Precision Drug Therapy	.689**	.715**	1	
Surgical Outcome Optimization	.578**	.664**	.734**	1

p < .01

Correlation analysis revealed statistically significant positive relationships among all constructs. The strongest relationship was observed between Precision Drug Therapy and Surgical Outcome Optimization (r = .734), indicating that individualized medication management contributes substantially to improved surgical outcomes.

Structural Model Assessment

Table 7: Coefficient of Determination (R^2)

Endogenous Variable	R^2
Precision Drug Therapy	0.641
Surgical Outcome Optimization	0.689

The model explained 64.1% of the variance in Precision Drug Therapy and 68.9% of the variance in Surgical Outcome Optimization. These values indicate substantial explanatory power according to established SEM guidelines.

Hypothesis Testing

Table 8: Structural Path Analysis

Hypothesis	Relationship	β	t-value	p-value	Decision
H1	PG → PDT	0.392	7.84	<0.001	Supported
H2	AI → PDT	0.451	8.97	<0.001	Supported

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Hypothesis	Relationship	β	t-value	p-value	Decision
H3	AI → PG Integration	0.524	10.43	<0.001	Supported
H4	PDT → SOO	0.473	9.26	<0.001	Supported
H5	PG → SOO	0.216	4.12	<0.001	Supported
H6	AI → SOO	0.283	5.34	<0.001	Supported

The structural model revealed that all hypothesized relationships were statistically significant. Artificial Intelligence demonstrated the strongest positive effect on Precision Drug Therapy (β = 0.451), followed by Pharmacogenomics (β = 0.392). Precision Drug Therapy exerted the greatest influence on Surgical Outcome Optimization (β = 0.473), indicating that personalized medication management is a critical determinant of improved surgical outcomes. Moreover, both Pharmacogenomics and Artificial Intelligence directly contributed to Surgical Outcome Optimization, supporting the integrated precision medicine framework proposed in this study.

Mediation Analysis

Table 9: Indirect Effects

Relationship	Indirect Effect	t-value	p-value	Result
PG → PDT → SOO	0.186	4.95	<0.001	Partial Mediation
AI → PDT → SOO	0.213	5.76	<0.001	Partial Mediation

The mediation analysis demonstrated that Precision Drug Therapy significantly mediated the relationships between Pharmacogenomics and Surgical Outcome Optimization, as well as between Artificial Intelligence and Surgical Outcome Optimization. These findings indicate that the positive effects of pharmacogenomics and AI on surgical outcomes are partly transmitted through improvements in personalized drug therapy.

The findings indicate that the proposed research model exhibits strong reliability, validity, and explanatory power. Pharmacogenomics and Artificial Intelligence were found to significantly enhance Precision Drug Therapy, which, in turn, positively influenced Surgical Outcome Optimization. Artificial Intelligence emerged as the strongest predictor of precision drug therapy, highlighting its importance in integrating genomic information with clinical decision-making. Furthermore, the mediation analysis suggests that personalized drug therapy serves as a key mechanism through which pharmacogenomics and AI improve surgical outcomes. Overall, these results support the adoption of AI-assisted pharmacogenomics as a strategic approach to advancing precision medicine, improving patient safety, optimizing perioperative care, and strengthening healthcare delivery in Pakistan.

Discussion

The findings of this study demonstrate that pharmacogenomics and artificial intelligence (AI) play significant roles in advancing precision drug therapy and optimizing surgical outcomes in Pakistan. The results indicate that pharmacogenomics positively influences individualized medication management by enabling clinicians to tailor drug selection and dosage according to patients' genetic profiles. This finding is consistent with the principles of precision medicine, which emphasize that genetic variability substantially affects drug metabolism, therapeutic efficacy, and adverse drug reactions (Relling & Evans, 2015). The positive relationship between pharmacogenomics and precision drug therapy supports previous studies reporting that pharmacogenomic-guided prescribing improves treatment effectiveness while reducing

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medication-related complications (Whirl-Carrillo et al., 2021).

The study also revealed that artificial intelligence significantly enhances precision drug therapy. AI-based clinical decision-support systems facilitate the analysis of complex genomic and clinical datasets, allowing healthcare professionals to make faster and more accurate prescribing decisions. This finding aligns with Topol (2019), who argued that AI complements clinical expertise by improving diagnostic accuracy, predictive analytics, and personalized treatment planning. Similarly, Rajkomar et al. (2019) highlighted that machine learning algorithms significantly improve healthcare decision-making through continuous learning and integration of multidimensional clinical information.

Another important finding is that precision drug therapy significantly improves surgical outcome optimization. Personalized medication strategies contribute to better perioperative management, reduced postoperative complications, improved pain control, and enhanced patient recovery. This observation supports previous evidence suggesting that individualized pharmacological interventions reduce surgical risks and improve perioperative safety (Muir et al., 2022). The findings also reinforce the growing recognition that surgical success depends not only on operative techniques but also on optimized pharmacological management before, during, and after surgery.

The direct positive effects of pharmacogenomics and AI on surgical outcome optimization further demonstrate the importance of integrating genomic information and intelligent technologies into surgical practice. AI-assisted predictive models enable clinicians to identify high-risk patients, anticipate complications, and develop personalized perioperative management strategies. These findings are consistent with Hashimoto et al. (2020), who reported that AI improves surgical planning, risk prediction, and postoperative decision-making.

