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Effectiveness of pharmacogenomics educational interventions on healthcare professionals and health professions students: A systematic review

Safa Omran [a], Siew Lian Leong [a], Ali Blebil [a], Devi Mohan [b], Siew Li Teoh [a,*]

[a] School of Pharmacy, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway, 47500, Subang Jaya, Selangor, Malaysia
[b] Jeffrey Cheah School of Medicine and Health Sciences, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway, 47500, Subang Jaya, Selangor, Malaysia

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ABSTRACT

Background: The field of pharmacogenomics is rapidly advancing, but its adoption and implementation remain slow and lacking. Lack of pharmacogenomics knowledge among healthcare professionals is the most frequently cited barrier to adopting and implementing pharmacogenomics in clinical settings.
Objectives: This study aimed to critically evaluate and determine the effectiveness of educational interventions in improving pharmacogenomics knowledge and practice.
Methods: Four electronic databases were searched: MEDLINE, EMBASE, CENTRAL, and PsycINFO. Studies on pharmacogenomics educational interventions for health care professionals and students with pre- and post-intervention assessments and results were included. No restrictions were placed on time, language, or educational contexts. The educational outcomes measured include both objective and subjective outcomes. The pharmacogenomics competency domains used to judge educational interventions are based on the competency domains listed by the American Association of Colleges of Pharmacies (AACP). The National Heart, Lung, and Blood Institute of the National Institutes of Health was used for the quality assessment of pre-post studies with no control group and the controlled intervention studies. No meta-analysis was conducted; the data were synthesized qualitatively. The systematic review was reported in accordance with the PRISMA statement.
Results: Fifty studies were included in this review. All included studies integrated the AACP pharmacogenomics competency domains into their educational interventions. Most of the studies had educational interventions that integrated clinical cases (n = 44; 88%). Knowledge was the most frequently evaluated outcome (n = 34; 68%) and demonstrated significant improvement after the educational intervention that integrated AACP pharmacogenomics competency domains and employed active learning with clinical case inclusion.
Conclusion: This review provided evidence of the effectiveness of educational interventions in improving pharmacogenomics knowledge and practice. Incorporating pharmacogenomics competency domains into education and training, with patient cases for healthcare professionals and students, dramatically improved their pharmacogenomics knowledge, attitudes, and confidence in practice.

1. Introduction

Pharmacogenomics (PGx) is a rapidly evolving field with corresponding ethical, social, religious, legal, and clinical challenges that may impact its practice in general and patient outcomes in particular. As pharmacogenomics continues to make strides, the future of the field is gaining global attention.[1] The Obama Administration's 2015 Precision Medicine Initiatives in the United States addressed the need for precision therapy.[2] Similarly, the Food and Drug Administration (FDA) now labels many medications with pharmacogenomics-related information.[3] Evidence demonstrates that the use of pharmacogenomics test results can prevent 20 to 30% of adverse drug events (ADEs) and significantly reduce the overall healthcare costs and deaths associated with ADEs.[4,5] Although the use of pharmacogenomics information has a significant clinical and economic impact, its adoption and implementation in clinical settings have been slow and lacking.[4]

The distinction between pharmacogenomics and genomics is necessary, as the latter is a broader field that includes the study of genes and

* Corresponding author.
E-mail addresses: safa.omran@monash.edu (S. Omran), teoh.siew.li@monash.edu (S.L. Teoh).

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their functions, whereas pharmacogenomics combines pharmacology and genomics to optimize medication safety and efficacy based on a person's genetic constitution.[6] In addition, a multidisciplinary approach that integrates the efforts of several healthcare specialities is essential in the pharmacogenomics field.[7] A review[8] of multidisciplinary in-hospital teams emphasized the teamwork efforts and benefits in different clinical settings: psychiatry, neuroscience, respiratory care, intensive care units, operating rooms, surgical wards, and others. This review[8] included staff from different levels of care, such as nurses, surgical staff, physicians, anaesthesiologists, etc. Furthermore, the review[8] showed that a multidisciplinary approach in healthcare improved patient outcomes, reduced hospital expenditures and complications, and maximized healthcare professionals' performance. Therefore, while evaluating pharmacogenomics knowledge and practice, it is important to consider not just one healthcare profession but all healthcare providers.

The lack of knowledge regarding pharmacogenomics among healthcare professionals is the most commonly cited key barrier to the adoption and implementation of pharmacogenomics in clinical settings[9] (i.e., less than 5% of physicians are familiar with pharmacogenomics).[10] Systematic reviews of knowledge, attitudes, and practice concerning pharmacogenomics and genetics among pharmacists,[11] doctors,[12] and nurses[13] showed poor knowledge and practice despite positive attitudes. These systematic reviews[11–13] concluded that there is an urgent need for additional pharmacogenomics education for healthcare professionals and that pharmacogenomics should be included in school curricula, with a focus on implementing pharmacogenomics in clinical settings.

Currently, a few reviews have been identified to summarize educational interventions and their outcomes. Three reviews[14–16] evaluated the effectiveness of educational interventions, but they were limited to genomics, did not include all healthcare professionals, and did not define genomics competencies.[14–16] Two reviews,[4,17] even though they were focused on pharmacogenomics, did not evaluate the effectiveness of educational interventions. The first one discussed barriers and solutions for the clinical implementation of pharmacogenomics,[4] while the second review evaluated pharmacogenomics knowledge among pharmacists.[17] However, to the best of our knowledge, no reviews have explicitly focused on pharmacogenomics as a distinct field that includes all healthcare professionals and evaluates educational interventions on the basis of a clear definition of pharmacogenomics competency. Therefore, this systematic review aimed to synthesize evidence on pharmacogenomics education through critical evaluation and identification of the effectiveness of educational interventions in improving knowledge and practice of pharmacogenomics.

2. Methodology

2.1. Design

This systematic review was conducted following the principles outlined in the Cochrane Handbook for Systematic Reviews of Interventions. It was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Appendix S1). The review protocol was registered in PROSPERO, and the registration number is CRD42022385400.

2.2. Search strategy and selection criteria

Four electronic databases were searched from their inception to October 31, 2022: MEDLINE, EMBASE, the Cochrane Central Register of Controlled Trials (CENTRAL), and PsycINFO. In addition, relevant trial registries were searched for ongoing studies in the WHO International Trial Registry Platform and ClinicalTrials.gov. Three research concepts were used for searching pharmacogenomics, healthcare professionals and health professions students, and education. The Medical subject headings (MeSH) browser was searched for key terms and synonyms. A range of search terms related to the research concepts was combined with appropriate Boolean operators. The complete search strategy applicable to different databases is available in Appendix S2. The bibliographies of the included studies were used to identify additional papers.

2.3. Inclusion/exclusion criteria

In this review, we included primary, original studies in which pharmacogenomics is the primary core activity, with pre-and post-intervention assessments and results. No restrictions were placed on time, language, or educational contexts. The following criteria must be specified in the study: 1) The participants include healthcare professionals in practice or/and health professions students; 2) the intervention was any educational intervention in pharmacogenomics; 3) the outcomes include objective outcomes, including knowledge and competency or/and subjective outcomes, including attitudes, perceptions, confidence, and others, such as comfort level, views, and opinions.

