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THE REVOLUTIONARY IMPACT OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING ON CLINICAL PHARMACY PRACTICE

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ABSTRACT

Pharmaceutical practice is being transformed in revolutionary ways through advances in artificial intelligence (AI) technology, particularly by assisting with drug discovery; making recommendations about the use of drugs based on patient characteristics; and improving the safety of medications through adherence monitoring. Pharmacists are better able to make informed decisions about drug interactions and other aspects of medication management with the support of AI tools that provide insight into patient-specific data. This review discusses how AI is utilized for clinical decision-making, improving medication safety, and supporting precision medicine, while also identifying barriers to successful implementation of AI in pharmacy practice, including concerns with privacy of patient data, algorithmic bias, and integration into the workflow of pharmacy practice. There is a need for all healthcare providers to be ethically vigilant and work together in order to successfully integrate AI into pharmacy practice, which has the potential to enhance the delivery of pharmaceutical care and improve patient outcomes.

KEYWORDS: Artificial intelligence; machine learning; clinical pharmacy practice; medication management; adherence monitoring; pharmacovigilance.

1. INTRODUCTION

AI and ML are revolutionizing how clinical pharmacy approaches the use of drugs for patients. These tools increase the level of accuracy, speed, and individualization of patient care through the use of greater amounts of patient-specific characteristics to detect patterns from past experience [1]. Historically, clinical pharmacists have had to rely on non-scientific guidelines and clinical expertise when determining what drug(s) to use with patients to provide the best outcome possible. However, as medicines and diseases continue to evolve into more complicated forms, the way clinical pharmacists apply clinical judgement has struggled to keep pace [2].

The introduction of AI and ML has addressed this problem by providing tools that allow for the evaluation of real-time data to expedite the identification of medication errors, adverse drug reactions, and treatment failure, among other issues. The application of AI and ML to clinical pharmacy has extended their use to drug therapy management, drug safety monitoring (pharmacovigilance), clinical decision support systems, and hospital operational processes [3]. These technological advancements allow pharmacists not only to anticipate how patients will respond to medications, but also to design individualized treatment plans based on patient-specific clinical and genetic data, alongside improved methods of monitoring therapeutic response [4].

The use of AI in pharmacy practice is therefore highly significant. With AI technology, pharmacists will be able to provide safer, more accurate, evidence-based care, and these technologies will play an important role in educating future pharmacists, shaping new pharmacy policy frameworks, and improving patient outcomes [5]. The traditional roles of pharmacists with respect to medication safety and adherence to clinical guidelines will also evolve, as AI assists in managing the increasingly complex nature of pharmacotherapy. AI and ML will not eliminate the role of the pharmacist, but rather will support pharmacists, enabling a shift from reactive care toward proactive and predictive services [6].

2. MATERIALS AND METHODS

This article is a narrative literature review synthesizing current evidence on the applications of artificial intelligence (AI) and machine learning (ML) in clinical pharmacy practice. A literature search was conducted across electronic databases, including PubMed/MEDLINE, ScienceDirect, Scopus, and Google Scholar, supplemented by manual screening of the reference lists of relevant articles, to identify English-language publications dated between 2012 and 2025. Search terms were used in various combinations and included "artificial intelligence," "machine learning," "clinical pharmacy," "clinical decision support systems," "adverse drug reactions," "drug–drug interactions," "pharmacovigilance," "precision medicine," "medication safety," and "pharmacy education."

Original research articles, systematic and narrative reviews, scoping reviews, and relevant policy or perspective papers addressing AI/ML applications in drug therapy optimization, medication safety, drug discovery, clinical decision support, and pharmacy education were considered for inclusion. Sources unrelated to clinical pharmacy or healthcare applications of AI/ML, non-English-language publications, and material without an accessible abstract or full text were excluded. A total of 37 sources meeting these criteria were retained, synthesized thematically, and are cited throughout this review.

3. RESULTS AND DISCUSSION

3.1 Need for AI/ML Integration in Clinical Pharmacy Practice

In the era of the "data tsunami"—the vast amount of intricately complex patient health record data now available digitally—clinical pharmacy must embrace AI and ML. Because traditional methods of drug management have not kept pace with this influx of data, clinical pharmacy practitioners need to leverage these technologies as part of the transition from 'reactive' to 'precision' medicine [7]. Using advanced analytical techniques, AI and ML can analyse large amounts of data, such as laboratory results, pharmacogenetic information, and the complete history of a patient's interactions with healthcare systems, to accurately predict how an individual will metabolize a drug and to determine the optimal dose—an especially important factor for patients taking high-risk medications. Employing AI/ML in clinical pharmacy practice can prevent many drug-related errors and significantly reduce provider fatigue by reducing the volume of data presented and focusing attention on the clinical issues of highest priority [8].

By filtering out irrelevant and extraneous information, AI streamlines a pharmacist's daily practice, enhancing productivity while promoting patient safety. By automating lower-level, non-clinical tasks such as data verification and administrative work, AI systems also enable pharmacists to invest more time in higher-level responsibilities such as patient counselling and complex clinical decision-making [9]. The ability to identify drug interactions, dosing errors, and drug contraindications more accurately than traditional methods is among the key benefits AI and ML bring to clinical pharmacy practice in terms of medication safety. Using AI to power clinical decision support systems ultimately leads to improved identification of adverse medication effects and enhanced quality of patient care [10].

