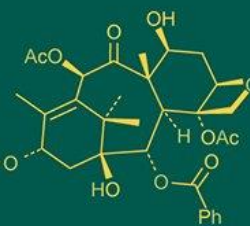
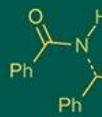


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The evolving role of artificial intelligence and emerging technologies in pharmacy practice: A comprehensive review

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Abstract

Pharmacy Education 5.0 represents a transformative paradigm integrating artificial intelligence (AI) and emerging technologies into contemporary pharmacy education and healthcare practice. This article examines the evolution of pharmacy education toward a technology-enabled, interdisciplinary, and patient-centered learning framework. AI-driven personalized learning, data-centric insights, telepharmacy, and blockchain technology are explored as key components of this transformation. These technologies can enhance educational outcomes, support evidence-based decision-making, improve accessibility to pharmaceutical care, and strengthen medication safety. Incorporating such innovations into pharmacy curricula can equip future pharmacists with essential digital, analytical, and collaborative competencies. Pharmacy Education 5.0 therefore has significant potential to bridge technological advancement with evolving healthcare needs while promoting adaptive and lifelong learning. Successful implementation will require responsible technology adoption, faculty development, ethical considerations, and continuous curriculum innovation to ensure high-quality, patient-focused healthcare delivery.

Keywords: Pharmacy education 5.0, artificial intelligence, emerging technologies, personalized learning, Telepharmacy, Blockchain technology, digital healthcare

Introduction

The healthcare landscape is undergoing a profound transformation driven by rapid advances in digital technologies, artificial intelligence (AI), machine learning, big data analytics, and increasing demand for personalized and patient-centred healthcare [1-7]. AI and machine-learning technologies are increasingly being applied across healthcare, including clinical decision-making, biomedical research, drug discovery, medication management, and patient care [8-12]. These developments are progressively expanding the scope of contemporary pharmacy practice and creating a need for pharmacists with enhanced digital, analytical, clinical, and interdisciplinary competencies [13-15].

Within this evolving environment, pharmacy education must adapt to prepare graduates for increasingly technology-enabled healthcare systems. Recent evidence indicates growing integration of AI and digital health technologies into pharmacy education, with applications spanning personalized learning, assessment, clinical reasoning, digital literacy, and technology-enabled patient care [1-4, 16]. The concept of Pharmacy Education 5.0 can therefore be considered an emerging educational framework that integrates AI, machine learning, digital health, data analytics, robotics, and other emerging technologies into pharmaceutical education and practice [1, 16-18]. This framework emphasizes technology-enabled learning while maintaining human-centred care, professional judgement, ethical responsibility, and interdisciplinary collaboration [19-21].

The Evolution of Pharmacy Education

Traditionally, pharmacy education has focused on foundational knowledge in pharmacology, pharmaceutical sciences, medicinal chemistry, therapeutics, and patient care. However, the increasing complexity of healthcare delivery and the emergence of digital technologies require pharmacists to develop broader competencies beyond conventional pharmaceutical knowledge [13, 16, 22].

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Contemporary pharmacy education is therefore moving toward an integrated model that incorporates digital literacy, data interpretation, critical thinking, clinical reasoning, communication, and interdisciplinary collaboration [1, 5, 16].

The transition toward Pharmacy Education 5.0 represents a conceptual shift from predominantly knowledge-centred learning toward a more integrated and technology-enabled educational approach. AI and digital health technologies can support adaptive learning, simulation-based education, data-driven decision-making, and the development of technology-related competencies among pharmacy students [1, 3, 5, 18]. Recent evidence from pharmacy education demonstrates increasing student familiarity with AI and considerable interest in incorporating AI-related knowledge and skills into pharmacy curricula [2, 3, 16]. Consequently, pharmacy education should combine technological proficiency with scientific reasoning, professional judgement, ethical awareness, and patient-centred practice [19-21].

The Role of Artificial Intelligence in Pharmacy Education

Artificial intelligence is at the forefront of the digital transformation of healthcare and pharmacy practice. AI systems can process large and complex datasets, identify patterns, support prediction, and generate information that can assist healthcare professionals in clinical and research settings [6-12]. Within pharmacy practice, AI has potential applications in medication management, clinical decision support, drug-interaction assessment, adverse-event prediction, workflow optimization, and personalized therapeutic decision-making [13, 14, 23].