Two independent reviewers screened the titles and abstracts for eligibility. Following full-text retrieval, both reviewers independently assessed each record against our inclusion and exclusion criteria. After that, the full texts of relevant studies were reviewed. Any discrepancies and disagreements were settled through consensus-building discussions with all authors.

2.4. Data extraction and synthesis

All the necessary information for the systematic review was independently extracted by two reviewers from the included studies, such as authors, publication year, country, number and characteristics of participants, educational intervention and delivery method, intervention content and competency domains covered, intervention duration and follow-up, and outcomes. The intervention content was divided into basics and applied. The "basics" content referred to the fundamental concepts, terminologies, and definitions in pharmacogenomics and genomics, while "applied" referred to the clinical application involving clinical cases either using patient or personal genotyping data. The pharmacogenomics competency domains used to judge educational interventions' content in the criteria for studies are based on the competency domains listed by the American Association of Colleges of Pharmacies (AACP). The AACP competency domains were chosen as they combine and summarize the National Human Genome Research Institute (NHGRI) competency domains for healthcare disciplines in a comprehensive and simple way that can be applied to all healthcare disciplines.[18] The AACP competency domains are four and include basic genetic concepts, genetics and disease, pharmacogenetics/pharmacogenomics (PGx), and ethical, legal, and social (ELS) implications (Appendix S3).[19] The study that fulfilled the description or example of activity or responsibility of the competency domain was considered a competency-included study. A qualitative synthesis and narrative summary with tabled results were used to illustrate how the findings relate to the review's objectives.

2.5. Quality assessment

The methodological quality of each study was independently assessed by two reviewers using the National Heart, Lung, and Blood Institute of the National Institutes of Health (NIH) for quality assessment of before-and-after (pre-post) studies with no control group and quality assessment of the controlled intervention studies.[20]

3. Results

3.1. Identification and selection of studies

The details of the PRISMA flow chart results of the literature searches are illustrated in Fig. 1. The search of published articles in various

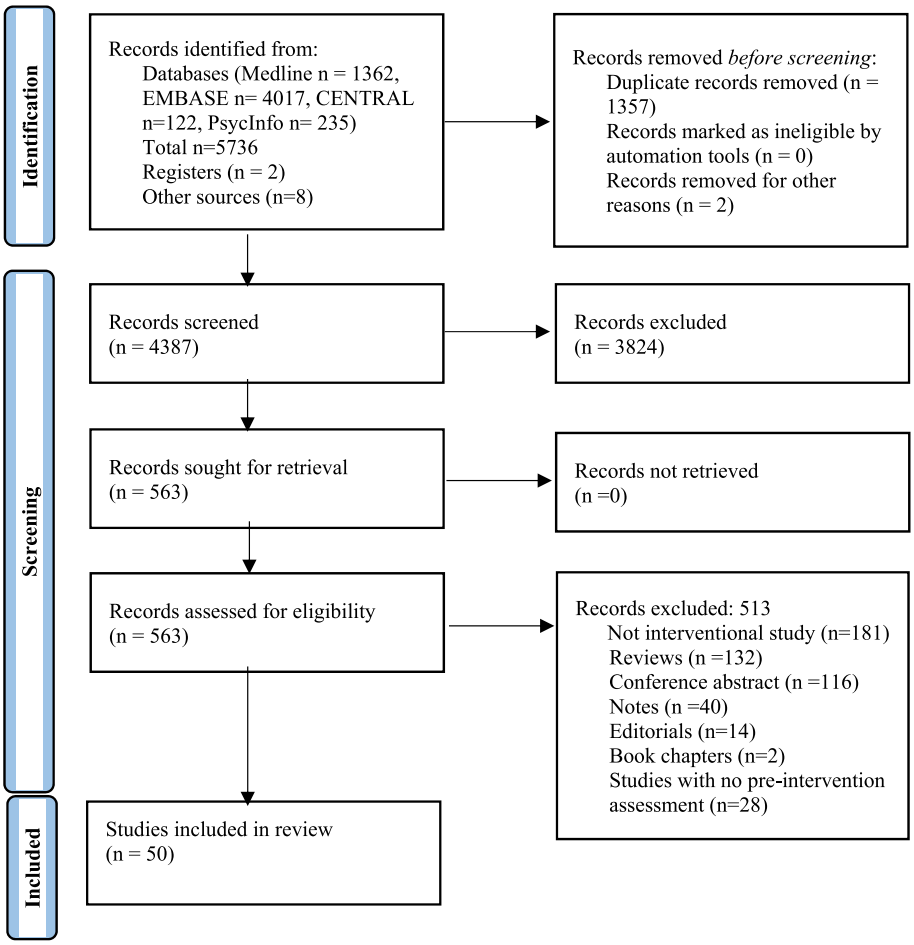

Fig. 1. Search outcomes and study selection reported according to PRISMA guidelines.

databases resulted in 4379 articles after removing duplicates. An additional 8 articles were identified through citation searching. The remaining articles were screened through titles and abstracts, of which 3824 were removed because of their irrelevance to pharmacogenomics. This resulted in 563 articles being full-text reviewed for eligibility. Of those, 513 articles were excluded for the reasons stated in Fig. 1. Finally, a total of 50 studies were included in this systematic review.

3.2. Study characteristics

The characteristics of the included studies are summarised in Table 1. Most studies were conducted in the United States (n = 43; 86%),[21–63] followed by Canada (n = 3; 6%),[64–66] and one study each from the United States and Canada,[67] Singapore and Indonesia,[9] Italy,[68] and Switzerland.[69]

3.3. Participants characteristics

The majority of studies were for students—29 (58%).[23,24,28–31,33–37,39,41–44,47–51,54,56–60,64,67] Pharmacy students made up the majority of the students' studies (n = 19; 65.5%),[24,30,31,33,35,37,41,42,44,47–50,54,56–59,67] with 9 out of 19 (47.4%) delivered to first-year pharmacy students.[30,31,33,41,44,48,49,51,56] Four studies were conducted with medical students,[23,28,29,34] three with nursing students,[39,43,64] and three studies were conducted inter-professionally between pharmacy and medicine students.[36,51,60]

Nineteen studies (38%)[9,21,22,25–27,38,40,45,46,52,55,61–63,65,66,68,69] were for healthcare professionals, and 7 out of 19 studies (36.8%)[26,27,46,63,65,66,69] were delivered to pharmacists, with the majority working in a hospital or inpatient settings (5/7; 71.4%).[26,27,46,63,69] Four out of 19 studies were for physicians,[38,40,62,68] and 3 out of 19 were for nursing staff.[21,45,52] Five of the 19 studies were for multidisciplinary professionals[9,22,25,55,61] as follows: two studies[22,61] included psychiatrists and other mental health professionals; another study[25] included nurses and a small number of other allied health professionals. Another study[55] comprised one staff preventive medicine physician, one staff aerospace medicine physician, three staff internists, five resident internists, and two trainee health nurse practitioners; the fifth study[9] included medical doctors, nurses, medical and pharmacy students, and other healthcare-related workers.