The mediation analysis further indicated that precision drug therapy partially mediates the relationships between pharmacogenomics, AI, and surgical outcome optimization. This finding suggests that pharmacogenomic information and AI technologies improve surgical outcomes primarily by facilitating personalized medication management. The results support the theoretical assumptions of Precision Medicine Theory, which emphasizes individualized healthcare interventions based on patient-specific biological characteristics (Collins & Varmus, 2015).

Within the context of Pakistan, the findings underscore the urgent need for investment in genomic medicine, AI infrastructure, and digital health systems. Although healthcare institutions are gradually adopting electronic health records and digital technologies, pharmacogenomics remains largely absent from routine clinical practice. The study therefore highlights the potential of integrating AI-assisted pharmacogenomic decision-support systems to improve healthcare quality, patient safety, and clinical efficiency.

Conclusion

This study examined the influence of pharmacogenomics and artificial intelligence on precision drug therapy and surgical outcome optimization in Pakistan. The findings demonstrated that both pharmacogenomics and AI significantly enhance precision drug therapy, which subsequently improves surgical outcomes. AI also directly contributes to surgical outcome optimization by supporting predictive analytics, clinical decision-making, and perioperative management.

The study confirms that integrating pharmacogenomics with AI represents an effective strategy for advancing precision medicine within Pakistan's healthcare system. Personalized drug therapy based on genetic information reduces adverse drug reactions, enhances therapeutic effectiveness, and improves patient safety. AI further strengthens these benefits by enabling rapid interpretation of complex genomic and clinical data, thereby supporting evidence-based clinical decisions.

Overall, the study concludes that successful implementation of AI-assisted pharmacogenomics has the potential to transform healthcare delivery in Pakistan through improved treatment effectiveness, optimized surgical care, reduced

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healthcare costs, and enhanced patient outcomes. However, achieving these benefits requires strategic investments in genomic infrastructure, digital health technologies, workforce development, and supportive national policies.

Implications

Theoretical Implications

The study extends Precision Medicine Theory by empirically demonstrating how pharmacogenomics and artificial intelligence jointly contribute to personalized drug therapy and improved surgical outcomes. It enriches the existing literature by integrating genomics, artificial intelligence, and perioperative care into a comprehensive conceptual framework. Furthermore, the study contributes to the growing body of knowledge on precision medicine in low- and middle-income countries, particularly Pakistan.

Practical Implications

The findings provide valuable guidance for physicians, surgeons, pharmacists, anesthesiologists, and hospital administrators regarding the implementation of pharmacogenomic-guided prescribing and AI-assisted clinical decision-support systems. Healthcare institutions may utilize the results to improve medication safety, reduce adverse drug reactions, optimize perioperative care, and enhance overall clinical performance.

Policy Implications

The study highlights the need for national policies supporting pharmacogenomic testing, artificial intelligence integration, and precision medicine implementation. Policymakers should establish national genomic databases, develop regulatory frameworks for AI applications, strengthen digital health infrastructure, and allocate funding for genomic research and workforce training. These initiatives would facilitate evidence-based healthcare and improve the efficiency of Pakistan's healthcare system.

Recommendations

Healthcare institutions should gradually integrate pharmacogenomic testing into routine clinical practice to support personalized prescribing and reduce medication-related complications.

Hospitals should adopt AI-based clinical decision-support systems capable of integrating genomic information with electronic health records for real-time therapeutic recommendations.

The Government of Pakistan should develop a national precision medicine strategy incorporating pharmacogenomics, artificial intelligence, and digital health technologies within public healthcare services.

Medical universities and professional organizations should introduce specialized training programs in pharmacogenomics, bioinformatics, artificial intelligence, and precision medicine to enhance healthcare professionals' competencies.

National genomic databases representing Pakistan's diverse population should be established to facilitate pharmacogenomic research and improve the accuracy of AI prediction models.

Healthcare organizations should strengthen ethical governance, cybersecurity measures, and data privacy regulations to ensure responsible use of genomic and artificial intelligence technologies.

Collaborative partnerships among universities, hospitals, government agencies, and the pharmaceutical industry should be encouraged to accelerate translational research and clinical implementation.

Future healthcare investments should prioritize advanced sequencing technologies, cloud computing infrastructure, and interoperable electronic health record systems to support precision medicine initiatives.

Limitations and Future Directions

The study has several limitations that should be acknowledged. First, the cross-sectional research design limited the ability to establish causal relationships among the study variables over time. Future studies should employ longitudinal research designs to examine the long-term effects

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of pharmacogenomics and AI on clinical outcomes.

Second, the study relied on self-reported responses from healthcare professionals, which may be subject to response bias and common method variance. Future research should incorporate objective clinical data, genomic testing results, and patient outcomes to validate the findings.

Third, the research focused on healthcare professionals working primarily in tertiary care institutions, limiting the generalizability of the findings to primary and secondary healthcare settings. Future studies should include broader healthcare populations across different regions of Pakistan.

Fourth, the study examined a limited number of variables within the precision medicine framework. Future research should investigate additional factors such as organizational readiness, digital health maturity, clinician acceptance, ethical concerns, regulatory compliance, technological infrastructure, patient trust, and healthcare financing.

Finally, future studies should evaluate the effectiveness of AI-assisted pharmacogenomic interventions through clinical trials, implementation studies, and cost-effectiveness analyses. Comparative studies across different healthcare systems and developing countries would further strengthen understanding of the practical implementation of precision medicine in diverse clinical environments.

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