

Pharmacogenomics and Precision Medicine in Pharmacy Practice: Current Evidence, Clinical Applications, Implementation Strategies, and Future Directions

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ABSTRACT

Pharmacogenomics (PGx) is an important component of precision medicine that uses genetic information to explain interindividual variability in medication response. Its clinical value is greatest when a validated genetic result can be translated into a specific therapeutic action, such as selection of an alternative drug, dose adjustment, intensified monitoring, or avoidance of a medicine associated with severe toxicity. The role of pharmacy practice is expanding because pharmacists possess expertise in pharmacology, pharmacokinetics, pharmacodynamics, medication safety, medication therapy management, patient counseling, and longitudinal follow-up. This review examines the current role of pharmacogenomics in pharmacy practice, including clinically actionable gene–drug relationships, pharmacist-led testing, community and hospital implementation, electronic health record (EHR) integration, clinical decision support, medication safety, health equity, ethics, pharmacoeconomics, and future research. Evidence from pharmacogenomic implementation literature, Clinical Pharmacogenetics Implementation Consortium (CPIC) guidance, and regulatory resources was considered. Important examples include CYP2C19–clopidogrel, CYP2D6–opioids and selected antidepressants, DPYD–fluoropyrimidines, TPMT/NUDT15–thiopurines, HLA-B–abacavir, HLA-B–carbamazepine and allopurinol, SLCO1B1–statins, CYP3A5–tacrolimus, and VKORC1/CYP2C9/CYP4F2–warfarin. Pharmacists can contribute across the complete PGx pathway: identifying candidates, arranging testing, interpreting results, documenting genotype/phenotype, recommending evidence-based medication changes, communicating with prescribers, counseling patients, monitoring outcomes, and evaluating service quality. Contemporary implementation studies indicate that community-pharmacy delivery is feasible and generally acceptable, but barriers include pharmacist knowledge and confidence, reimbursement, workflow integration, interoperability, standardized guidance, privacy, and equitable access. A successful precision-pharmacy model should therefore combine pharmacogenomic information with clinical phenotype, comorbidities, organ function, concomitant medicines, patient preferences, and therapeutic monitoring. Future pharmacy research should emphasize prospective clinical outcomes, cost-effectiveness, implementation science, Indian population data, diverse genomic representation, and responsible artificial-intelligence-supported clinical decision support.

Keywords: Pharmacogenomics, Pharmacogenetics, Precision Medicine, Personalized Medicine, Clinical Pharmacy, Community Pharmacy, Hospital Pharmacy, Pharmacists, Pharmacogenomic Testing, Medication Safety, Clinical Decision Support, Pharmacogenomic Implementation

INTRODUCTION

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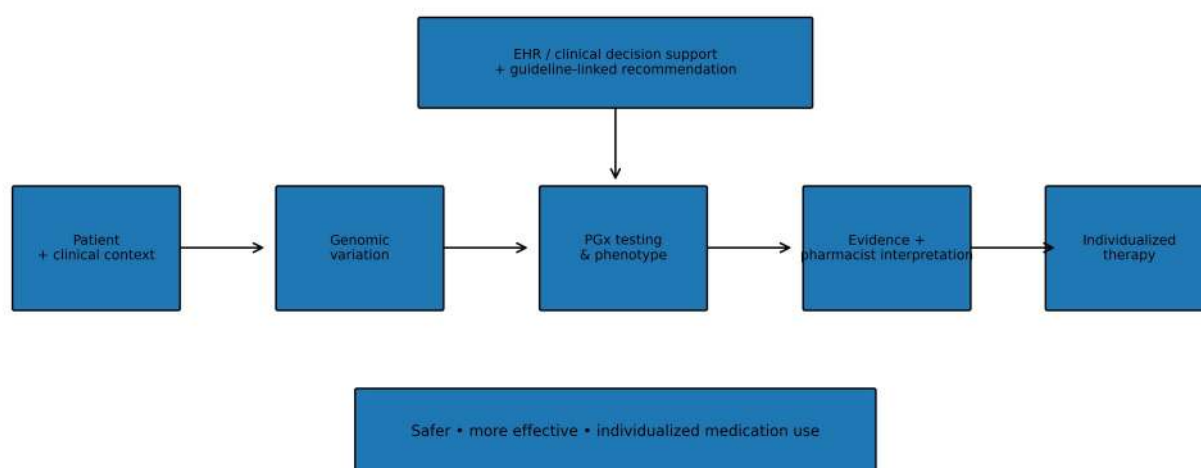


Figure 1: Graphical Abstract: Pharmacogenomics to Precision Pharmacy.

Variability in drug response is a fundamental problem in pharmacotherapy. Patients who receive the same medicine at comparable doses may experience therapeutic benefit, treatment failure, adverse drug reactions, or toxicity. Conventional medication optimization considers age, body weight, renal and hepatic function, disease severity, adherence, drug interactions, diet, lifestyle, and other clinical variables. Pharmacogenomics adds inherited genomic information to this decision-making framework and can identify patients who are more likely to respond to, fail, or experience toxicity from particular medicines.

The terms pharmacogenetics and pharmacogenomics are sometimes used interchangeably, although pharmacogenetics traditionally refers to the relationship between particular genetic variants and drug response, whereas pharmacogenomics is broader and can include multiple genes, genomic pathways and large-scale genomic data. In practical pharmacy care, the distinction is less important than the ability to translate a validated result into an appropriate medication decision.

The field has progressed beyond proof-of-concept research. CPIC publishes guidelines that explain how an existing genetic result can be used to guide prescribing, while regulatory pharmacogenomic resources identify biomarkers incorporated into drug labeling. The presence of evidence and guidance does not, however, guarantee implementation. Testing must be connected to the right patient, the right medication decision, an interpretable result, an accessible clinical recommendation, and follow-up.

Pharmacists are well positioned to connect these components. Pharmacists routinely evaluate drug therapy, identify medication-related problems, counsel patients, monitor safety, and communicate recommendations to prescribers. Published implementation studies describe pharmacist roles including genotype interpretation, medication selection and adjustment, adverse-event monitoring, patient education, and integration of PGx into medication-management services. Community pharmacies may also provide an accessible setting for testing, while hospital pharmacists can integrate PGx into specialty and multidisciplinary care.