Two studies were mixed-group studies that included healthcare professionals in practice and students [32, 53]. The participants in one of the studies[32] were pharmacists, pharmacy students, and pharmacy educators, while the other study's participants included pharmacists and pharmacy students in their second and third years.[53] The number of participants in each study varied; 25 (50%) studies had fewer than 100 participants.[22–24,28–30,32,34,36,38,40,42,43,45,48,51,55,58,59,61,63–66,69]

3.4. Educational intervention characteristics

The most common medical conditions discussed in the included studies were those in the cardiology,[9,24,26,27,32,35–38,40,42,44,46,47,49,50,53,54,56,57,65,66,68] psychiatry and neurology,[9,21,22,26,30,32,37,40,41,43,53,57,59,61,63,65,66] oncology,[25–27,32,40,42,44,46,47,53,56,57,59,68] and pain.[9,25,26,32,42,48,51,53–55,57,63–66,68] The educational interventions varied in content, competency domains covered, delivery method, and duration.

Most studies for students had an educational intervention that covered both the basics and applied contents (25/29; 86.2%).[24,28–31,33–37,41–44,47–50,54,56–59,64,67] Two out of 29 studies covered only the content of the basics,[23,39] and two out of 29 studies covered only the applied

Table 1
Full studies' characteristics.

Authors	Country	Participants	No. of Participants	Educational Intervention; Delivery Methods	Intervention Content; Competency Domains	Intervention Duration; Follow Up (FU)
Pestka 2004[21]	US	Nursing staff	172	Conference in psychiatry; in-person	Basics & applied; 4 Competencies	1- day; 3-month FU
Mrazek 2007[22]	US	Healthcare professionals	41	Course in psychiatric genomics (CME); in-person	Basics & applied; 4 Competencies	5 days
Ormond 2011[23]	US	Medical Students	86	**Required course** in human genetics; Delivered via lectures	Basics; 3 Competencies (Basic genetic concepts, genetics & disease, and ELS)	32 h
Springer 2011[24]	US	Pharmacy students	18	**Elective** course in drug safety & PGx using **GeneScription software** (a software program designed to mimic the professional pharmacy environment, delivered in session 7); in-class, 8 sessions between lectures, discussions, role-playing, & software use.	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and ELS)	10 weeks (2 hrs/week)
Wallen 2011[25]	US	Healthcare professionals	129	Program in genetics, combined 7 web-based self-education interactive modules with monthly traditional face-to-face lectures by genetics experts.	Basics & applied; 4 Competencies	1-hr for face to face lecture
Formea 2013[26]	US	Pharmacists	272	**Required CE** program in fundamental PGx & non-mandatory lectures (6-specialty lectures); Delivered via live- and web-archived lectures	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	1-h/lecture
Kuo 2013[27]	US	Pharmacists	673	PGx education program in bridging the gap between science and practice of 2 modules; Delivered via didactic live CE lecture presentation	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and ELS)	1- hour CE/module
Salari 2013[28]	US	Medical students	46	**Elective** course in genomics and personalized medicine; delivered via class discussion, lectures, and hands-on data analysis exercises, with optional PGT	Basics & applied; 4 Competencies	8- weeks
Sanderson 2013[29]	US	Medical and genetic counselling students	19	Two Courses: the introductory genomics and the advanced genomics courses; Delivered via classes	Basics & applied; 4 Competencies	26-hrs for the introductory course
Bova 2014[30]	US	Pharmacy students	51	**An elective** one-semester course in personal genome evaluation; delivered via a weblog (blog),	Basics & applied; 4 Competencies	15 week semester
Nickola 2014[31]	US	Pharmacy students	NR	PGx **primer** course in essentials of PGx of 4 modules; Lectures with PGT	Basics & applied; 4 Competencies	Academic semester
Kisor 2015[32]	US	Pharmacists, pharmacy student, & pharmacy educators	21	Pharmacogenomics certificate training program based on competency guidelines for pharmacists; comprised of self- study (book chapters), & live session (presentation, simulated patient group visit of four rounds, & an in- class group discussion).	Basics & applied; 4 Competencies	6- week self-study & 1-day (7-h) live session
Lee 2015[67]	US & Canada	Pharmacy students	Pre-training (n = 2674), Post-training (n = 2542)	PGx training of 9 peer-reviewed therapeutic modules, shared PGx curricula between 43 schools, within 2 academic years.	Basics & applied; 3 Competencies (Basic genetic concepts, genetics & disease, and PGx)	180 min (median no. of min taught for the training)
Munson 2015[33]	US	Pharmacy students	113	**Required** course in the essentials of pharmacogenomics; Delivered via flipped classroom	Basics & applied; 3 Competencies (Basic genetic concepts, genetics & disease, and PGx)	5 weeks
Sanderson 2015[34]	US	Medical Students	19	Advanced genomic course in novel genome analysis with optional PGT; delivered via classes	Basics & applied; 4 Competencies	FU 6- months later
Adams 2016[35]	US	Pharmacy students	Students (n = 122), Faculty members (n = 10)	**Required course** in drug development, with educational program (Test2learn) **For students:** In-class didactic lectures with optional PGT, role playing, PTC experiment. **For Faculty**: "teach the teacher" model with optional PGT	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, & ELS)	NR
Calinski 2016[36]	US	Pharmacy and physician assistant (PA) students	96	**Required** interdisciplinary education (IPE) laboratory course focused on pharmacogenetics; Delivered via Power Point presentation on PGx testing, and team activity (case discussion)	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	1-hr/session
Frick 2016[37]	US	Pharmacy students	145	**Required** pharmaceutical care lab course; Lectures, weekly,1-h large group class sessions for all 145 students and	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	15 weeks

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Table 1 (*continued*)