In pharmacy education, AI can be applied across several domains:

Personalized Learning

AI-powered educational platforms can adapt learning materials to students' individual learning needs, performance patterns, and educational progress, thereby supporting personalized and self-directed learning [1, 3, 16, 24]. Adaptive learning approaches may facilitate the acquisition of complex pharmaceutical concepts by providing individualized educational content, feedback, and learning pathways [18, 24]. Generative AI tools such as large language models can further support interactive learning, question answering, content generation, and educational dialogue, although their use requires appropriate verification and faculty guidance [17, 19, 20].

Data-Driven Insights

AI and machine-learning technologies can facilitate the analysis of large datasets derived from medication utilization, patient outcomes, clinical records, and population health [6, 8, 11, 13]. Exposure to data-driven approaches may help pharmacy students develop skills in data interpretation, evidence-based decision-making, and identification of clinically relevant patterns [1, 16]. Integrating these competencies into pharmacy curricula may also improve students' preparedness for data-intensive healthcare environments and emerging pharmacy-informatics roles [5, 16, 22].

Telepharmacy

Telepharmacy has emerged as an important component of digitally enabled pharmaceutical care, particularly for

patients living in rural, remote, and underserved settings [25-27]. Telepharmacy enables pharmacists to provide remote medication counselling, medication-management services, patient education, prescription-related support, and other pharmaceutical care activities through telecommunications technologies [25, 26]. Evidence suggests that telepharmacy can improve access to pharmaceutical services, although the quality and effectiveness of individual telepharmacy models may vary and require appropriate implementation and evaluation [26, 27].

Within Pharmacy Education 5.0, students should therefore be introduced to telepharmacy technologies and trained in the competencies required for safe and effective virtual patient interactions [5, 16, 27]. Such training should encompass digital communication, patient privacy, clinical assessment, documentation, technology use, and professional responsibility within virtual care environments [5, 21, 27].

Blockchain Technology

Blockchain technology is a distributed digital-record system with potential applications in healthcare data management, pharmaceutical supply chains, and product traceability [28, 29]. In pharmaceutical supply chains, blockchain-based approaches may enhance transparency, traceability, data integrity, and verification of transactions across multiple stakeholders [29, 30]. Such applications are particularly relevant to pharmaceutical supply-chain management and efforts to strengthen the traceability of medicines and reduce vulnerabilities associated with counterfeit products [30].

Within Pharmacy Education 5.0, introducing students to the principles and potential applications of blockchain technology may strengthen their understanding of emerging digital pharmaceutical systems [28, 29]. Knowledge of blockchain-enabled workflows may help future pharmacists understand pharmaceutical traceability, supply-chain integrity, data security, and emerging approaches to medication authentication. However, blockchain implementation remains associated with technical, regulatory, interoperability, privacy, and scalability challenges, and its applications should therefore be considered critically rather than as universally established solutions [28, 29].

Conclusion

Pharmacy Education 5.0 represents an emerging paradigm for integrating artificial intelligence, machine learning, digital health, data analytics, telepharmacy, blockchain, and other emerging technologies into pharmaceutical education and practice [1, 5, 16-18]. The integration of these technologies can enhance learning, strengthen digital and analytical competencies, and prepare future pharmacists for increasingly complex and technology-enabled healthcare environments [1-5, 16].

Successful implementation, however, requires more than technological adoption. Pharmacy curricula should incorporate structured AI and digital-health education, critical appraisal of technology-generated information, data literacy, ethical and regulatory principles, interdisciplinary collaboration, and appropriate faculty development [1, 5, 16, 19-21]. Particular attention should also be given to data privacy, algorithmic bias, transparency, digital inequities, and the risk of excessive dependence on automated systems [9, 19, 21]. Ultimately, Pharmacy Education 5.0 should complement rather than replace the human and professional dimensions

of pharmacy practice. By integrating emerging technologies with scientific knowledge, clinical reasoning, ethical responsibility, and patient-centred care, pharmacy education can prepare graduates to contribute effectively to a rapidly evolving healthcare ecosystem while maintaining professional accountability and patient safety^[13, 19-21].

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