AI and ML also support the evolution of personalised medicine, using genetic profiles and treatment histories to generate customised therapeutic recommendations and optimal dosage schedules [11]. The automation of routine tasks, such as prescription screening and inventory management, has streamlined pharmacy workflows, allowing professionals to spend more time on patient care and collaboration with other healthcare professionals. The integration of AI and ML in healthcare is therefore critical to improving the effectiveness, accuracy, and efficiency of patient-centred care as the healthcare ecosystem continues to evolve [12].

3.2 Role of AI/ML in Drug Therapy Optimization

The application of AI and ML enhances pharmacology by providing methods for modelling pharmacokinetics, optimizing dose regimens, and, through predictive modelling and molecular simulations, speeding up lead-compound selection. Methods used to model drugs and their actions include quantitative structure–activity relationship (QSAR) analysis and AI-assisted rational drug design [13]. These advances have increased therapeutic effectiveness, safety, and bioavailability while decreasing drug development time and cost. AI enables the analysis of genetic and clinical data to identify therapies most appropriate for individual patients and to select molecules with the best therapeutic index, revolutionizing drug therapy through the accurate prediction of how medications will perform based on extensive clinical data [14].

With AI-powered Clinical Decision Support Systems (CDSS), healthcare professionals receive recommendations for suitable treatment options, alerts about potential drug interactions, and guidance on dose adjustment based on a patient's clinical status. The ability of CDSS to provide real-time recommendations allows clinicians to make timely therapeutic decisions using data that was not previously accessible [15]. Furthermore, ML algorithms can identify and track trends in medication use and clinical outcomes that were previously undetectable or difficult to monitor. AI-integrated CDSS also address "alert fatigue" by focusing only on alerts relevant to specific patients, helping providers recognize early signs of adverse drug events or the need for proactive monitoring of complex drug dosing or therapy [16]. AI can synthesize complex data to help address polypharmacy, ensuring consistent, high-quality therapeutic approaches across diverse patient populations.

3.3 AI-Based Prediction of Adverse Drug Reactions (ADRs)

The healthcare sector increasingly utilizes AI and ML to predict the occurrence of ADRs, which can have an inadvertent impact on patients after taking specific medications. Conventional methods for detecting ADRs typically rely on spontaneous reporting and post-marketing surveillance [17], which are time-consuming and often lack sufficient data to be fully effective. By leveraging the connectivity between diverse data sources, including drug structural information, electronic health records (EHRs), and pharmacogenomic information, AI/ML models can extract patterns relating to ADR occurrence [18]. This allows for early identification of potential hazards associated with drug response and enables clinicians to rapidly evaluate or amend treatment options when necessary.

AI/ML models for predicting ADRs support patient outcomes by providing tailored safety assessments through the identification of high-risk drug–reaction pairs. Predictive models that utilize algorithmic techniques such as deep learning, random forests, and gradient boosting have demonstrated superior predictive capability over traditional pharmacovigilance techniques, enabling more precise prediction of ADR-associated risk [19]. The key methodologies underlying AI-based ADR prediction include the following:

1. Large-scale data analysis: AI can process large volumes of genomic data and electronic health records to identify relationships between specific drugs and potentially harmful effects. By analysing drug structure (commonly via SMILES codes), deep learning methods can forecast risks of hepatotoxicity, cardiotoxicity, and other forms of toxicity [20]. Predictive accuracy for specific drug reactions is typically reported above 90% when comparing a new drug's structure with that of known harmful compounds.
2. Machine learning techniques: Prediction of specific drug reactions has been achieved with varying degrees of success using algorithms such as Random Forest, Support Vector Machines (SVM), and gradient boosting methods [21].
3. Deep learning models: More complex models have been developed to identify patterns among drugs, their associated genes, and potential ADRs, making it possible to use convolutional neural networks (CNNs) and integrated systems such as DGANet to predict ADRs [22].
4. Improving pharmacovigilance: AI substantially improves pharmacovigilance processes through real-time ADR monitoring, automated analysis of reports, and accelerated clinical risk evaluation [23].

3.4 AI/ML in Drug Interaction Detection and Prevention

The use of AI and ML for identifying drug–drug interactions (DDIs) hold tremendous potential for the future of drug safety monitoring and the reduction of ADRs. DDIs can reduce medication efficacy or increase toxicity, particularly among elderly patients on multiple medications [24]. Retrospective methods of DDI detection commonly miss rare interactions, whereas AI/ML approaches—including supervised, semi-supervised, graph-based, and deep learning methods—achieve high predictive accuracy for detecting DDIs.

