Review Article

Trends in Pharmaceutical Sciences and Technologies 2026: 12(2):107-116.

A Comprehensive Review of Education and Training in Pharmacogenomics for the Modern Pharmacist

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Abstract

The incorporation of pharmacogenomics (PGx) into everyday clinical practice marks a major leap forward in contemporary healthcare, heralding a new era of personalised medicine where drug choices and dosages are customised based on an individual's genetic profile. Pharmacists, as the most accessible healthcare providers and experts in medication, are ideally positioned to lead this transformation. However, the shift of PGx from a research field to a fundamental aspect of patient care hinges on having a well-trained workforce. This comprehensive review explores the current state, significant challenges, and prospects of PGx education and training for pharmacists. It examines the historical background of pharmacy education, the identified deficiencies in PGx knowledge, the various emerging educational models from doctoral programmes to ongoing professional development and innovative certificate courses, and the significant obstacles to implementation, such as curriculum overload, faculty expertise, and practical training challenges. Additionally, it discusses the essential skills needed for a practising PGx pharmacist and the unresolved issues related to certification and credentialing. The conclusion emphasises that without a coordinated, multi-stakeholder effort to prioritise and standardise high-quality, practical PGx education, the full potential of personalised medicine will remain untapped, and the pharmacy profession risks missing a crucial opportunity to redefine its role in patient care.

Keywords: Pharmacogenomics, Pharmacy Education, Personalized Medicine, Curriculum Development, Continuing Professional Development.

Please cite this article as: Krishnamurthy A. A Comprehensive Review of Education and Training in Pharmacogenomics for the Modern Pharmacist. Trends in Pharmaceutical Sciences and Technologies. 2026;12(2):107-116. doi: 10.30476/tips.2026.108376.1314

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1. Introduction

Pharmacogenomics (PGx) has redefined personalized medicine by enabling tailored drug therapy based on a patient's genetic profile. With the increasing volume of evidence linking specific gene variants to drug efficacy and safety, PGx is set to play a regular role in routine pharmacy practice (1). It examines how genes influence drug responses, is fundamentally transforming pharmacokinetic and pharmacodynamic principles that have been the foundation of pharmacology for years. It shifts us from a generalized, "one-size-fits-all" dosing model to a personalized approach that enhances drug effectiveness and reduces adverse drug reactions (ADRs) (2). The clinical and economic impacts of this are immense. Drug response variability driven by genetic differences underpins many adverse drug reactions and therapy failures. The

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Received: 21/10/2025; Accepted: 01/03/2026

FDA now includes PGx labeling on numerous drugs, urging the healthcare workforce to adapt. Pharmacists, given their expertise in pharmacotherapy, are integral stakeholders in applying PGx insights for safer, more effective care. However, surveys and studies consistently highlight a gap in PGx knowledge and confidence among pharmacists globally (3).

ADRs are a major cause of hospitalization and death, costing healthcare systems billions each year. PGx has demonstrated the potential to significantly lessen this burden for numerous drug-gene pairs, such as clopidogrel (CYP2C19), warfarin (CYP2C9 and VKORC1), statins (SLCO1B1), and cancer treatments (DPYD and TPMT). In this transformative shift, the pharmacist's role is not only supportive but also pivotal (4). Pharmacists' knowledge of pharmacology, therapeutics, and patient communication positions them as the ideal healthcare professionals to interpret PGx test results, convert complex genetic data into actionable therapeutic advice, counsel patients, and work with prescribers. This represents a logical and powerful extension of the pharmacy profession's transition from a product-focused to a patient-centered care model (5). However, a significant gap exists between the envisioned role and the current situation. Several chemists believe they lack the necessary training to analyze genetic data, assess clinical actionability, or offer advice based on PGx results. Even freshly qualified chemists may lack practical, hands-on experience, and those who graduated before PGx was widely taught frequently lack a core understanding. It can be difficult to explain genetic results and their consequences, especially to individuals who are not educated in health care or who have privacy and discrimination concerns. Pharmacists may feel unqualified to discuss genetics-related ethical, legal, and societal problems (6, 7).