2. Rationale for Pharmacogenomics in Pharmacy Practice

The rationale for PGx is based on the observation that genetic variation can influence pharmacokinetics, pharmacodynamics, immune-mediated drug reactions, and disease biology. For pharmacokinetic genes, variants may alter absorption, metabolism, transport, or elimination and thereby change systemic exposure. For pharmacodynamic genes, variants may alter drug targets or downstream pathways. Human leukocyte antigen (HLA) variants provide a different mechanism: they can identify patients at increased risk of severe immune-mediated reactions to selected medicines. In oncology, tumor genomic biomarkers may identify molecular targets and are conceptually related to precision medicine even though they are not always germline pharmacogenomic tests.

3. Objectives

- To provide a comprehensive pharmacy-practice-focused review of pharmacogenomics and precision medicine.
- To summarize important actionable gene–drug relationships and their clinical significance.
- To describe pharmacist responsibilities before, during, and after pharmacogenomic testing.
- To examine community-pharmacy, hospital-pharmacy, and primary-care implementation models.
- To discuss EHR integration and clinical decision support requirements.
- To evaluate educational, economic, ethical, privacy, and health-equity challenges.
- To identify research priorities, particularly for implementation in India and other diverse populations.

4. Review Methodology

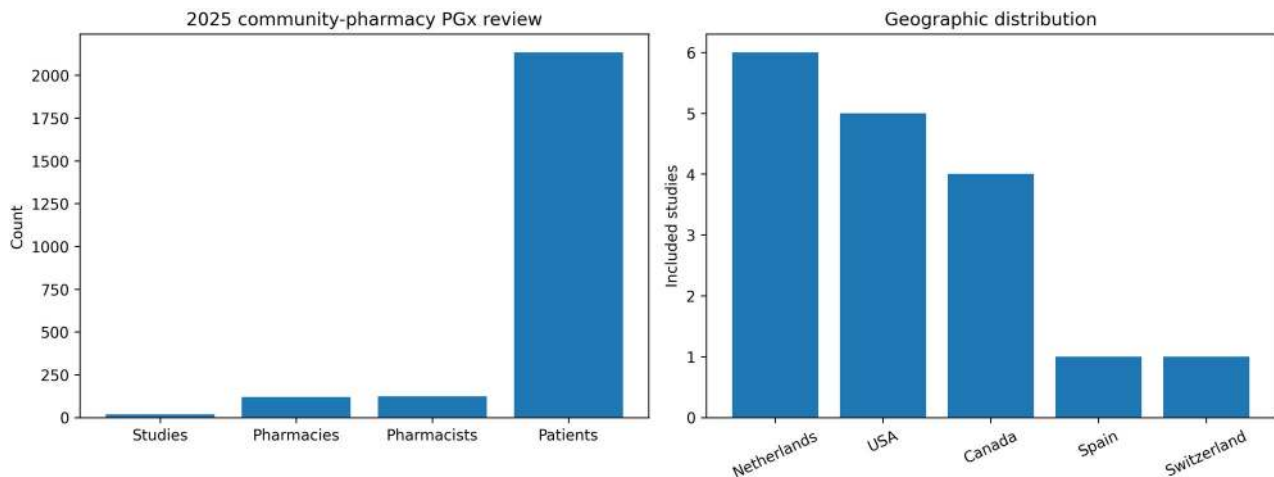


Figure 2: Published Community-Pharmacy PGx Evidence Landscape. Counts Are Study-Level Totals Reported by Coumau Et Al. (2025), Not Pooled Clinical-Effect Estimates.

This full-length narrative review was developed using a focused literature and guideline approach. Searches were conducted conceptually around PubMed-indexed literature and authoritative pharmacogenomic resources using combinations of pharmacogenomics, pharmacogenetics, precision medicine, pharmacy practice, pharmacist, community pharmacy, implementation, pharmacogenomic testing, clinical decision support, medication safety, CPIC, gene–drug interaction, and precision pharmacy. Priority was given to CPIC guidance, regulatory pharmacogenomic information, recent implementation studies, systematic/scoping reviews, and pharmacist-focused studies. Landmark implementation studies were retained where they established important service models. The review synthesizes published evidence rather

than presenting new patient-level data. Consequently, no original patient outcomes, laboratory results, effect sizes, or statistical analyses are claimed.

The evidence was organized into five clinical-practice domains: (1) actionable gene–drug relationships; (2) pharmacist-led testing and interpretation; (3) implementation in community and institutional settings; (4) clinical informatics, ethics, and equity; and (5) future research. Because PGx recommendations are periodically updated, clinicians should use the current version of the relevant CPIC guideline, regulatory labeling, and institutional protocol at the time of prescribing.

5. Pharmacogenomic Mechanisms Relevant to Pharmacy

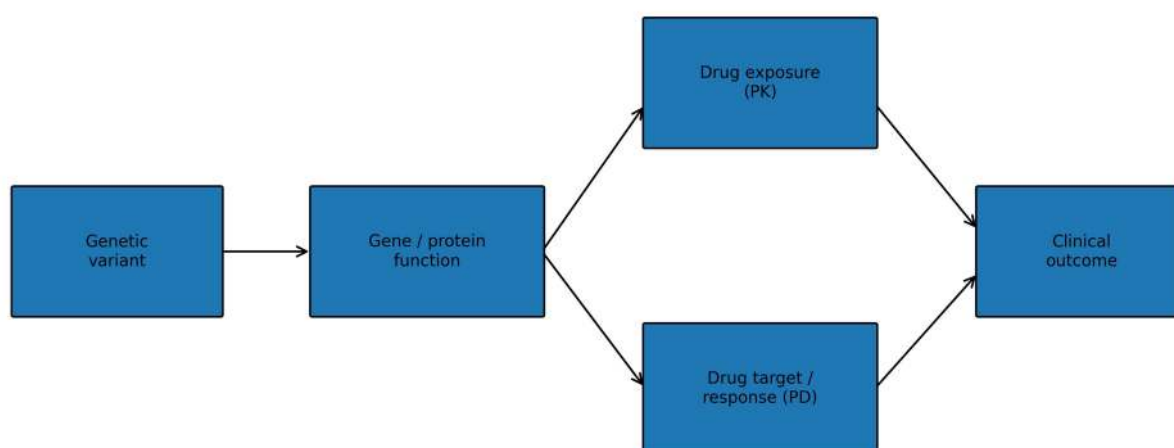


Figure 3: Mechanistic Pathway Linking Genetic Variation with Pharmacokinetic or Pharmacodynamic Changes.

