Review Article

Bridging the Gap Between Competency-Based Medical Education and Artificial Intelligence Integration in Pharmacology: A Narrative Review

Chandra Mouli Krishna Kotakala[1], Omkar RamaKrishna Puvvala[2], Yashaswini K[3]

[1]Professor, Department of Pharmacology, Maharajah's Institute of Medical Sciences (MIMS), Vizianagaram, Andhra Pradesh, India. [2]Professor, Department of Pathology, AUA College of Medicine, Antigua and Barbuda, Caribbean, West Indies. [3]MBBS Phase III Part II Student, Maharajah's Institute of Medical Sciences (MIMS), Vizianagaram, Andhra Pradesh, India.

Abstract

Background: Competency-based medical education (CBME) and artificial intelligence (AI) are reshaping medical training and clinical practice. Pharmacology is central to this transition because prescribing, pharmacovigilance, drug information retrieval, and individualized therapy are increasingly supported by digital and AI-enabled systems. The objective is to review implementation gaps in CBME-based pharmacology education, identify deficiencies in AI readiness, and propose a practical integration framework for undergraduate pharmacology training. **Material and Methods:** A narrative review was conducted using literature from PubMed, Scopus, and Google Scholar. Publications addressing CBME, AI in medical education, clinical decision support, pharmacovigilance, rational prescribing, and pharmacology teaching were reviewed. Evidence was synthesized thematically to identify curricular, faculty, assessment, technology, and governance-related gaps. **Results:** Important gaps were identified in curricular time allocation, faculty preparedness, assessment alignment, self-directed learning, and institutional infrastructure. AI-related deficiencies included lack of explicit competency standards, limited exposure to clinical decision support systems, insufficient training in AI-assisted pharmacovigilance, weak appraisal of generative AI outputs, and inadequate ethical preparation. **Conclusion:** AI integration in CBME pharmacology should be competency-based rather than tool-based. A five-component model involving curriculum redesign, faculty development, technology integration, assessment reform, and continuous evaluation may help institutions prepare graduates for safe, ethical, and evidence-informed prescribing in AI-augmented healthcare environments.

Keywords: Artificial Intelligence; Clinical Decision Support Systems; Competency-Based Education; Pharmacology; Pharmacovigilance.

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Introduction

Medical education is moving away from time-bound training toward the observable demonstration of competence. Competency-based medical education (CBME) defines learning outcomes, links teaching to measurable professional activities, and makes progression dependent on performance rather than duration alone.[1] In India, the National Medical Commission introduced the competency-based undergraduate curriculum in 2019, creating a uniform framework for the Indian Medical Graduate across preclinical, paraclinical, and clinical disciplines.[2]

At the same time, artificial intelligence (AI) is becoming part of routine healthcare. Drug discovery, pharmacokinetic prediction, clinical decision support, pharmacovigilance, and precision therapeutics now use machine learning, natural language processing, and large-scale data analytics.[3,4] Pharmacology education therefore faces a dual obligation: it must deliver conventional competencies in rational prescribing and drug safety while also preparing students to interpret, question, and apply AI-supported recommendations.

The convergence of CBME and AI remains insufficiently developed. Recent reviews show that AI applications in competency-based medical programs are increasing, but their integration is fragmented and lacks common standards.[5] This narrative review examines gaps in CBME implementation in pharmacology, maps AI-readiness deficits, and proposes a structured framework for AI-integrated pharmacology education.

Materials and Methods

A narrative review design was selected because the topic includes educational theory, policy documents, empirical studies, clinical informatics, pharmacovigilance, and ethical governance. Literature was searched in PubMed, Scopus, and Google Scholar for publications from January 2010 to April 2025. Earlier seminal sources were retained when they provided foundational concepts for CBME, self-directed learning, or pharmacovigilance methods.

Search terms included combinations of: competency-based medical education, CBME, outcome-based education,

Address for correspondence: Dr. Chandra Mouli Krishna Kotakala, Professor, Department of Pharmacology, Maharajah's Institute of Medical Sciences (MIMS), Vizianagaram, Andhra Pradesh, India.
E-mail: drchandramoulikrishna@gmail.com

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competency assessment, artificial intelligence, machine learning, clinical decision support, AI in medical education, pharmacology education, rational prescribing, and pharmacovigilance training. English full-text articles, reviews, policy documents, and relevant books were considered. Conference abstracts without accessible full text, nonmedical education papers, and AI papers without an educational or pharmacology link were excluded. The inclusion and exclusion criteria are summarized in [Table 1].