Authors	Country	Participants	No. of Participants	Educational Intervention; Delivery Methods	Intervention Content; Competency Domains	Intervention Duration; Follow Up (FU)
				weekly, 4-h small group sessions of 8–10 students, and voluntary PGT.		
Luzum 2016[38]	US	Physicians	30	Grand round presentations in PGx (CE); in-person	Basics & applied; 4 Competencies	1- hour CE program
Munroe 2016[39]	US	Nursing students	109	Semester program with genomics content; delivered via lectures	Basics; 3 Competencies (Basic genetic concepts, genetics & disease, and PGx)	Academic semester
Reed 2016[40]	US	Physicians	34	A course in medicine's future genomics (10 modules) CE; in- person (group discussion, patient video, case- based problem solving)	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and genetics & disease)	2- hours/module, monthly from October 2013 through July 2014; 6- months FU after module 10
Surofchy 2016[41]	US	Pharmacy students	122	**Required** pharmacogenomics course in genetics & pharmacogenetics with optional PGT	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	10- weeks, 120 min class period for discussing PGT data, & 15 min for case discussion
Weitzel 2016[42]	US	Pharmacy students	69	**Elective courses** in the clinical applications of PGx & clinical applications of genomic medicine (two online courses, 8-weeks/course); Mix Online (1-hr/week pre-recorded lectures, 1-hr/week live sessions via synchronous webinar in a flipped-classroom model that used a Socratic question-and-answer teaching strategy, role-playing, patient-case discussion) with PGT or de-identified data). PGT was not performed in genomic course.	Basics & applied; 4 Competencies	Academic semester (16-weeks)
Williams 2016[43]	US	Nursing students	11	**Required** 3-credit course in genetics for clinicians of 14 modules (module of 6 components/week); Delivered online cross course (collaboration between nursing faculty and pathology faculty with expertise in genomic)	Basics & applied; 3 Competencies (Basic genetic concepts, genetics & diseases, and ELS)	14 week-long modules; 9-months FU
Remsberg 2017[44]	US	Pharmacy students	133	**Required course** in the basic and clinical PGx, of 3 modules with PGT lab exercise; Delivered via an in- class, 3 modules, one 2-h lecture per week, lab exercise, group term paper	Basics & applied; 4 Competencies	Academic semester
St- Martin 2017[64]	Canada	Nursing students	32	Brief genetics education session, with case- study discussion; In- person, lecture- based format with the inclusion of activities involved applying concepts, ex. explaining simple modes of inheritance	Basics & applied; 2 Competencies (Basic genetic concepts, and genetics & disease)	1- hour/session; FU 3-weeks after the session.
Dodson 2018[45]	US	Nursing staff	78	PGx interactive CE education program (games, videos, puzzles)	Basics; 2 Competencies (Basic genetic concepts, and PGx)	45 min (module & survey)
Formea 2018[46]	US	Pharmacists	435	PGx 4- module educational program; delivered online, interactive (interprofessional between campuses), competency modules (case- based approach)	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	15- min per module
Frick 2018[47]	US	Pharmacy students	222	**Required course** in pharmaceutical care lab course; through lectures (1-hr/week large group lecture & 4-hr/week small group sessions), & patient cases with optional PGT.	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	15 weeks
Gálvez Peralta 2018[48]	US	Pharmacy students	76	Course in biopharmaceutics and pharmacogenomics (4- credit course); via active learning, lectures, team activities (29 sessions for PGx with 4 team activities)	Basics & applied; 4 Competencies	Academic semester, 1-hr/week for team activity. The other 3 sessions were for lectures; 6- month FU after PGx course.
Marcinak 2018[49]	US	Pharmacy students	NR	**Required** principle of genetics and PGx course (2 CE hour)	Basics & applied; 4 Competencies	Academic semester
Patel 2018[50]	US	Pharmacy students	113	**Required** two courses of 3 credits in translational PGx & pharmaceutical skills; Online lectures, & simulation activities	Basics & applied; 2 Competencies (basic genetic concepts, and PGx)	Academic semester (16-week), & the simulation activity for 40 min.
Quesnelle 2018[51]	US	Pharmacy & medical students	90	**Required** PGx IPE, telehealth team-based learning (TBL), between 2 faculties: medical & pharmacy; Telehealth classroom (IPE), of 2 groups conferencing (small & large)	Applied; 3 Competencies (Basic genetic concepts "in terms of diagnosis and treatment", genetics & disease, and PGx)	2-h stand-alone exercise within each curriculum

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Table 1 (*continued*)

Authors	Country	Participants	No. of Participants	Educational Intervention; Delivery Methods	Intervention Content; Competency Domains	Intervention Duration; Follow Up (FU)
Fee-Schroeder 2019[52]	US	Nursing staff	165	Online genetics and genomics education program, with **required** prework mainly on basics, and in person class (mainly on applied); Flipped strategy classes: assigning (required) prework for learners in the form of videos, animations, illustrations, readings, or other materials to be completed before the face-to-face class.	Basics; 3 Competencies (Basic genetic concepts, genetics & disease, and PGx)	From Feb 2015 to April 2016. In- person class was 60 min; FU at various time points (>9-m)
Kisor 2019[53]	US	Pharmacist and pharmacy students	137	**Elective** PGx program, of 2 modules, 11 lessons per module. First module covered the science of PGx, and the second module covered the practical application of PGx; delivered online	Basics & applied; 4 Competencies	NR
Powers 2019[54]	US	Pharmacy students	130	**Required** active- learning laboratory session in clinical pharmacogenetics (1-credit course), of 2 parts: team cases & counselling activity for simulated patients, & pre-recorded lecture (presented before the lab session)	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	Semester (50 min for lecture/week, 2-h for lab sessions, three times per week); 3-weeks later FU at the end of the semester.
Crown 2020[65]	Canada	Pharmacists	26	PGx continuing professional development (CPD) program of 3 components: online lectures, a two-day live training workshop, and simulated patient case studies; Blackboard, live (lectures, discussion, case presentations, role play)	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and ELS)	2 months (3-hrs/lecture, 2-days/training)
Maxwell 2020[55]	US	Primary health-care providers (HCPs)	12	Brief education intervention, focused on providing post- genetic test counselling services for patients; delivered through presentations	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and genetics & disease)	3- hours
Zhang 2020[56]	US	Pharmacy students	296	**Required** course in the basic and clinical PGx, (2 CE); Peer-led study groups (PLSGs)	Basics & applied; 4 Competencies	14 weekly 1-h PLSG sessions for one semester
Adesta 2021[9]	Singapore & Indonesia	Healthcare providers (HCPs)	102	PGx implementation training program of 2 modules (TM1, TM2), TM1 Offline, in-person classroom session followed by focus group discussion, and TM 2 online via private e-learning platform	Basics & applied; 2 Competencies (Basic genetic concepts, and PGx)	90 min/module (30-min after the class were spared for focus group discussion)
Arwood 2021[57]	US	Pharmacy students	285	Two online courses: **elective** course in clinical applications of personalized medicine, emphasized patient cases, employed didactic teaching and active engagement), and **required** course in personalized medicine, introductory course, utilized multiple self-directed didactic learning), with optional PGT for both groups; For elective course patient cases were conducted in a classroom, with option to join via webinar. Only the elective course, students had the opportunity to use their PGT data in their learning activities before the interactive session, while students enrolled in the required course did not receive their PGT results until the end of the course.	Basics for the required course, and basics & applied for the elective course; 4 Competencies (for both courses)	Semester (16-week for elective course, & 10-week for required course)
Assem 2021[58]	US	Pharmacy students	45	**Required** two courses in principles of drug actions, PGx, and patient care laboratory, with voluntary PGT, students who declined to participate in PGT received mock data; Lectures, flipped classroom discussions, and patient care lab training	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and ELS)	NR
Bailey 2021[59]	US	Pharmacy students	2	**Elective** two courses in advanced PGx independent study, for 2 nd year students of 3 CE, and advanced pharmacy practice experiences (APPE)", for 4th year students, hands- on courses. Both courses included 'wet-laboratory' and 'dry-laboratory' components. Wet-lab component was similar for both courses. Both included PGT, raw genetic sequence data analysis, and wet-laboratory genetic testing. The APPE	For APPE course: Basics & applied; with 4 Competencies. For the Advanced PGx course: Basics with 1 competency (Basic genetic concepts)	The independent course was for semester, 3-h/week). APPE course was for 6- week (8-hr/week)

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Table 1 (*continued*)