Mechanism	Examples	Clinical implication
Drug metabolism	CYP2C19, CYP2D6, CYP2C9, CYP3A5, DPYD	Altered drug exposure, efficacy or toxicity
Drug transport	SLCO1B1 and related transporters	Altered tissue/systemic exposure
Drug target/pathway	Selected receptor or pathway variants	Altered pharmacodynamic response
Immune-mediated reaction	HLA-B variants	Prediction/avoidance of severe hypersensitivity
Drug activation	Clopidogrel, codeine	Genotype may alter formation of active metabolite
Tumor biomarker	EGFR, ALK, BRAF, HER2, KRAS	Targeted treatment selection

6. Major Clinically Actionable Gene–Drug Relationships

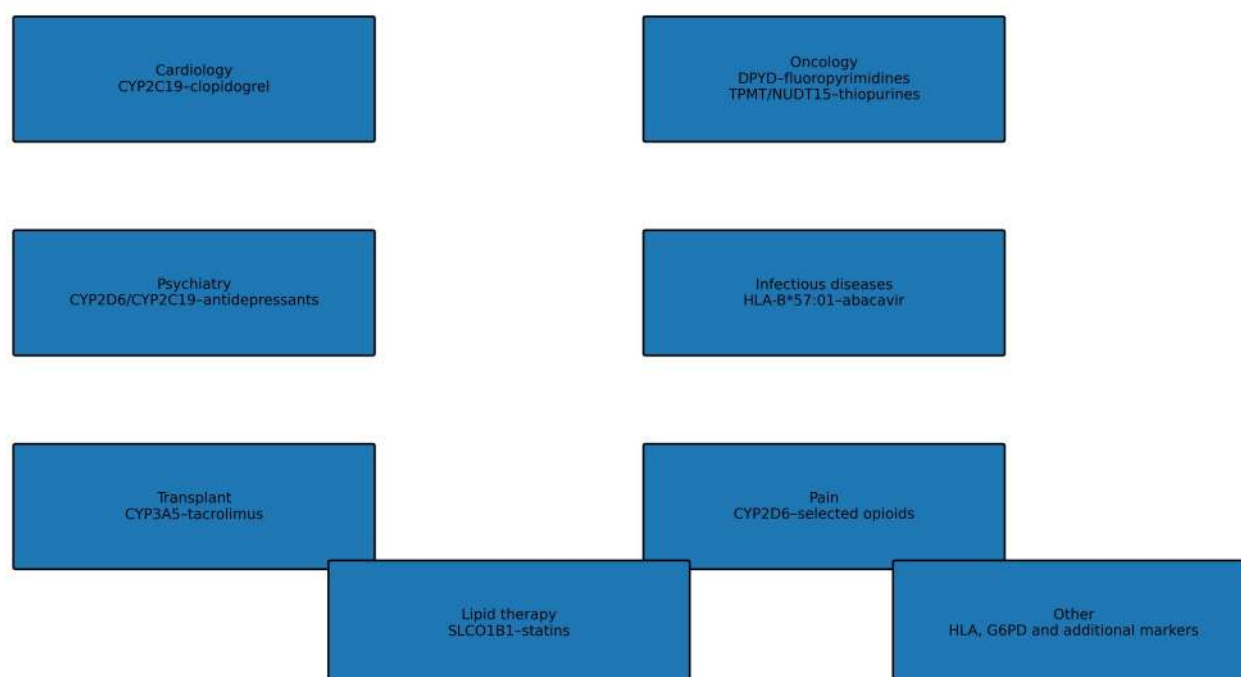


Figure 4: Major Clinical Domains in Which Pharmacogenomics Can Inform Precision Pharmacy.

Gene/biomarker	Drug(s) / class	Clinical issue	Pharmacy-practice action
CYP2C19	Clopidogrel	Reduced activation in relevant loss-of-function phenotypes	Use current CPIC recommendation to assess alternative antiplatelet therapy when indicated
CYP2D6	Codeine	Ultrarapid or poor metabolism can alter opioid response/toxicity	Avoid inappropriate use and select alternative based on current guidance
CYP2D6	Selected antidepressants	Altered metabolism can affect exposure	Use phenotype-informed dosing/selection where guideline-supported
CYP2C19	Selected antidepressants	Exposure can differ by metabolizer status	Consider genotype-guided therapy with clinical context
DPYD	Fluorouracil, capecitabine	Reduced DPD activity may increase severe toxicity	Support pre-treatment testing and genotype-guided dose/alternative where recommended
TPMT	Azathioprine, mercaptopurine, thioguanine	Reduced activity increases myelosuppression risk	Use genotype/phenotype information to guide starting therapy
NUDT15	Thiopurines	Reduced function increases myelosuppression risk	Incorporate genotype with TPMT and clinical factors
HLA-B*57:01	Abacavir	Hypersensitivity risk	Positive result supports avoidance
HLA-B*15:02	Carbamazepine	SJS/TEN risk in relevant populations	Consider testing/alternative therapy when appropriate
HLA-B*58:01	Allopurinol	Severe cutaneous adverse reaction risk	Use current guideline-supported strategy
SLCO1B1	Selected statins	Increased exposure/myopathy risk for relevant variants	Consider statin selection/dose and clinical monitoring
CYP3A5	Tacrolimus	Variable metabolism and exposure	Integrate genotype with therapeutic drug monitoring
VKORC1/CYP2C9/CYP4F2	Warfarin	Dose variability	Use validated genotype-informed dosing with clinical factors
MT-RNR1	Aminoglycosides	Ototoxicity susceptibility in relevant variants	Consider risk information where testing is clinically applicable

7. Detailed Clinical Applications

7.1 Cardiovascular Pharmacotherapy

Clopidogrel is among the most visible examples of PGx-guided cardiovascular therapy. Clopidogrel requires bioactivation, and CYP2C19 function contributes to the formation of its active metabolite. Reduced-function phenotypes can therefore be associated with reduced antiplatelet effect. The pharmacist's role is not simply to identify a genotype; it is to interpret the phenotype within the clinical context, determine whether the patient is receiving a relevant medication, consult the current evidence, and communicate a specific recommendation to the prescriber. PGx may also be relevant to statin-associated muscle toxicity and warfarin dose variability, although clinical variables remain important and genotype should not be interpreted in isolation.