Table 1: Inclusion and Exclusion Criteria

Criterion	Inclusion	Exclusion
Publication type	Peer-reviewed articles, systematic reviews, narrative reviews, empirical studies, policy documents, and relevant books	Conference abstracts only, non-peer-reviewed sources without academic relevance, and inaccessible full texts
Language	English	Non-English publications
Time frame	January 2010 to April 2025; earlier seminal sources retained for theoretical or historical context	Publications before 2010 without foundational relevance
Focus	CBME implementation, AI in medical/pharmacology education, pharmacology teaching, rational prescribing, pharmacovigilance, and competency assessment	Nonmedical education papers and AI applications without educational or pharmacology relevance
Full text	Available	Unavailable

Data were synthesized thematically. Retrieved sources were reviewed for recurring issues related to curriculum design, faculty development, assessment methods, educational infrastructure, AI literacy, ethical governance, and discipline-specific pharmacology requirements.

CBME in Pharmacology: Current Educational Context

CBME requires pharmacology teaching to move beyond factual recall and toward demonstrable competence. In pharmacology, relevant outcomes include rational prescription writing, application of pharmacokinetic and pharmacodynamic principles, identification and reporting of adverse drug reactions, patient counseling, evidence-informed therapeutic reasoning, and safe medication selection for special populations.[6,7]

Table 2: Assessment Alignment in CBME-Based Pharmacology Education

Competency domain	Traditional assessment	CBME-aligned assessment	Current implementation status
Pharmacological knowledge	MCQs and written examinations	Integrated case-based questions and therapeutic reasoning tasks	Partially implemented
Prescribing skills	Written prescription questions	OSCE stations, simulated prescription writing, and prescription audit	Limited implementation
ADR recognition and reporting	Theory questions	ADR case analysis, causality assessment, and reporting exercises	Rarely implemented
Therapeutic reasoning	Short-answer questions and viva voce	Clinical reasoning assessments, case-based viva, and problem-solving exercises	Variable across institutions
Drug counseling communication	Not formally assessed	Standardized patient encounter and counseling checklist	Rarely implemented

Teaching strategies used under CBME include small group discussion, problem-based learning, self-directed learning, integrated teaching, simulation, and case-based learning. These methods are intended to connect drug knowledge with patient care, clinical reasoning, and professional communication. However, implementation has varied considerably across institutions. A faculty-based study from pharmacology departments in India reported concerns regarding reduced teaching time, increased workload, and difficulty in conducting learner-centered sessions under the compressed CBME schedule.[8]

The challenge is not only the number of teaching hours. It is also the shift in educational culture. Faculty members accustomed to lecture-based delivery must now facilitate active learning, provide formative feedback, observe student performance, and document competency attainment. Without sustained support, CBME risks becoming a change in terminology rather than a change in training quality.

Key Gaps in CBME Implementation

The first major gap is curricular compression. Pharmacology has a wide syllabus, yet the implementation of CBME reduced the duration available for second professional MBBS teaching in many settings. When content volume remains largely unchanged, faculty tend to prioritize syllabus completion over application-based learning.[8] This weakens the central promise of CBME.

Table 3: Pharmacology-Specific Gaps in CBME-AI Integration

Gap area	Current state	Desired state	Key barrier
AI-assisted prescribing	Minimal or no supervised exposure during training	Competency in using and critically appraising clinical decision support outputs	Curricular gaps and limited access to platforms
AI in pharmacovigilance	Mainly theoretical ADR teaching	Hands-on understanding of signal detection and AI-assisted safety workflows	Limited databases and faculty expertise
Drug information retrieval	Manual literature searching predominates	AI-augmented evidence synthesis with verification of sources	Tool access and training deficits
Personalized dosing	Formula-based calculations	Understanding of AI-based and pharmacogenomic dosing support	Curricular space and knowledge gaps

Simulation-based learning	Limited and inconsistent use	AI-enhanced virtual patient encounters and prescribing scenarios	Cost, infrastructure, and institutional capacity

The second gap is incomplete integration. Horizontal and vertical integration should connect pharmacology with physiology, pathology, microbiology, community medicine, and clinical disciplines.[9] In practice, integrated teaching may become a timetable exercise without meaningful case linkage. Students may learn antimicrobial mechanisms, microbial resistance, and clinical infection management in disconnected sessions rather than as a single therapeutic problem.

The third gap is assessment misalignment. Traditional written examinations and multiple-choice questions remain dominant, whereas CBME requires direct assessment of performance, reasoning, and communication.[10] Objective structured clinical examinations, prescription-writing stations, simulated counseling, adverse drug reaction reporting exercises, and workplace-based assessments are still inconsistently used in pharmacology. [Table 2] outlines this mismatch across core competency domains.