Authors	Country	Participants	No. of Participants	Educational Intervention; Delivery Methods	Intervention Content; Competency Domains	Intervention Duration; Follow Up (FU)
				included sessions with clinical pharmacists who use PGx and a genetic counsellor, as well as a visit to a genetic reference laboratory		
Calabrò 2021[68]	Italy	Physicians	1637	Course in genetics and genomics practice; via distance learning (included audio-video lectures and interactive clinical, problem-based learning and case-based learning)	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and genetics & disease)	Feb 27th, 2017 to Feb1st, 2018; 8- month FU
Calinski 2021[60]	US	Pharmacy & medical students	164	PGx clinical implementation IPE experience, between 2 institutions (pharmacy & medical; optional for pharmacy students, & required for medical students), with optional PGT; IPE experience of 3 components: PGx-focused patient case discussion, prescription writing & review, and voluntary PGT	Applied; 1 Competency (PGx)	3-hr IPE
Stäuble 2021[69]	Switzerland	Pharmacists	21	Training program in advanced PGx; The program is blended, included an asynchronous self-study online module, synchronous virtual classroom sessions with lectures and workshops, a follow-up case study, and PGT	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and ELS)	3- month; FU with case study
Ward 2021[61]	US	Healthcare providers (HCPs)	32	Psychiatric PGx CE course; videoconferencing via Blue Jeans conferencing technology, of 3 sessions, offered 3 times; via online live didactic and interactive learning styles.	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and ELS)	3- weekly lessons, 90-min/lesson; FU at 1- and 3- months
Hajek 2022[62]	US	Physicians and advanced practice providers	NR	**Mandatory** program in genetics education; of web-based, 8 modules, one of the modules addressed Sanford Chip Program.	Basics & applied; 3 Competencies (Basic genetic concepts, PGx, and genetics & disease)	2-year (3 months/module)
Hayashi 2022[66]	Canada	Pharmacists	69	Educational program in PGx; Synchronously (live, virtual/Zoom) and asynchronously (online using the recordings of the live sessions, self-study), and mixed (combination of both options).	Basics & applied; 4 Competencies	2-day (5-h/day)
Lee 2022[63]	USA	Pharmacists	57	Educational program in PGx; via a longitudinal online, live webinar series within a large health system	Basics & applied; 2 Competencies (basic genetic concepts, and PGx)	3 weeks (total 3-hr, 1-hr/webinar) Long term assessment; 4–8 weeks FU after the final webinar

content.[51,60] In total, applied content was covered in 27 studies out of 29, of which 24 used patient cases[24,29,30,33–37,41–44,47–51,54,56,57,59,60,64,67] and three used personal genotyping data.[28,31,58] Twelve out of 29 studies (41.4%) covered all four competency domains,[28–31,34,44,48,49,56,57,59,60] nine out of 29 studies (31%) covered three competency domains,[23,24,33,35,39,43,51,58,67] seven out of 29 studies covered two competency domains (24.1%),[36,37,41,47,50,54,64] and the remaining study covered only one competency domain.[60] Twenty-one out of 29 studies (72.4%) delivered educational interventions in the classroom.[23,24,28,29,31,33–37,39,41,44,47,48,54,56,58–60,64] Six out of 29 studies used online educational methods.[30,42,43,50,51,57] The remaining two studies did not report the education delivery method. Seventeen out of 29 studies delivered the educational intervention as a required academic course enrolment,[23,31,33,35–37,41,43,44,47,49–51,54,56–58] while six studies were delivered as electives.[24,28,30,42,59,60] The enrolment classification was not reported for the remaining six studies.[29,34,39,48,64,67] Only three studies delivered interprofessional education (IPE) interventions to pharmacy and medical students.[36,51,60]

For healthcare professionals, most studies had educational interventions that covered the basics and applied contents (17/19 studies (89.5%).[9,21,22,25–27,38,40,46,55,61–63,65,66,68,69] The remaining two studies covered only the content of the basics.[45,52] Five of the 19 studies covered four competency domains,[21,22,25,38,66] three competency domains (9/19),[27,40,52,55,61,62,65,68,69] and two competency domains (5/19).[9,26,45,46,63] The most common method of delivering education was online (9/19; 47.4%).[26,27,46,61–63,66,68,69] Four out of 19 studies had educational interventions delivered via hybrid means (4/19; 21%),[9,25,52,65] in which offline (in-person) and online methods were used, while three out of nineteen studies used in-person delivery.[21,40,45] The remaining three studies did not specify the education delivery method.[22,38,55]

The educational interventions in the two mixed-group studies included all four competency domains, as well as the contents of the basics and applied.[32,53] One study [32]comprised a self-study approach with one live session, whereas the other employed an online method.[53]

The most common competency domains covered in the included studies are the domains of the basic genetic concepts[9,21–59,61–69] and the pharmacogenetics/pharmacogenomics.[9,21,22,24–42,44–63,65–69] The duration of the educational interventions varied from a few hours[9,21,22,25–27,38,45,46,55,61,63,66] to several months.[40,52,62,65,68,69] Eight out of 19 studies were provided through continuing education.[22,26,27,38,40,45,61,65]

3.5. Outcomes measured

The effects and outcomes of the included studies are summarised in Table 2. The most common outcome assessment tool was a self-administered survey. Thirty-five out of 50 (70%) studies used the same survey content for pre- and post-intervention assessments[22–24,26–30,32,33,36–38,40–44,46,47,49–51,53–55,58–61,63–66,68] (Appendix S4). A few studies (13/50; 26%)[21,34,40,43,48,49,52,54,61,63,64,68,69] included follow-up

Table 2
Outcomes measured.

Authors	Outcomes					
	Objective Outcomes		Subjective Outcomes			
	Knowledge	Competency	Attitudes	Perceptions	Confidence	Others
Pestka 2004[21]	(+)	X	X	X	X	X
Mrazek 2007[22]	X	X	(+)	X	X	X
Ormond 2011[23]	(+)	(+)	V	X	X	X
Springer 2011[24]	X	X	(+)*	X	X	X
Wallen 2011[25]	(+)*	X	X	X	X	X
Formea 2013[26]	(+)	(+)	X	X	X	X
Kuo 2013[27]	(+)*	X	(+)	X	(+)*	X
Salari 2013[28]	(+)*	X	V	V	X	X
Sanderson 2013[29]	(−)	X	(−)	X	X	X
Bova 2014[30]	(+)*	X	X	X	X	X
Nickola 2014[31]	(+)*	X	X	X	X	X
Kisor 2015[32]	X	X	X	X	(+)*	X
Lee 2015[67]	X	X	(+)	X	(+)*	X
Munson 2015[33]	(+)*	X	X	X	X	X
Sanderson 2015[34]	(+)*	X	(−)	X	X	(+)
Adams 2016[35]	(+)*	X	(+)*	X	X	X
Calinski 2016[36]	X	X	X	X	(+)*	X
Frick 2016[37]	(+)*	X	(+)*	X	(+)*	X
Luzum 2016[38]	X	X	(+)	X	X	X
Munroe 2016[39]	(+)*	X	X	X	X	X
Reed 2016[40]	(+)*	(+)*	X	X	(+)	X
Surofchy 2016[41]	(+)	X	(+)	X	X	X
Weitzel 2016[42]	(+)*	(+)*	(+)*	X	(+)	(+)
Williams 2016[43]	X	X	X	X	(+)*	X
Remsberg 2017[44]	X	X	X	(+)	(+)*	X
St- Martin 2017[64]	(+)*	X	X	X	X	X
Dodson 2018[45]	(+)*	X	X	X	X	X
Formea 2018[46]	X	(+)*	X	X	X	X
Frick 2018[47]	X	X	(+)*	X	(+)*	X
Gálvez-Peralta 2018[48]	X	X	X	X	(+)*	X
Marcinak 2018[49]	X	X	(+)	(+)	X	(+)
Patel 2018[50]	(+)*	X	X	(+)*	X	X
Quesnelle 2018[51]	X	X	(+)*	(+)*	(+)*	X
Fee-Schroeder 2019[52]	(+)*	X	X	X	X	X
Kisor 2019[53]	X	X	X	X	(+)*	X
Powers 2019[54]	(+)*	X	X	X	(+)*	X
Crown 2020[65]	(+)*	X	(+)	X	(+)*	X
Maxwell 2020[55]	(+)*	X	X	X	(+)*	X
Zhang 2020[56]	(+)*	X	X	X	X	X
Adesta 2021[9]	(+)*	(+)*	X	(+)*	(+)*	X
Arwood 2021[57]	(+)*	X	X	X	(+)*	X
Assem 2021[58]	(+)*	X	X	(+)*	(+)*	(+)*
Bailey 2021[59]	(+)	X	X	(+)	(+)	X
Calabrò 2021[68]	(+)*	X	X	X	(+)	X
Calinski 2021[60]	X	X	X	(+)	(+)	X
Stäuble 2021[69]	(+)*	X	(+)	X	(+)	X
Ward 2021[61]	(+)	X	X	X	X	X
Hajek 2022[62]	X	X	X	(+)*	(+)*	X
Hayashi 2022[66]	(+)*	X	X	X	(+)*	X
Lee 2022[63]	(+)*	X	X	X	(+)*	X