Harmonizing learning outcomes and guaranteeing uniformity across institutions globally are the goals of global initiatives to develop standardized PGx competence requirements for pharmacy education (8). Pharmacogenomic information is increasingly being required to be taken into account when prescribing drugs by regulatory bodies and professional associations worldwide, underscoring the need for chemists to be knowledgeable in this area. In addition to enabling chemists to support precision medicine, good education and training will enhance patient outcomes by enabling more individualized drug therapy options. Many practicing pharmacists graduated before PGx became a significant part of the curriculum (9). Many recent graduates, although possibly familiar with the concepts, lack practical confidence in applying them. This review contends that systematic and comprehensive education and training of pharmacists in pharmacogenomics is the most crucial factor for the successful adoption of personalized medicine. It will examine our past and present and the necessary steps to ensure that the pharmacy profession is fully prepared to lead this initiative.

2. Review Methodology

This narrative review synthesized peer-reviewed literature on pharmacogenomics education and training for pharmacists. A literature search was conducted in PubMed, Scopus, and Web of Science for articles published between 2010 and 2025 using combinations of the keywords "pharmacogenomics", "pharmacogenetics", "pharmacy education", "pharmacist", "curriculum", "continuing professional development", and "certificate program". Additional relevant articles were identified by screening reference lists of key papers and recent reviews. Priority was given to empirical studies, surveys, educational interventions, and policy documents focusing on pharmacist or pharmacy student populations; commentaries without substantive data and non-English publications were excluded.

3. The Changing Dynamics of PGx in Pharmacy Education

3.1. Historical Background: The Knowledge Deficit

Pharmacists who obtained their licenses before the early 2000s typically received minimal formal education in genetics, often limited to a brief mention in biochemistry or microbiology courses, with little to no connection to clinical pharmacology. The completion of the human genome project in 2003 marked

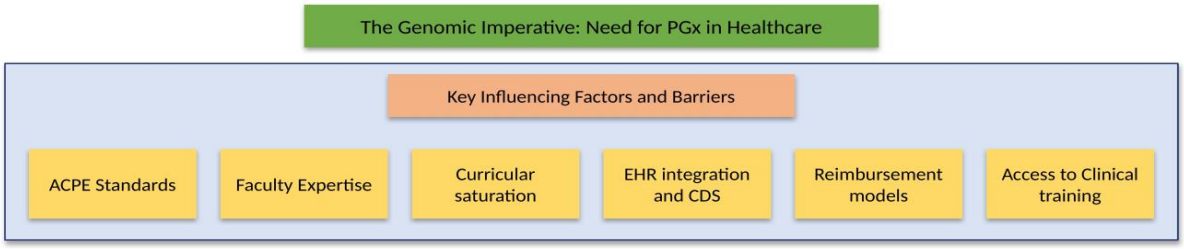


Figure 1. Key influencing factors and barriers in PGx healthcare.

the beginning of its influence on healthcare curricula, which gradually increased over the decade (10). As a result, there is a significant generational knowledge gap. Surveys of practicing pharmacists frequently show that they rate their competence in PGx as low. They express unease with interpreting results, advising patients, and making clinical decisions based on genetic information. This gap represents the first and largest group that needs to be targeted through postgraduate training and ongoing education (11). Figure 1 depicts the key influencing factors and barriers of PGx in healthcare.

3.2. Accreditation Standards: A Catalyst for Transformation

The incorporation of PGx into accreditation standards for Doctor of Pharmacy (Pharm.D.) programs has been the most significant catalyst for curricular reform. The Accreditation Council for Pharmacy Education (ACPE) in the United States has gradually reinforced its position. Beyond ACPE, regulatory and professional bodies in other regions are increasingly embedding PGx expectations into standards and guidance for pharmacy education and practice. For instance, European initiatives under the UPGx project and national pharmacy councils have encouraged inclusion of PGx competencies in undergraduate curricula, while some countries in the Middle East and Asia have begun to reference PGx in national competency frameworks and scope of practice documents. Such policy signals act as important levers for curriculum reform, legitimizing institutional investment in PGx content and creating clearer expectations for pharmacist involvement in precision medicine services. The 2016 standards explicitly require that the curriculum must equip graduates to apply pharmacogenomic data to clinical decision-making. This has forced pharmacy schools to transition from optional lectures to integrated, mandatory content (12). This standards-based approach guarantees a minimum level of exposure for all new graduates. However, the depth, format, and effectiveness of this integration vary widely among institutions, resulting in considerable differences in graduate readiness (13).