7.2 Oncology

Oncology is one of the most mature areas of precision medicine. Germline PGx examples include DPYD-guided fluoropyrimidine therapy and TPMT/NUDT15-guided thiopurine therapy. These applications illustrate an important medication-safety principle: testing can identify a subgroup in whom standard dosing may produce disproportionate toxicity. Pharmacists can support pre-treatment screening, result interpretation, dose communication, toxicity monitoring and documentation. Oncology precision medicine also uses somatic tumor biomarkers such as EGFR, ALK, BRAF, HER2 and KRAS to select targeted therapies. Pharmacy practice therefore intersects both pharmacogenomics and broader molecularly guided treatment.

7.3 Psychiatry

Psychiatric pharmacotherapy is characterized by substantial variability in response and tolerability.



CYP2D6 and CYP2C19 are relevant to the metabolism of several antidepressants, and CPIC has developed guidance for selected serotonin reuptake inhibitors. PGx should be viewed as a decision-support tool rather than a substitute for psychiatric assessment. Prior treatment response, adverse effects, comorbidities, concurrent medicines, adherence, substance use, and patient preferences remain important. Pharmacists can identify patients with repeated treatment failure or intolerance, review genotype results when available, and help clinicians apply current evidence.

7.4 Infectious Diseases

In infectious diseases, HLA-B*57:01 testing before abacavir is a classic example of PGx preventing severe hypersensitivity. Additional pharmacogenomic considerations may include selected CYP-mediated interactions and MT-RNR1-associated aminoglycoside ototoxicity. Antimicrobial stewardship programs could incorporate PGx where a validated test produces a meaningful treatment or safety action.

7.5 Transplantation

Tacrolimus exposure varies considerably between patients. CYP3A5 genotype can contribute to this variability, although therapeutic drug monitoring remains essential. A genotype-informed starting dose

may complement rather than replace concentration-guided dose adjustment. Pharmacists in transplant programs can integrate genotype, measured concentrations, adherence, interacting medicines, organ function and clinical status.

7.6 Pain Management

CYP2D6 influences the activation and disposition of several opioids, including codeine. Genotype-informed recommendations can help identify patients at risk of inadequate analgesia or toxicity. Opioid pharmacogenomics should be integrated with non-genetic factors including opioid tolerance, age, renal/hepatic function, interacting medicines, respiratory risk and the clinical indication.

7.7 Rheumatology and Other Chronic Diseases

Pharmacogenomic applications are also being evaluated in inflammatory diseases, gastroenterology, dermatology and other chronic conditions. The strength of evidence varies substantially. Pharmacy practice should prioritize relationships with validated recommendations and clinically meaningful outcomes rather than adopting every commercially available genetic association.

8. Role of Pharmacists Across the PGx Care Pathway

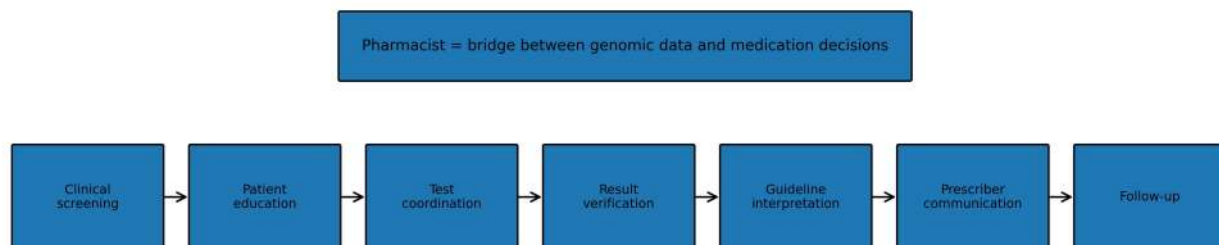


Figure 5: Pharmacist Role Across the PGx Care Pathway.

Step	Detailed pharmacist responsibility
1. Identify	Screen medication lists and clinical scenarios for actionable gene–drug relationships.
2. Assess	Confirm indication, clinical urgency, prior response, adverse effects, comorbidities, organ function and interacting medicines.
3. Educate	Explain why testing is being considered, what it can and cannot predict, and potential implications.
4. Coordinate testing	Use an appropriate validated laboratory/testing pathway and ensure correct patient/specimen identification.
5. Receive result	Confirm genotype/diplotype and quality/validity of the report.
6. Interpret	Translate genotype into phenotype using a current evidence-based guideline.
7. Recommend	Communicate drug choice, dose, alternative or monitoring recommendation when supported.
8. Document	Record result, phenotype, source, interpretation, recommendation and date.

Step	Detailed pharmacist responsibility
9. Counsel	Explain medication changes, expected benefits, safety considerations and follow-up.
10. Monitor	Assess efficacy, adverse effects, adherence, laboratory parameters and therapeutic concentrations when relevant.
11. Reassess	Update interpretation when guidelines or clinical circumstances change.
12. Evaluate	Measure clinical, economic, workflow and patient-reported outcomes.

9. Community Pharmacy Implementation

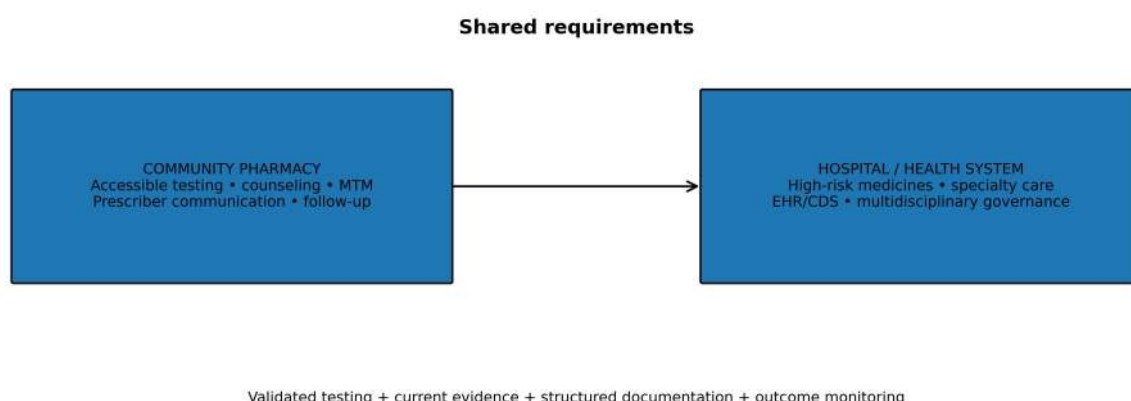


Figure 6: Community and Hospital Pharmacy Implementation Models.