Keys.
CME: continuing medical education, FU: follow up, NR: not reported, PGx: pharmacogenomics, PGT: personal genotyping test, (+): positive outcome without statistically significant changes, (+)*: data reported with statistically significant improvement, (−): data reported with statistically non-significant effect, (−)*: data of negative direction outcome, X: no data reported in numbers or percentages, V: varied results based on the assessment items.

assessments in addition to the post-intervention assessment, and the duration of the follow-up ranged from three weeks to nine months after the educational intervention. (Table 1).

Thirty studies (60%) assessed more than one outcome.[9,23,26–29,34,35,37,40–42,44,47,49–51,54,55,57–60,62,63,65–69] Knowledge was the most frequently measured outcome that was evaluated in 34 studies (68%).[9,21,23,25–31,33–35,37,39–42,45,50,52,54–59,61,63–66,68,69] Correct responses to knowledge questions and program scores were used to evaluate the changes in knowledge between the baseline and after the educational intervention. Six studies out of 50 (12%) evaluated competency outcomes as measured by correct responses to proficiency and pharmacogenomics application questions.[9,23,26,40,42,46]

Seventeen out of 50 studies (34%) evaluated attitudes towards pharmacogenomics, clinical genotyping tests, and the roles of healthcare professionals in the pharmacogenomics.[22–24,27–29,35,37,38,41,42,47,49,51,65,67,69] Ten out of 50 studies (20%) assessed perceptions about pharmacogenomics and its clinical impact.[9,28,44,49–51,58–60,62] The confidence outcome in terms of overall ability, self-efficacy, self-assessed perceptions and competence, perceived confidence, and competence in interpreting and implementing pharmacogenomics information in clinical settings was assessed in 26 (52%) studies.[9,27,32,36,37,40,42–44,47,48,51,53–55,57–60,62,63,65–69]

All studies demonstrated improvements in the evaluated outcomes, both objective and subjective. The improvements in outcomes have a low grade of evidence due to a high risk of bias, as more than half of the studies were rated poor in quality assessment (Table 3).

3.6. The context of pharmacogenomics educational interventions

The educational interventions varied in contents, competency domains covered, delivery method, and duration. Particular studies were presented based on their specific educational interventions and contexts, with an emphasis on their significant effects on outcomes. The presented studies were selected and compared based on common themes such as the interdisciplinary education approach, application of pharmacogenomics in different disciplines, delivery of educational interventions, and rating of quality assessment.

3.6.1. Interdisciplinary education approach (IPE)

The educational context that occurs when two or more professionals learn about, from, and with one another other to enable effective collaboration and enhance health outcomes is known as the interprofessional education (IPE).[70] All three studies[36,51,60] that apply IPE are similar in terms of the included participants. In addition, the educational interventions covered the applied content by integrating patient cases. The mutual competency domain that was covered in all three studies is the domain of pharmacogenetics/pharmacogenomics; through this competency domain, healthcare professionals will be able to interpret and implement genetic data using evidence-based guidelines, such as the Clinical Pharmacogenetics Implementation Consortium (CPIC).[71] IPE has been shown to be valuable and useful to be incorporated into healthcare curricula.[36]

In two studies[36,60], cases associated with the CYP2C19 enzyme were incorporated to present the content of applied aspects. Participants in one of the studies[36] were pharmacy and physician assistant students. This study utilized a laboratory session in which a 1-h presentation was given on the use of buccal swabs to obtain DNA, PCR amplification of target genes, and interpretation of PGx data. After the session, teams of 3–4 pharmacy students and 1–2 physician assistant students were given patient cases. The patient cases, created in collaboration with a pharmacy practice faculty member, provided a clinical setting in which antiplatelet medication would be suggested. Each patient case included the patient's CYP2C19 genotype. After the case discussion, the interprofessional teams made an antiplatelet therapy recommendation based on the CPIC guidelines for the clopidogrel-antiplatelet-CYP2C19 drug-gene interaction.

The second study[60] involved teams of pharmacy and medical students in which pharmacy students were already familiar with PGx and IPE in contrast to medical students. The IPE was 3 h long and consisted of three components. The first component was a PGx-focused patient case discussion using CPIC guidelines, with the aim of giving pharmacy students the opportunity to teach medical students about PGx information and its application. The second component of the IPE was prescription writing and review, and the goal of this component was to mimic real-life situations in which physicians write prescriptions authentically and pharmacists verify the prescriptions for accuracy. The third component was to genotyping students for the drug-metabolizing enzyme single nucleotide polymorphism (SNP) CYP2C19*2. Students benefited from the genotyping experience in terms of knowledge retention and application of their own PGx data.

The third study[51] included telehealth team-based learning activities for 2 h (TBL) in the IPE. The TBL was adopted to overcome the geographical and financial barriers to IPE. Medical students were in their first year of study, while pharmacy students were in their third. Medical students were frequently engaged in TBL at this point in their study program and had limited IPE involvement, contrary to pharmacy students. Neither group was exposed to routine telehealth simulations. The activity exercise was initially delivered in a large group setting using conferencing technology (PolyCom™). A patient case with a sickle cell crisis was discussed. The medical student exercise focused on the pathophysiology and biochemistry of the disease, as well as the design of a treatment plan, while for the pharmacy students, the exercise focused on the analysis of pharmacogenomic data that may aid in anticipating the response to narcotics and recommending the most suitable one. At the end of the activity, small groups reconvened via cross-platform (Google Hangouts™) to educate each other on the case and treatment strategy. The small group activities were intended to be student-led in accordance with the IPE definition.

The IPE studies revealed that participants were able to practically see the role of each profession, collaborate and communicate, work in a team environment, and develop an optimum medication plan for better patient outcomes.

3.6.2. Application of pharmacogenomics in different disciplines

Three studies[21,38,66] were selected to compare and contrast the application of PGx in different disciplines: nursing, medicine, and pharmacy. In all three studies, the educational intervention included all four competency areas and the contents of basics and applied.