4. Educational and Training Models

Pharmacist education in PGx takes place within a multifaceted ecosystem, with each component serving a specific purpose and audience. Figure 2 outlines how these stages combine into a lifelong education pathway.

4.1. The Doctor of Pharmacy (Pharm.D.) Curriculum

Some institutions offer dedicated courses in pharmacogenomics or personalized medicine, providing comprehensive coverage but potentially creating a "silo" effect where students may not connect PGx principles to other therapeutic areas. The Integrated Model is widely regarded as the gold standard. In this model, PGx concepts are interwoven into existing courses. For instance, CYP2C19 and clopidogrel are covered in cardiovascular therapeutics, TPMT and thiopurines in oncology/immunology, and CYP2D6 in psychiatry (14). This approach reinforces the notion that PGx is not a separate entity but an integral part of pharmacology and medicine. The challenge lies in ensuring consistent and comprehensive coverage across different modules and instructors. Many programs use a combination: a core introductory course followed by integrated therapeutic applications. This ensures all students receive a solid foundation while also understanding its clinical relevance. Moving

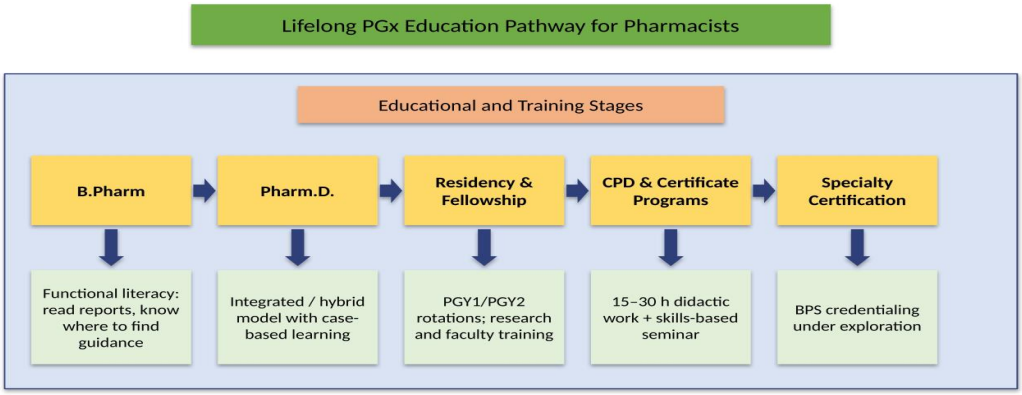


Figure 2. Lifelong pharmacogenomics (PGx) education pathway for pharmacists.

beyond traditional lectures is essential (15). Students must engage with real-world clinical cases, interpret mock genetic test reports, and provide therapeutic recommendations. This develops the critical thinking and practical skills necessary for practice. Some innovative programs include practical lab sessions where students perform DNA extraction or genotyping assays, demystifying the technology behind the testing. While not essential for everyone, it provides valuable context (16). Table 1 compares the 4 core models used to deliver PGx content to pharmacy students (standalone course, fully integrated model, hybrid or 'threaded' model, and elective course), summarising their descriptions, advantages, and disadvantages.

4.2. Bachelor of Pharmacy (B.Pharm) Curriculum

The main issue facing B. Pharm programs is a fundamental concentration and curriculum overload. It is an enormous challenge to incorporate a complex and rapidly evolving area like PGx into a syllabus that is already overloaded. Instead of being an integral part of pharmaceutical education, PGx runs the risk of being a pointless extra, a single lecture on biochemistry or pharmacology (17). The practice-education gap is therefore maintained from the outset of graduates' jobs, since they may be aware of PGx as a concept but lack the practical skills to put it into reality. The objective for a B.Pharm graduate should be functional literacy rather than expertise: the capacity to comprehend a PGx test report, identify its possible clinical importance, and know where to get resources and guidelines for interpretation. They serve as the first line of defence when it comes to determining which patients would benefit from testing (18).