Community pharmacy is an attractive setting because pharmacists are accessible, routinely manage medicines, and frequently encounter patients before and after prescribing decisions. A 2025 scoping review identified 17 studies of PGx implementation in community pharmacies and reported generally favorable feasibility, patient engagement and satisfaction, while noting inconsistent prescriber adoption and continuing barriers related to standardized guidance, education, reimbursement, and workflow integration. Earlier mapping of community-pharmacy literature

identified knowledge gaps, confidence in interpretation and communication, cost, privacy, and workflow integration as recurring barriers.

An early community-pharmacy implementation study demonstrated the practical feasibility of a CYP2C19 service for patients receiving clopidogrel. In that study, pharmacist recommendations for patients with actionable variants were accepted by prescribers, but reimbursement was a major challenge. This illustrates a recurring implementation pattern: technical testing may be feasible while sustainable financing and integration into routine care remain difficult.

9.1 Proposed Community Pharmacy Workflow

Stage	Action	Documentation
Patient identification	Medication-based PGx screening	Eligibility checklist
Initial consultation	Discuss clinical indication and testing	Consent/education note
Testing	Collect specimen via validated pathway	Laboratory accession
Result review	Verify report and phenotype	PGx result record
Recommendation	Apply current guideline	Pharmacist intervention note
Prescriber communication	Send concise recommendation	Communication record
Patient follow-up	Review medication and symptoms	Follow-up note
Outcome assessment	Clinical/workflow/economic measures	Program dashboard

10. Hospital and Health-System Pharmacy

Hospital pharmacy services can integrate PGx into high-risk medications, oncology, transplant, cardiology, psychiatry, antimicrobial stewardship and medication-safety programs. The principal advantage is

proximity to laboratory medicine, EHR infrastructure and multidisciplinary teams. A hospital PGx program should establish governance, define testable medication scenarios, identify who interprets results, create standardized recommendations, build EHR/CDS

functionality, and establish responsibility for longitudinal follow-up.

10.1 Multidisciplinary Team

Professional group	Potential contribution
Clinical pharmacist	Medication assessment, PGx interpretation, recommendation and monitoring
Physician	Diagnosis, therapeutic decision and clinical integration
Laboratory/genomics specialist	Testing quality and analytic interpretation
Pharmacy informatics	EHR integration and clinical decision support
Genetic counselor/genetics specialist	Genomic counseling and complex findings
Nursing	Patient education and monitoring
IT/data governance	Security, interoperability and audit
Health economist	Cost-effectiveness and budget impact
Research team	Implementation and outcome evaluation

11. Preemptive Versus Reactive Testing

Characteristic	Reactive PGx testing	Preemptive PGx testing
Trigger	Specific medication decision	Anticipated future medication needs
Timing	After clinical need identified	Before need arises
Testing scope	Usually targeted	Often multi-gene
Immediate usefulness	High	May be delayed
Reuse	Limited to relevant result	Potentially reusable across medicines
Infrastructure	Moderate	Requires durable EHR storage and governance
Potential efficiency	Good for selected scenarios	Potentially high over lifetime
Major challenge	Turnaround time	Upfront cost and interpretation of broad data

Preemptive testing may be particularly valuable when a patient's results can be stored in a structured EHR and reused. However, a preemptive model should avoid indiscriminate testing without an implementation plan. The clinical value of a PGx panel depends on the evidence for each gene–drug relationship, the

probability that the patient will receive relevant medicines, and the ability of the health system to act on results.

12. Electronic Health Records and Clinical Decision Support

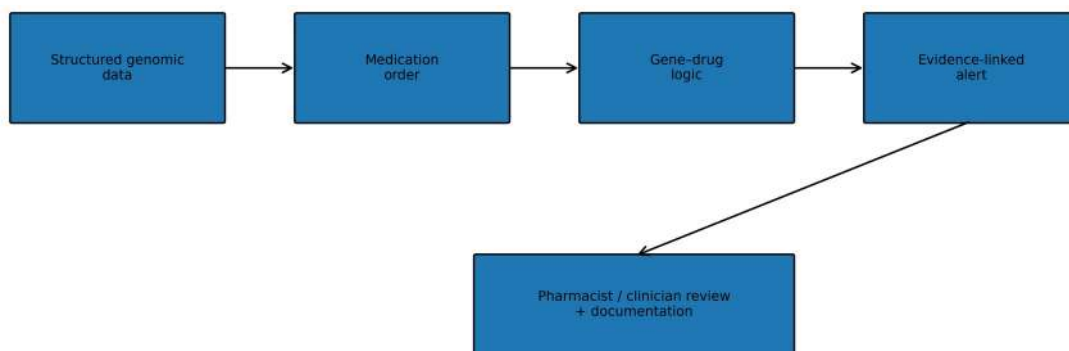


Figure 7: EHR-based Clinical Decision-Support Architecture for PGx.

PGx implementation is fundamentally an informatics problem as well as a laboratory and clinical problem. A result that remains in a PDF or external laboratory portal may not be available when a prescriber orders a relevant medicine. Structured storage allows automated recognition of gene–drug relationships. The

EHR should ideally preserve the genotype/diplotype, predicted phenotype, test source, date, and evidence-linked recommendation.

CDS layer	Example
Genomic data	CYP2C19 diplotype
Phenotype	Intermediate metabolizer

CDS layer	Example
Medication	Clopidogrel
Evidence	Current CPIC guideline
Trigger	Medication order
Alert	Actionable gene–drug interaction
Recommendation	Consider guideline-supported alternative
Override/documentation	Reason for accepting or overriding recommendation
Follow-up	Clinical outcome monitoring

CDS should be designed to minimize alert fatigue. Alerts should be targeted to clinically actionable situations, distinguish urgent safety warnings from lower-priority recommendations, provide concise rationale, and allow documentation of clinical judgment. Pharmacists can contribute to alert governance

by assessing clinical relevance and monitoring override patterns.