Two of the selected studies[21,38] employed similar educational delivery methods in which the in-person mode was used. In one of the studies,[21] a one-day conference was held for nursing staff with psychiatric specialities. The conference focused on the treatment of mental illnesses and the significant benefits of practicing PGx since more genes associated with schizophrenia, bipolar disorder, obsessive-compulsive disorder, and other psychiatric conditions continue to be identified. In addition to the didactic information, a video case study demonstrating the diagnosis and treatment of a young man with schizoaffective disorder was presented to the participants. The case was evaluated and diagnosed based not only on phenotypical (observable) symptoms but also on genetic information. The patient's treatment was tailored to their genetic profile.

In the second study,[38] a 1-h grand rounds presentation was administered to physicians. The presented patient case was based on a real cardiac patient and included two reflective questions: "How would you interpret this genetic data?" and "How would it affect your clinical decision-making?". The patient's medication regimen included clopidogrel, simvastatin, and warfarin. In the clinical setting, the effects of genetic polymorphism on each of the three medications were compared to the effects of other factors already considered in drug therapy, such as

Table 3
Summary of findings of the effectiveness of pharmacogenomics educational intervention.

Effectiveness of Pharmacogenomics Educational Interventions on Healthcare Professionals and Health Professions Students			
Patient or population: Healthcare professionals and students Setting: Any educational context Intervention: Pharmacogenomics educational intervention			
Outcomes	N° of participants (studies) Follow-up	Certainty of the evidence (GRADE)	Impact
Knowledge	(34 observational studies)	⊕⊕⊖⊖ Low[a] due to risk of bias	Knowledge outcome was improved after the educational intervention.
Confidence	(26 observational studies)	⊕⊕⊖⊖ Low[a] due to risk of bias	The confidence outcome was improved post-educational intervention.
Attitudes	(17 observational studies)	⊕⊕⊖⊖ Low[a] due to risk of bias	Attitudes were positively improved following the educational intervention.

GRADE Working Group grades of evidence: High certainty: we are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: we are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect.
Very low certainty: we have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.

[a] High risk of bias as more than half of the studies were rated poor in quality assessment.

drug-drug and food-drug interactions. The clinical recommendations and treatment plans for the patient were based on FDA and CPIC guidelines.

The third study[66] was delivered to any pharmacist with an active pharmacy practice Alberta license in Canada, where virtual venues were employed during COVID-19. The training program included 11 lectures delivered over two days, for 5 h each day, by PGx experts recruited from Canada, the USA, Egypt, and Qatar to incorporate an international PGx approach. The program addressed therapeutic areas in cardiology, psychiatry, and pain management. Six case studies were discussed in large and small groups (known as "breakout rooms" in Zoom) in synchronous sessions and provided for self-study in the asynchronous subgroup. Materials and handouts containing lecture slides and case studies were provided the night before each day. Participants could attend both days live (synchronously, virtually via Zoom), self-study (asynchronously, online using recorded sessions), or a mixture of both options (mixed). One of the cases presented was that of a patient with a cardiac condition who was taking clopidogrel, antihypertensives, and statin. The CPIC guidelines were used to discuss the case and individualize the treatment plan based on the patient's genetic data.

The application of PGx through the case-based learning method mimics real clinical settings, and the knowledge gained from the educational interventions can be applied to the delivery of patient-centered precision therapy; therefore, it improves the confidence of healthcare professionals in practicing PGx.

3.6.3. Hybrid educational delivery methods

The educational settings that employed hybrid learning were presented in some of the included studies. Three studies[9,25,32] were selected and presented based on the features of their educational settings and delivery modalities. The selected studies are similar in terms of the educational intervention content, which covered both the basics and the applied aspects. They also featured an interactive component of a patient case discussion with a diverse set of participants.

Two of the studies[25,32] are comparable in that they both contained self-study learning components and covered all four competency domains. The hybrid educational intervention in one of the studies[25] was administered to multiple healthcare professionals, including nurses and other allied health professionals. This program combined 7 web-based self-education modules with monthly face-to-face lectures provided by genetic experts. The program modules include genetics basics, disease to genes, learning from the family, ethical and social challenges of human genome research, genomics, pharmacogenomics, and case study presentation. This study is good in that it included a variety of participants; although the study did not clearly disclose the rationale for integrating other allied healthcare professionals, it aligned with the concept of the multidisciplinary practice of PGx. In addition, the outcomes were evaluated blindly. All of these characteristics contributed to the quality assessment's fair rating result.

In the other study,[32] pharmacogenomics certificate training was given to a mixed group of pharmacists, pharmacy students, and pharmacy educators. The program was based on pharmacogenomics competency domains and consisted of a 6-week self-study (13 h) and a 1-day (7 h) "live interactive session." The 6-week self-study included subject matter such as basic science (three chapters) and the clinical application of pharmacogenomics (eight chapters on drug-gene interactions such as Clopidogrel-CYP2C19). The day-long, 7-h live program included a review of the competency statements and counselling sessions with seven different simulated patients (primarily pharmacy students). Self-study and a live, interactive component resulted in a greater self-understanding of stated pharmacogenomics competencies. Furthermore, pharmacy students, in the role of simulated patients, gained knowledge.

The third study[9] was delivered to multiple healthcare professionals, including physicians, nurses, pharmacists, and medical and pharmacy students. The educational intervention had two modules: an offline module, followed by a focused group discussion, and then an online module. The offline module was developed using the "5W1H″ approach, detailing the "what, when, why, where, who, and how" of PGx. The training started with "what" PGx is, defining basic terminology and key genetic concepts. Information on "where" healthcare professionals can find relevant PGx information and "how" to navigate through PGx resources, such as CPIC. A patient case was integrated to cover four concepts: "when" PGx testing can be implemented, "why" PGx is essential, "how" healthcare professionals can interpret PGx information, and "who" to apply PGx to in clinical settings. The online module was developed in response to the most frequent requests identified during the focus group discussion, such as making the course more interactive.

Hybrid delivery methods incorporate the benefits of online and offline delivery methods. The online mode provided flexibility and accessibility in program participation, while the offline mode appeared to further strengthen the program by overcoming a limitation established by previous studies that described online-based learning as a "relatively lonely process." Hybrid learning has been shown to be a potential approach for delivering educational intervention in PGx.

3.7. Quality assessment (risk of bias) of included studies

Forty-seven studies (94%) were pre- and post-studies (before and after) without control, of which 32 (68%)[9,21–24,27,28,30–32,34–36,38,39,43,45,46,50–53,55,56,58–62,65,67,68] were assessed as poor and 15 as fair (32%)[25,26,29,37,40–42,44,47–49,54,63,66,69] (Appendix S5**).** Three studies (6%) were controlled intervention studies and were rated as poor[33,57,64] (Appendix S6). Lack of blinding (48/50; 96%),[9,21–24,26–40,42–69] absence of follow-up evaluations (37/50; 74%),[9,22–33,35–39,41,42,44–47,50,51,53,55–60,62,65–67] and unclear sampling methods (100%) were the main criteria that affected the final quality rating. In addition, all the included studies (100%) had educational interventions that were delivered at the group level and did not consider the use of individual-level data to determine effects at the group level.