4.3. Postgraduate Training: Residencies and Fellowships

An increasing number of pharmacy residencies, particularly in specialized fields such as oncology, psychiatry, and ambulatory care, are incorporating PGx rotations and experiences. A PGY2 residency, specifically in pharmacogenomics, is emerging, producing experts who can lead clinical services and educate others, while fellowships focus on developing research skills in PGx, contributing to the evidence base, and training future faculty and industry leaders (19). Advanced themes in personalized medicine, such as practical workshops with case studies, PGx research methodology, and the complexities of operating a clinical service, might take up a whole module in a Pharmacy Practice program. An M.Pharm in Pharmacology can concentrate on the cutting-edge field of pharmacogenomics, delving further into the molecular processes behind drug-gene interactions, omics technologies, and state-of-the-art research (20).

4.4. Continuing Professional Development (CPD) and Certificate Programs

Organizations such as the American Society of Health-System Pharmacists (ASHP) and the American Pharmacists Association (APhA) offer live and online workshops (21). These are good for awareness but often lack depth for practical implementation. Certificate Training Programs are the cornerstone of postgraduate PGx education. Intensive programs,

Table 1. Comparing Core Pharmacogenomics Education Models for Pharmacy Students.

figure	Description	Advantages	Disadvantages
Stand-Alone Course	A dedicated, required course in PGx, typically offered in the second or third professional year.	- Provides comprehensive coverage of PGx principles and applications in one dedicated course.	- Can create a "silo" effect, in which students may not connect PGx principles to other therapeutic areas.
Fully Integrated Model	PGx concepts are woven into existing pharmacology and therapeutics courses throughout the curriculum (e.g., CYP2C19 and clopidogrel in cardiovascular therapeutics, TPMT and thiopurines in oncology/immunology, CYP2D6 in psychiatry).	- Reinforces PGx as a fundamental principle of pharmacology and medicine rather than a separate entity.- Demonstrates clinical relevance within each therapeutic area.	- Risk of inconsistent coverage and depth depending on the expertise and interest of individual module instructors.
Hybrid ("Threaded") Model	A short foundational course or module introduces core principles, which are then expanded upon and applied in an integrated manner across subsequent therapeutic courses.	- Provides a necessary foundational knowledge base for all students.- Allows for subsequent application and reinforcement in clinical therapeutics courses.	- Requires meticulous coordination between course directors to avoid redundancy or gaps.
Elective Course	An optional, in-depth course for students with a specific interest in PGx.	- Allows in-depth study of PGx for motivated students.- Can include advanced content such as case-based work and practical laboratory sessions.	- Reaches only self-selected students, so not all graduates gain exposure.- Does not ensure a uniform baseline of PGx competence across the cohort.

such as those offered by universities and professional organizations, typically involve 15-30 hours of didactic work, often online, followed by a live or virtual skills-based seminar where participants work through cases and assessments. For example, the University of Florida College of Pharmacy offers a well-established pharmacogenomics certificate that combines self-paced online modules, interactive case discussions, and direct access to clinical faculty with implementation experience, which has been shown to improve participants' confidence and application of PGx recommendations in practice. Similarly, Manchester University and other institutions have developed longitudinal programs that integrate didactic content, case-based learning, and practice-based projects, emphasizing institutional support, multidisciplinary teaching teams, and alignment with clinical guidelines as key determinants of success. Successful completion grants a certificate of achievement to the learner (22). These programs are designed specifically to bridge the knowledge-practice gap for clinicians. The Board of Pharmacy Specialties (BPS) is exploring the potential for specialty certification in PGx, which would represent the highest level of recognized expertise and could significantly impact reimbursement and scope of practice (23).