13. Medication Safety and Adverse Drug Reactions

One of the strongest arguments for PGx is prevention of severe adverse drug reactions. HLA-B*57:01 testing has become a model for genotype-guided avoidance of abacavir-associated hypersensitivity. HLA-B*15:02 and carbamazepine, HLA-B*58:01 and allopurinol, DPYD and fluoropyrimidines, and TPMT/NUDT15 and thiopurines illustrate different mechanisms by which genetic information can identify patients at increased risk. Pharmacists can strengthen safety by ensuring results are available before therapy when appropriate, documenting them prominently, and preventing inadvertent re-exposure.

Clinical area	Gene/biomarker	Potential safety value	Key pharmacy activity
Antiretroviral therapy	HLA-B*57:01	Avoid severe hypersensitivity	Verify result before abacavir
Neurology	HLA-B*15:02	Reduce SJS/TEN risk in relevant populations	Review ancestry/testing context and alternative therapy
Gout	HLA-B*58:01	Reduce severe cutaneous reaction risk	Check genotype before appropriate allopurinol use
Oncology	DPYD	Reduce fluoropyrimidine toxicity	Support testing and dose recommendation
Immunomodulatory therapy	TPMT/NUDT15	Reduce thiopurine myelotoxicity	Guide initial therapy and monitoring

14. Pharmacogenomics Education and Competency

The pharmacist workforce is a major determinant of successful implementation. A systematic review of pharmacists and pharmacy students found generally positive attitudes toward PGx but persistent gaps in knowledge and confidence, together with strong interest in additional education. Community pharmacists have described needs for enriched PGx education, active learning, reputable clinical resources, team-based implementation, and access to experts. PGx education should therefore emphasize clinical application rather than genetics alone.

Competency domain	Expected capability
Foundational genetics	Understand alleles, diplotypes, phenotype and inheritance
Pharmacology	Explain how genotype changes exposure or response
Guidelines	Locate and apply current CPIC/FDA/institutional guidance
Clinical reasoning	Integrate PGx with non-genetic factors
Communication	Explain results clearly to patients and prescribers
Informatics	Use EHR/CDS and document results
Ethics	Address consent, privacy and data governance
Research literacy	Interpret evidence quality and uncertainty

15. Health Economics and Reimbursement

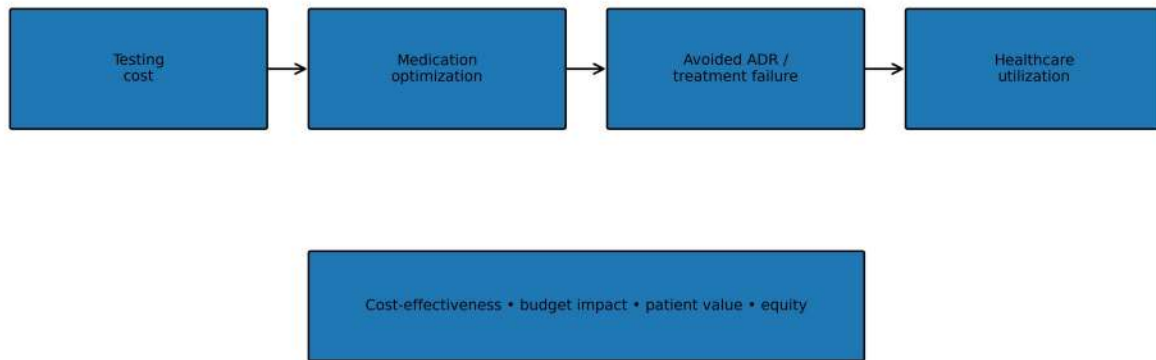


Figure 8: Conceptual Framework for Pharmacoeconomic Evaluation; It Does Not Represent Original Economic Outcome Data.

The economic case for PGx depends on the clinical scenario, testing cost, prevalence of actionable variants, alternative medication cost, cost of adverse events, hospitalization risk, and the degree to which testing changes treatment. A high-cost test may be economically attractive when it prevents a severe adverse reaction or avoids repeated treatment failures. Conversely, broad testing may have uncertain value when actionable results are unlikely to influence prescribing. Pharmacoeconomic studies should therefore measure not only testing costs but also medication changes, adverse events, hospitalizations, emergency visits, treatment response, patient productivity, and long-term healthcare utilization.

Reimbursement remains a practical barrier, particularly in community settings. A sustainable model may require a combination of payer reimbursement, health-system investment, value-based care arrangements, or inclusion of PGx within pharmacist-provided medication-management services.

16. Patient Perspectives, Consent and Health Literacy



Figure 9: Recommended Patient and Health-System Outcome Domains for Evaluating Precision-Pharmacy Services.

Patient understanding is essential because genetic information can appear more definitive than it actually is. Pharmacists should explain that PGx usually changes probabilities rather than guaranteeing an outcome. A patient may have a genetic phenotype associated with altered metabolism while still responding differently because of disease, adherence, interacting medicines or other biological factors. Consent processes should clarify the purpose of testing, specimen handling, data storage, possible clinical uses, and limitations.

Health literacy should guide communication. Rather than beginning with allele nomenclature, pharmacists can start with the medication decision: “This test may help us determine whether your body is likely to process this medicine differently.” Results can then be explained using practical terms such as typical, slower, or faster metabolism when scientifically appropriate.