The fourth gap relates to faculty development. CBME requires teachers who can design competencies, facilitate small-group learning, assess observed behavior, and provide constructive feedbac.[11] Short orientation workshops alone may not create this capability. Self-directed learning also remains uneven; when objectives, resources, and feedback are unclear, SDL becomes unsupervised reading rather than guided professional development.[12] Finally, infrastructure disparities restrict simulation, digital platforms, skills laboratories, and supervised technology-based learning, particularly in resource-constrained institutions.[13]

Artificial Intelligence in Pharmacology Practice and Education

AI is already relevant to the professional work for which pharmacology prepares students. In drug discovery, machine-learning models support target identification, molecular screening, toxicity prediction, and pharmacokinetic optimization.[14] In clinical care, AI-enabled clinical decision support systems assist with drug interactions, renal dose adjustment, contraindication alerts, and therapeutic alternatives.[15] In pharmacovigilance, machine learning and natural language processing help classify adverse event reports, identify duplicate reports, prioritize signals, and manage large safety datasets.[16] In precision medicine, AI can integrate genetic, biochemical, demographic, and clinical data to predict drug response and individualize therapy.[17]

AI is also entering medical education. Adaptive learning systems, virtual patients, AI-generated assessment items, automated feedback, and intelligent tutoring tools are now being studied in several disciplines, including pharmacology and therapeutics.[18] These methods may support personalization of learning, improve formative feedback, and help students practice decision-making in low-risk environments.

Nevertheless, AI should not be introduced as a technological novelty alone. Pharmacology students must learn when to trust, verify, override, or reject AI-generated recommendations. This requires basic AI literacy, understanding of training data and bias, awareness of uncertainty, and the ability to integrate algorithmic output with clinical context and patient values.

Gaps in AI Integration Within Medical Education

The most important AI-related gap is the absence of explicit competency standards. Many graduates will enter clinical settings where digital prescribing tools and AI-enabled decision support are present, yet they may not have been taught how such tools are built, validated, regulated, or monitored.[19,20] This produces operational familiarity without critical competence.

Faculty AI literacy is another limitation. Medical teachers may be confident in their disciplinary content but less confident in explaining datasets, model validation, algorithmic bias, explainability, or performance drift.[21] Without faculty capacity, AI integration may remain superficial or be outsourced to technology vendors, weakening curricular ownership.

Ethical and governance issues are equally important. AI systems raise concerns about privacy, accountability, bias, transparency, equitable access, and responsibility for clinical decisions.[22] Students also increasingly use generative AI for learning and writing, but many have limited skill in verifying outputs, identifying fabricated references, or recognizing plausible but inaccurate explanations.[23] Infrastructure and equity barriers add further complexity, as reliable connectivity, licensed software, technical support, and digital learning environments are not distributed evenly across institutions.[24]

Pharmacology-Specific CBME-AI Gaps

Pharmacology is particularly exposed to the CBME-AI gap because drug therapy is both data-intensive and risk-sensitive. Current curricula commonly teach drug mechanisms, indications, adverse effects, and interactions, but they rarely provide supervised exposure to clinical decision support systems. Students may therefore enter internship without knowing how to interpret interaction alerts, dose-adjustment suggestions, or AI-generated therapeutic alternatives.

Pharmacovigilance training also requires modernization. Students are usually taught how to identify and report adverse drug reactions, but not how contemporary signal detection systems process large datasets, free-text reports, or real-world evidence. [Table 3] summarizes pharmacology-specific gaps, desired competencies, and major barriers.

A deeper competency gap involves therapeutic reasoning in AI-augmented environments. Future physicians will encounter situations in which an algorithmic recommendation conflicts with clinical judgment, patient preference, comorbidity burden, affordability, or local formulary constraints. CBME-based pharmacology must train learners to combine algorithmic support with humane, accountable, patient-centered decision-making.

Proposed CBME-AI Integration Framework

A useful framework for AI integration in pharmacology should be competency-based rather than tool-based. The aim is not to train students on one software platform but to develop transferable capabilities for safe, critical, and ethical use of AI-supported therapeutic information. The proposed model has five connected components and is illustrated in [Figure 1].

Component 1 is curriculum redesign. AI competencies should be mapped against existing pharmacology outcomes. For example, rational prescribing can include appraisal of AI-generated prescribing advice; pharmacovigilance can include understanding AI-assisted signal detection; and drug information skills can include evaluation of AI-generated evidence summaries. This approach avoids creating an isolated AI module and instead embeds AI literacy into core pharmacology learning.