The digital revolution has greatly equalized PGx education. Webinars, online modules, podcasts, and interactive platforms allow pharmacists to access world-class content at their own pace from any location (24). Digital repositories of drug-gene guidelines, such as the Clinical Pharmacogenetics Implementation Consortium (CPIC) and the Dutch Pharmacogenetics Working Group (DPWG), provide freely available, constantly updated,

and evidence-based resources that are essential tools for both learning and daily practice (25).

5. Obstacles and Difficulties in Achieving Effective Education

Pharmacy programs are already densely packed with content, and introducing new material, particularly something as intricate as genomics, often necessitates challenging compromises, resulting in only cursory treatment (26). Many current faculty members belong to a generation that did not receive any PGx training. Therefore, investing in faculty development is essential for effective student education (27). Although the ACPE provides a general standard, there is no comprehensive, detailed curriculum that outlines the necessary depth and breadth of PGx knowledge for Pharmacy graduates, leading to inconsistent

Table 1. Essential Competencies for a PGx-Competent Pharmacist.

Domain	Specific Competencies
Foundational Knowledge	- Explain fundamental genetic concepts (genes, alleles, genotypes, phenotypes, and polymorphisms). - Describe the role of key pharmacokinetic (e.g., CYP450 enzymes, transporters) and pharmacodynamic genes in the drug response. - Understand the technologies used in clinical testing (e.g., genotyping and sequencing) and their limitations. - Discussed important ethical, legal, and social implications (ELSI), including privacy, confidentiality, and genetic discrimination (GINA Act).
Clinical Interpretation & Application	- Accurately interpret clinical PGx test reports and identify clinically significant variants. - Translate the genotype into a predicted phenotype (e.g., CYP2D6 → poor metabolizer). - Utilize evidence-based resources (e.g., CPIC and DPWG guidelines) to guide drug therapy recommendations. - Formulate specific, evidence-based recommendations for drug selection, dosing, alternative therapy, and monitoring based on genetic data.
Communication & Collaboration	- Effectively communicate the purpose, benefits, and limitations of PGx testing to patients and caregivers in an understandable and empathetic manner. - Counsel patients on the implications of their results for current and future therapies. - Clearly articulate clinical recommendations and the evidence behind them to physicians, nurses, and other healthcare providers in a collaborative manner. - Understand the role of and know when to refer to a genetic counselor.
Practice Implementation & Evidence-Based Practice	- Understand the logistical steps to establish a PGx service (test ordering, EHR integration, billing, sustainability). - Critically appraise primary literature and clinical guidelines related to PGx. - Apply clinical decision-making to complex cases where evidence may be conflicting or absent. - Identify patients who are ideal candidates for PGx testing based on their medication history, family history, or planned therapy.

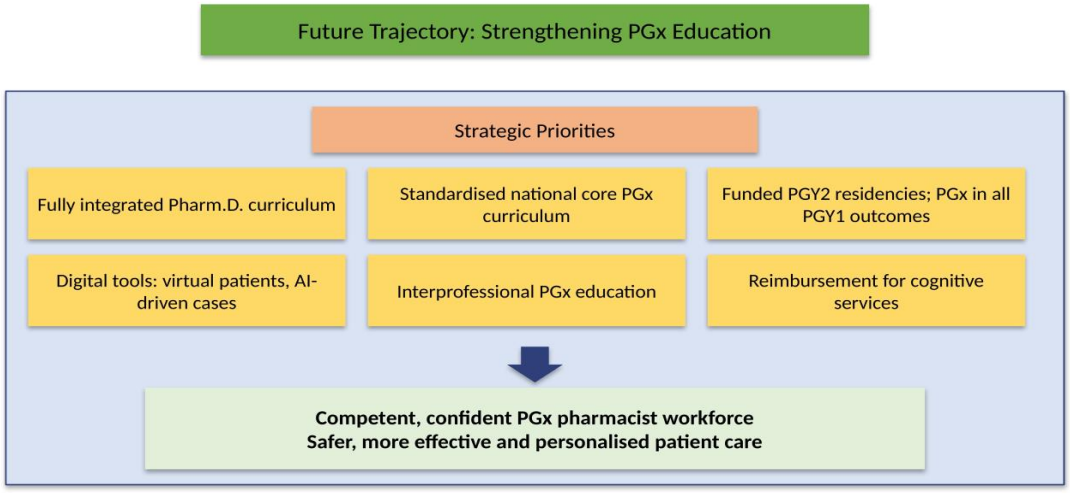


Figure 3. Strategic priorities for strengthening PGx education and training of pharmacists.