17. Privacy, Ethical, Legal and Social Considerations

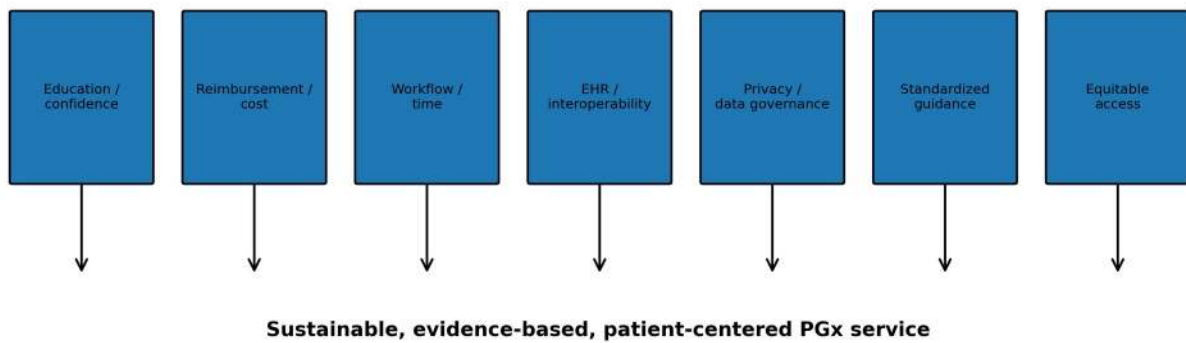


Figure 10: Key Implementation Barriers Affecting Sustainable PGx Practice.

- Genomic data should be stored securely and accessed only by authorized personnel.
- Patients should receive understandable information about the purpose and limitations of testing.
- Institutions should define retention, sharing and secondary-use policies.
- Clinicians should avoid overinterpreting variants that do not have validated prescribing implications.
- Potential discrimination or misuse of genomic information should be addressed through institutional governance and applicable law.
- Equitable access should be considered so that precision medicine does not widen existing health disparities.
- Patients should retain autonomy in deciding whether to undergo testing where consent is required.

India presents a major opportunity for pharmacy-led precision medicine research because of its large population, extensive genetic diversity, expanding healthcare infrastructure, and increasing use of advanced diagnostics. At the same time, implementation must consider affordability, laboratory availability, uneven digital infrastructure, variable health literacy, regional diversity, and access differences between urban and rural settings. Indian research should avoid simply importing evidence generated in other populations without evaluating local relevance.

Priority areas include characterization of actionable pharmacogenomic variants in Indian populations; pharmacist knowledge and training; patient acceptance; cost-effectiveness; EHR readiness; laboratory quality; community-pharmacy models; and integration with existing medication-safety programs. Multicenter Indian studies would be particularly valuable because regional genetic variation may affect the prevalence and predictive performance of some biomarkers.

18. Pharmacogenomics and Health Equity in India

Indian research area	Suggested study outcome
Population genomics	Frequency of actionable variants by region/population
Pharmacist education	Knowledge, confidence and competency improvement
Community pharmacy	Feasibility, acceptance and workflow time
Hospital pharmacy	ADR reduction and medication optimization
Economics	Cost per actionable result and cost per clinical event avoided
EHR/CDS	Alert acceptance and clinical-action rate
Patient perspective	Understanding, consent and satisfaction
Equity	Access and outcome differences across socioeconomic groups

19. Artificial Intelligence in Precision Pharmacy

Artificial intelligence (AI) and machine learning may strengthen PGx implementation by identifying patients who are likely to benefit from testing, integrating genomic and clinical variables, prioritizing clinically meaningful alerts, and supporting longitu-

dinal outcome analysis. AI could also help pharmacists summarize complex genomic reports and identify relevant guidelines. However, AI should not replace clinical responsibility. Models must be validated in the populations in which they will be used, monitored for bias, linked to authoritative evidence, and subjected to human oversight.

AI application	Potential benefit	Risk requiring control
Patient identification	Find eligible patients from EHR data	Incomplete/biased data
Genotype interpretation support	Reduce manual lookup burden	Incorrect interpretation
CDS prioritization	Reduce alert fatigue	Missed important alerts
Outcome prediction	Identify high-risk patients	Model bias/poor calibration
Documentation support	Improve consistency	Hallucinated clinical information
Research analytics	Identify implementation patterns	Privacy and data governance

20. Proposed Comprehensive Pharmacist-Led Precision Medicine Model

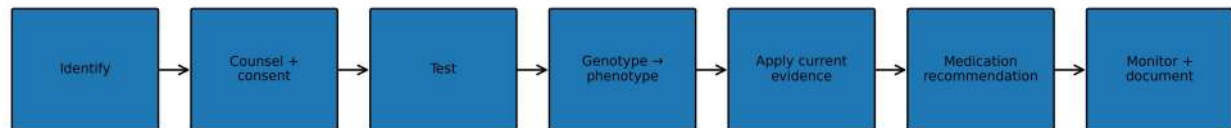


Figure 11: End-to-end Clinical Workflow for Pharmacogenomic Implementation in Pharmacy Practice.

A practical service can be organized into four interconnected phases: preparation, testing, action, and evaluation. Preparation includes selecting priority gene–drug pairs, defining eligibility, training pharmacists, establishing laboratory partnerships, and configuring EHR documentation. Testing includes patient identification, education, consent where required, specimen collection, laboratory analysis, and

result verification. Action includes genotype-to-phenotype translation, evidence review, prescriber communication, medication modification, and monitoring. Evaluation includes clinical outcomes, patient outcomes, economic outcomes, workflow measures, and equity indicators.

Phase	Activities	Key performance indicators
Preparation	Protocol, training, laboratory, EHR	Staff competency; workflow readiness
Testing	Eligibility, counseling, specimen, laboratory	Turnaround time; test completion
Interpretation	Genotype → phenotype → recommendation	Actionable-result rate
Clinical action	Recommendation and medication change	Recommendation acceptance; time to action
Monitoring	Efficacy, toxicity, adherence	ADR rate; treatment response
Evaluation	Economic and implementation analysis	Cost-effectiveness; sustainability
Quality improvement	Audit and protocol updates	Alert overrides; guideline currency

21. Tables of Selected Evidence From Pharmacy Practice Literature

Study/evidence	Setting	Main finding relevant to pharmacy
Ferreri et al., 2014	Community pharmacy	PGx service for CYP2C19/clopidogrel was feasible; prescriber acceptance was high, while reimbursement was problematic.
Mahmoud et al., 2021	Pharmacy practice scoping review	43 non-oncology studies identified; CYP2C19/antiplatelet models were prominent and pharmacist education, collaboration and CDS were important facilitators.
Aref et al., 2023	Community pharmacy scoping review	39 studies mapped; benefits were recognized, while knowledge, confidence, cost, privacy and workflow barriers were common.
Knowledge/perceptions systematic review, 2024	Pharmacists and students	Positive attitudes were common, but knowledge and confidence remained insufficient and further education was desired.