4. Discussion

This is the first comprehensive review focused on pharmacogenomics and used clearly defined competency domains to evaluate educational interventions. This review demonstrated that the incorporation of pharmacogenomics competency domains into education for healthcare professionals and students improved their knowledge and confidence in practice. In addition, active learning through the integration of clinical cases showed improvements in pharmacogenomics understanding. The delivery method of educational interventions varied between healthcare professionals and students. The review also found that the early inclusion of healthcare students in education would be prudent to prepare them with the necessary skills to practice pharmacogenomics.

The findings of this review indicated that all the included studies had educational interventions that used pharmacogenomics competency domains in their content to assess changes in the outcomes. The pharmacogenomics competency domains describe the four major aspects of practicing pharmacogenomics in clinical settings, beginning with the foundation and progressing to the rules that govern the practice with examples of clinical activities and responsibilities that illustrate their application.[19] They are more extensive than the broader area of genomics, which focuses primarily on the use of genetic data in the disease diagnosis.[6] It was found that integrating AACP pharmacogenomics competency domains improved the learning experiences and outcomes in terms of pharmacogenomics understanding, attitudes, and confidence in clinical application. These competency domains are considered the accredited, compulsory standards for the Professional Program in Pharmacy Leading to the Doctor of Pharmacy Degree by the Accreditation Council for Pharmacy Education (ACPE). Whereas for healthcare providers, pharmacogenomics competencies can be utilized to demonstrate a knowledge base for pharmacogenomics practice requirements.[72]

Therefore, pharmacogenomics competency domains should be incorporated into the design and delivery of educational interventions to improve the practice of pharmacogenomics in clinical settings.

Despite the fact that pharmacogenomics is a significant component of precision therapy that can be applied to all medical conditions, and the US FDA[3] has labelled many medications with PGx-related information in drug leaflets and clear guidelines for implementing pharmacogenomics in clinical settings,[71] the included studies revealed that pharmacogenomics was mostly applied to conditions in cardiology, neurology, psychiatry, oncology, and pain. Therefore, it is essential for healthcare professionals who specialize in these areas to be competent in the clinical application of PGx.

In 86% of the included studies, the case-based method for delivering educational interventions was found to be effective in improving pharmacogenomics knowledge and practice. Integrating clinical cases was considered one of the components of the active learning mode,[73] and it was found that it enhanced the understanding and practice of pharmacogenomics. A similar result was also found in another previous meta-analysis[74] comparing active learning to the traditional mode, which established scientific support for the superiority of active instruction for learning outcomes over the traditional mode. Although the main findings of this meta-analysis[74] were limited to students in the humanities and social sciences, a meta-analysis[75] of the impact of active learning on students in science, engineering, and mathematics also supported the conclusion that active learning is the preferred teaching method. Hence, innovative learning modes, such as the active approach of integrating clinical cases, either using patient or personal genetic data, should be encouraged in order to enhance the practice of pharmacogenomics in real-world clinical settings.

This review demonstrated that the delivery method of educational interventions differed between healthcare professionals and students. In-class mode was the most prevalent delivery method used for student education. While the online mode was the most frequent means used to deliver education to healthcare professionals. The review revealed that in-class was an effective strategy for delivering educational interventions for students with the ability to improve pharmacogenomics knowledge through interactive, participatory, and student engagement. This result aligns with the findings of a large-scale, two-year study[76] of students enrolled in the general education program. This study[76] applied a layout for the classroom that could be changed into multiple settings to assist and accommodate different in-class activities and demonstrated its usefulness in terms of learning experiences and the development of creativity/innovation. While the online mode was found to be more practical and flexible for healthcare professionals, given their limited availability due to demanding work schedules, this finding is consistent with the findings from the scoping review[77] conducted to evaluate the evidence of interprofessional online learning for primary healthcare. The preceding review[77] showed that the online approach could enhance the learning experience, reduce time constraints, overcome physical location barriers, and provide more flexibility. Accordingly, the means of delivering an educational intervention should be tailored in accordance with the targeted audience and their needs.

This review indicated that the majority of the intended participants in pharmacogenomics education were students. The review revealed that educating and training healthcare students in advance during their school years would be prudent to equip them with adequate knowledge and skills to practice pharmacogenomics, unlike other reviews[14–16] that excluded students due to the feasibility and difficulty of comparing students to practicing healthcare professionals. This implication is consistent with the recommendations concluded from published systematic reviews conducted among pharmacists,[11] doctors,[12] and nurses.[13] These reviews[11–13] emphasized the importance of early healthcare student education and the inclusion of pharmacogenomics in school curricula.

One of the most noteworthy findings was that pharmacists and pharmacy students made up the majority of the health professions. This finding may explain the emerging role of pharmacists in the field of pharmacogenomics as drug experts,[78] given the fact that pharmacists lead more than 50% of the Clinical Pharmacogenetics Implementation Consortium implementers' sites.[17] Despite the fact that few studies that applied the IPE were included in the review, they demonstrated significant improvements in pharmacogenomics knowledge, and, notably, pharmacy students were included in all IPE studies. This finding is consistent with the AACP's recommendation that increasing opportunities for IPE integration will significantly contribute to the development of a critical mass of healthcare professionals, particularly pharmacists with pharmacogenomics exposure, thereby driving adoption across practice settings and enhancing the patient care.[79] Therefore, it is crucial that pharmacists and pharmacy students be included in the educational process in this demanding and quickly developing field of pharmacogenomics.

4.1. Strengths and limitations

This is the first systematic review that explicitly focuses on pharmacogenomics, where genetic testing data is utilized to optimize medication safety and efficacy. The review clearly defines the competency domains needed to practice pharmacogenomics in clinical settings. Furthermore, it considers all healthcare professionals and students, regardless of speciality, with no educational context restriction. There are probably pedagogies and evaluations being used that are not actively published but are instead used for internal quality improvement as PGx education becomes standard and mandatory in some universities and health professions. In addition, there might be unpublished studies that were not included, but all relevant databases were searched, and an effort was made to include grey literature to ensure that all available studies were included. As with any systematic review, the review is inherent with the original studies' limitations. A significant concern is that no meta-analysis was conducted due to the heterogeneity of the included studies, not only in outcomes but also in the characteristics of the studies and participants, in addition to the high risk of bias in the included studies. Therefore, good-quality studies that apply double-blinding procedures to a large sample with follow-up evaluations are needed.

5. Conclusion

This review provided evidence of the effectiveness of educational interventions in improving pharmacogenomics knowledge and practice. Incorporating pharmacogenomics competency domains into education and training, as well as integrating patient cases for healthcare professionals and students, significantly enhanced their pharmacogenomics knowledge, attitudes, and confidence in clinical practice. Furthermore, the review identified current gaps in the literature that evaluated the impact of educational intervention on maintaining the level of pharmacogenomics knowledge and competency among healthcare professionals and provided recommendations for future research. Medical and health organizations, academic institutions, and management should consider the significance of proper and adequate pharmacogenomics education and training for their staff and students in order to improve pharmacogenomics practice and keep up with this rapidly evolving field for better health outcomes.

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Availability of data and material

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declaration of competing interest

No potential conflict of interest was reported by the author(s).

Appendix A. Supplementary data

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