levels of their preparedness (28). Importantly, several implementation studies suggest that when pharmacists are adequately trained to interpret PGx results and act on guideline-based recommendations, PGx-guided therapy can reduce preventable adverse drug reactions, improve treatment response, and, in some settings, lower overall healthcare utilization. Strengthening PGx education for pharmacists is therefore not only an academic priority but also a pragmatic strategy to translate evidence on drug–gene interactions into measurable patient benefit. Students learn most effectively through practical experiences. However, not all academic institutions have partnerships with clinical sites that offer active PGx services, where students can gain hands-on experience during Advanced Pharmacy Practice Experiences (APPEs) (29). High-quality certificate programs and conferences often come with registration fees and travel expenses, which can be prohibitive for individual pharmacists, particularly those in community or independent settings. Education remains theoretical, lacking practical tools (30). A significant barrier to practice is the absence of integrated clinical decision support (CDS) within electronic health records. Without CDS alerts and embedded guidelines, applying pharmacogenomic (PGx) knowledge is a manual and time-consuming task (31). Table 2 outlines the essential competencies required of a PGx-competent pharmacist across four domains: foundational knowledge, clinical interpretation and application, communication and collaboration, and practice implementation.

6. The Future Trajectory

Pharmacy programs must fully embrace the integrated model, ensuring that pharmacogenomics (PGx) is a consistent theme throughout the curriculum, supported by advanced simulation and case-based learning. National pharmacy organizations should collaborate to create a more detailed, standardized core PGx curriculum to guarantee uniformity and quality among all graduating pharmacists. Increased funding and support for PGY2 residencies in PGx will lead to the development of more experts. Additionally, PGx should be a mandatory educational outcome for all PGY1 residencies to ensure proficiency among specialists in every field. The creation of more advanced, interactive, and cost-effective digital learning tools, such as virtual patient simulations and AI-driven case studies, offers scalable, high-quality education. Professional organizations must continue to push for policies that acknowledge the pharmacist's role in PGx, including reimbursement for cognitive services (e.g., interpretation and consultation), which would establish a sustainable financial model for providing these services and justify the investment in education. PGx exemplifies team-based healthcare. Emerging interprofessional PGx education models bring pharmacy students together with medical, nursing, and genetic counseling trainees in shared case con-

ferences, simulated family meetings, or team-based OSCEs focused on PGx scenarios. Programs that use these formats report improved understanding of complementary professional roles, greater confidence in collaborative decision making around PGx test ordering and result interpretation, and more realistic preparation for team-based implementation in clinical settings. Embedding such interprofessional PGx activities within core curricula, rather than as optional electives, may be critical for normalizing pharmacists' leadership in multidisciplinary precision medicine teams. Figure 3 summarises these strategic priorities.

7. Conclusion

Pharmacogenomics is evolving from a specialized research area to a fundamental part of clinical practice. Bridging the gap between potential and practice necessitates a lifelong learning approach with a robust, integrated Pharm.D. program, advanced training for future leaders through residencies, and comprehensive and accessible upskilling for the current workforce. The challenges of curricular saturation, faculty development, and practical implementation are significant but not insurmountable issues. The profession can overcome these obstacles by standardizing curricula, adopting innovative teaching technologies, and advocating for a practice model that acknowledges and rewards pharmacist-led PGx services. Therefore, the education and training of pharmacists in pharmacogenomics is not merely an academic endeavor; it is an ethical obligation and the key to unlocking a safer, more effective, and truly personalized future for medicine.

Acknowledgements

The authors would like to express their gratitude to the College of Pharmacy, Madras Medical College.

Declaration of Generative AI in the Writing Process

The authors used Grammarly to assist in editing the text. They reviewed and modified the content as necessary, taking full responsibility for the final publication.

Conflict of Interest

The authors declare that they have no conflict of interest.

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