Study/evidence	Setting	Main finding relevant to pharmacy
Coumau et al., 2025	Community pharmacy scoping review	17 studies; feasibility and satisfaction were favorable, but reimbursement, standardization, education and workflow integration remained challenges.
Kiani et al., 2026	Community pharmacy	Recent survey evidence highlights interest in PGx alongside continuing implementation barriers and need for structured strategies.

DISCUSSION

The evidence supports a transition from asking whether pharmacogenomics is scientifically plausible to asking where it provides enough clinical value to become routine pharmacy practice. This distinction is important. Not every statistically significant gene–drug association is clinically actionable, and not every actionable relationship requires universal testing. Pharmacy practice should prioritize evidence in which a genetic result changes a medication decision and where the resulting action improves safety, efficacy, or resource use.

The pharmacist is uniquely positioned to operationalize this approach. In contrast to a laboratory-only model, pharmacist-led PGx services can connect testing with medication reconciliation, clinical assessment, patient counseling, prescriber communication and follow-up. Published literature has demonstrated feasibility in both institutional and community settings, while more recent implementation studies show that the principal challenges have shifted toward sustainability, education, reimbursement, workflow and interoperability.

Community pharmacy deserves particular attention because accessibility may improve equitable reach. However, the community setting also has practical constraints, including limited consultation time, variable access to EHR genomic data, reimbursement uncertainty and the need for collaboration with prescribers. Implementation should therefore be designed around existing medication-management workflows rather than as a completely separate service.

Hospital programs have the advantage of multidisciplinary infrastructure and access to laboratory and informatics resources. They may be especially suitable for high-risk medicines and specialty populations. Nevertheless, hospital PGx should also avoid

excessive alerting and ensure that results remain available after transitions of care.

Education is a cross-cutting requirement. Pharmacists may be enthusiastic about precision medicine while lacking confidence in interpreting diplotypes or applying guidelines. Continuing education should use case-based learning, simulated clinical decisions and direct practice with evidence resources. Undergraduate and postgraduate pharmacy curricula can introduce genomics while emphasizing the practical medication-management role.

The Indian context deserves specific investigation. The country has substantial genetic diversity, and implementation strategies developed in other health-care systems may not transfer directly. Indian pharmacy researchers can contribute by studying actionable variant frequencies, patient acceptance, laboratory pathways, affordability, EHR integration and pharmacist-led service models. Such research could support locally relevant precision-pharmacy guidelines.

23. Limitations of the Present Review

This manuscript is a narrative review and not a systematic review or meta-analysis. Searches were focused on clinically relevant literature and authoritative sources rather than designed as an exhaustive PRISMA systematic search. No pooled effect estimate is presented, and no original patient-level data were analyzed. Pharmacogenomic recommendations evolve as new evidence emerges; therefore, the tables are intended as a practical overview rather than a substitute for current prescribing guidelines or drug labeling. Before clinical implementation, each gene–drug relationship should be checked against the most recent CPIC recommendation, regulatory label, local formulary and institutional policy.

24. Future Directions

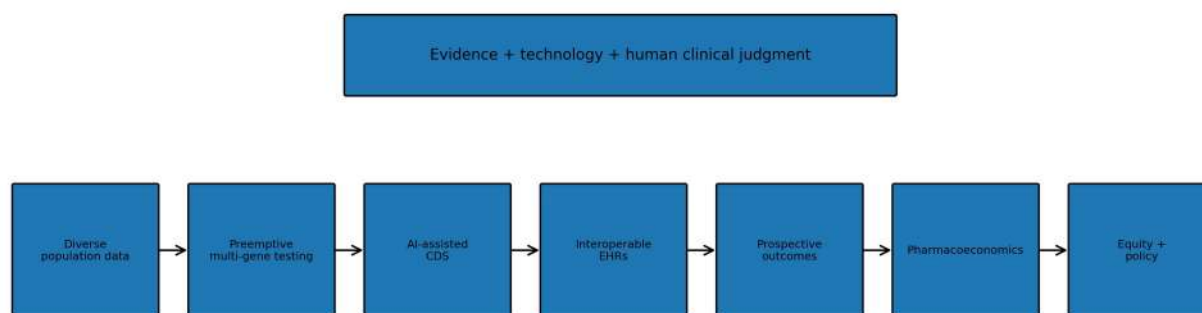


Figure 12: Future Research and Implementation Priorities for Precision Pharmacy.

1. Prospective randomized and pragmatic trials of pharmacist-led PGx services.
2. Real-world measurement of adverse drug reactions, treatment response and medication persistence.
3. Cost-effectiveness and budget-impact analyses in community and hospital pharmacy.
4. Preemptive multi-gene testing with long-term outcome assessment.
5. Development of standardized pharmacist competency frameworks.
6. Integration of PGx into pharmacy education and continuing professional development.
7. Indian multicenter studies evaluating genomic diversity and clinical implementation.
8. Patient-centered research on health literacy, consent and trust.
9. Interoperable EHR standards for persistent genomic data.
10. AI-assisted PGx decision support with transparent evidence linkage and pharmacist oversight.
11. Implementation science studies using standardized frameworks to compare models across healthcare systems.
12. Equity-focused research assessing who receives testing and who benefits from precision medicine.

CONCLUSION

Pharmacogenomics is becoming an increasingly relevant component of precision pharmacy. The strongest clinical applications are those in which a validated genetic result leads to an actionable change in medication choice, dose, monitoring, or avoidance. Pharmacists can provide value across the entire pathway, from identifying eligible patients and coordinating

testing to interpreting results, communicating recommendations, counseling patients, documenting findings, and monitoring outcomes. Community-pharmacy evidence demonstrates feasibility and patient acceptability, while hospital programs provide opportunities for multidisciplinary integration and high-risk medication management. The major barriers are no longer purely scientific; they include education, reimbursement, workflow, informatics, evidence standardization, privacy and equitable access. Future research should focus on prospective outcomes, pharmacoeconomics, implementation science, population diversity, and responsible digital and AI tools. A sustainable precision-pharmacy model should integrate genomic information with clinical judgment rather than treating PGx as an isolated laboratory result.

26. Declarations

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