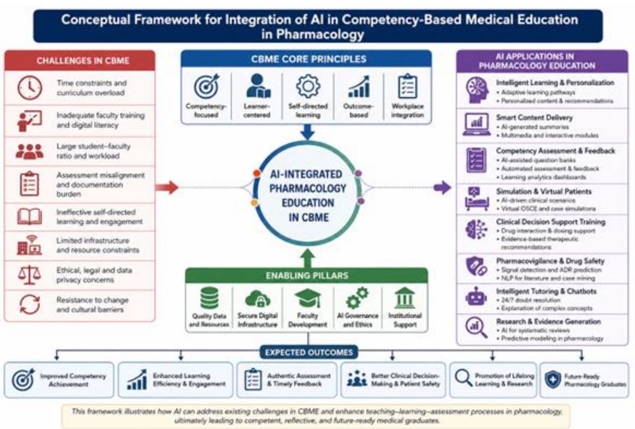

Figure 1: Proposed CBME-AI Integration Framework for Pharmacology Education. The framework links curriculum redesign, faculty development, technology integration, assessment reform, and continuous quality evaluation to support AI-ready, competency-grounded pharmacology graduates.

Component 2 is faculty development. Training should address fundamentals of AI, educational uses of AI, assessment of AI-related competencies, and ethical oversight. Faculty development must be longitudinal, practice-oriented, and supported by institutional leadership rather than delivered as a single workshop.

Component 3 is technology integration. Institutions need access to supervised clinical decision support demonstrations, simulation-based prescribing exercises, pharmacovigilance training datasets, and adaptive learning platforms. Low-cost or shared institutional models may be needed to prevent digital inequity.

Component 4 is assessment reform. AI-related competencies can be assessed through case-based written questions, objective structured clinical examination stations, simulated prescription tasks, reflective assignments, and workplace-based observations. Students should be assessed not only on whether they use AI but also on whether they verify, contextualize, and ethically apply its output.

Component 5 is continuous evaluation. Institutions should review student performance, faculty feedback, graduate readiness, employer perceptions, and patient-safety-related learning outcomes. International bodies have begun recognizing digital and AI-related competencies in graduate outcomes, indicating that regulatory alignment will become increasingly important [25,26]. Broader medical literature further highlights the need for explainability, bias detection, governance, biomedical informatics capacity, and transparent communication of model performance when AI is used in healthcare.[27-40]

Implications for Pharmacology Education

Integrating AI into CBME pharmacology has practical implications. Students who learn to evaluate clinical decision support can use alerts and recommendations as aids to reasoning rather than substitutes for it. Training in AI-augmented pharmacovigilance may improve understanding of adverse drug reaction reporting, signal prioritization, and drug safety monitoring. Exposure to precision therapeutics can prepare graduates for individualized dosing and pharmacogenomic decision-making.

The educational benefit is also longitudinal. AI tools will change rapidly; therefore, students require durable habits of critical appraisal, evidence verification, and ethical reflection. A graduate who can ask how a model was trained, whether it is valid for a patient population, what its limitations are, and who remains accountable for the final decision will be better prepared for modern therapeutic practice.

Limitations and Future Research

This review has limitations. The narrative design allows integration of diverse evidence but does not provide formal risk-of-bias assessment. The search was limited to English-language sources, and publication bias may favor successful reports of CBME or AI implementation. Institutional differences in resources, governance, and faculty preparedness may limit generalizability. Because AI is evolving quickly, some tools and policies may change after the search period.

Future research should develop and validate pharmacology-specific AI competencies, test AI-integrated teaching modules, evaluate assessment tools for AI-supported prescribing, and examine the effect of AI literacy training on prescribing safety and pharmacovigilance behavior. Implementation research is especially needed in low- and middle-resource medical colleges.

Conclusion

CBME and AI are reshaping the expectations of pharmacology education. Current pharmacology training faces gaps in time allocation, integration, assessment, faculty preparation, and infrastructure. AI introduces additional requirements related to clinical decision support, pharmacovigilance, precision therapy, ethics, and critical appraisal.

The proposed five-component framework - curriculum redesign, faculty development, technology integration, assessment reform, and continuous evaluation - offers a practical pathway for aligning pharmacology education with AI-augmented healthcare. The goal is not technological dependence, but safer, more reflective, and more competent therapeutic decision-making.

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Conflicts of interest

There are no conflicts of interest.

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