AI systems interfaced with EHRs enable real-time DDI screening, reducing the risk of ADRs and creating new opportunities for individualized therapy; however, challenges such as data imbalance and regulatory considerations remain before such systems can be used widely [25]. Hybrid systems and explainable AI are expected to see increased use in the coming years, further reducing ADR rates and demonstrating the potential of AI/ML to transform drug management. These developments have fundamentally shaped DDI prediction, particularly in complex polypharmacy situations. Model-Informed Precision Dosing (MIPD) is one of the first practical applications of these integration tools, enhancing dosing safety and precision by coupling patient-specific information with appropriate clinical models [26].

3.5 AI in Medication Error Reduction and Patient Safety

Healthcare is increasingly using AI to improve drug dosing management and medication safety. AI allows providers to select dosages based on multiple patient-specific factors, including genetics and personal history, resulting in better outcomes through individualized treatment [2]. By alerting clinicians to potential errors and notifying them of medication changes, the Clinical Decision Support System (CDSS) continues to improve in accuracy through accumulated experience and ongoing analysis of new data. CDSS performance is further enhanced by data collected from wearables and mobile devices, allowing instant adjustment of treatment plans and providing additional information to support dosing decisions, such as for anticoagulants [25].

Many medication errors—primarily attributable to mistakes made by healthcare providers during prescribing, dispensing, and administration—can be prevented through AI-enabled systems. CDSS allows providers to identify prescription errors, allergies, drug interactions, and incorrect dosing more accurately than traditional methods. By generating real-time alerts, AI solutions allow providers to manage the medication process more efficiently [16]. Improved alert systems that indicate severity levels also help reduce clinicians' experience of alert fatigue and optimize workflow.

AI-powered machine learning algorithms that analyse workflows enable physicians to identify mismatched medication vials in real time, improving the accuracy of medication verification [27]. Predictive analytics can further tailor medication doses to each patient's unique physiological profile, reducing the likelihood of dosing errors and lowering overall medication error rates.

3.6 AI in Research, Drug Discovery, and Development

Drug discovery is a complex and prolonged process, typically spanning approximately 12 years and costing approximately $2.6 billion to reach FDA approval. It remains a challenging enterprise, with high attrition rates among candidate compounds, particularly for chronic conditions. The introduction of AI has transformed drug development by providing sophisticated computational capabilities that increase the efficiency and accuracy of multiple phases of the discovery process [28]. The use of AI in protein–ligand docking, molecular dynamics modelling, and virtual screening of promising drug candidates, together with improved patient selection and monitoring in clinical trials, has accelerated the development of medicinal products. AI's impact on accelerating the development of new therapies, while adhering to ethical practice and regulatory requirements, is expected to have a substantial effect on global healthcare.

AI technologies enable analysis of large datasets, generation of novel molecular designs, and prediction of efficacy in drug discovery [29]. Notable AI tools used across these processes include AlphaFold, IBM Watson, DeepChem, DeepTox, ORGANIC, and Hit Dexter, which together span a wide range of drug research and development activities and contribute to greater efficiency and patient safety.

AI represents considerable potential for drug discovery but remains limited by several obstacles, including data quality and accessibility, data bias, resource intensity, regulatory constraints, and limited funding [29]. Effective AI models require diverse, high-quality datasets that are often difficult to obtain due to data-privacy regulations and cost. Predictions based on data that is biased against specific demographic groups may also yield inaccurate outcomes; methods such as SMOTE are being developed to mitigate such bias, though these remain the subject of ongoing research. Deep learning models typically require substantial computational resources, making collaboration between smaller research teams and AI technology vendors important. Collaboration among stakeholders is also critical for navigating the regulatory approval process, which requires substantiation of the safety and efficacy of AI-derived results [3]. Building partnerships and funding strategies to overcome these barriers will be essential to advancing AI in drug discovery.

3.7 Training and Education of Clinical Pharmacists in AI/ML

As healthcare systems increasingly adopt AI and ML, clinical pharmacists must develop competence in these technologies. The literature broadly supports early education in AI/ML and basic data science concepts within pharmacy curricula as the most effective way to ensure graduating pharmacists possess these skills [30]. Such education should address

AI/ML principles, applications in healthcare (including predictive analytics), and governance of AI tools (including ethics). Continuing education (CE) and certification programs are also essential to keeping practising pharmacists current with technological advances and associated ethical considerations.

Pharmacy students generally hold a positive view of AI/ML, but currently have limited formal training in the field, and many have called for greater opportunities for practical learning [31]. The International Pharmaceutical Federation (FIP) has responded by developing toolkits and guidelines to help integrate digital health literacy and AI competencies into pharmacy education.

This shift has given rise to initiatives emphasizing cross-disciplinary AI training in healthcare, centred on competencies such as algorithmic stewardship, AI ethics, and data fluency. Educational pathways for pharmacists are expected to combine initial degree training with advanced post-graduate certification [32]. Notable developments for the 2025–2026 period include the introduction of undergraduate programs that integrate basic AI principles and the development of dual-degree options (Pharm.D. and M.S. in AI/ML).

3.8 Use of AI/ML in Clinical Decision Support Systems (CDSS)

AI and ML have fundamentally transformed Clinical Decision Support Systems (CDSS). The major techniques applied include:

1. Supervised machine learning-based outcome prediction;
2. Deep learning for multi-dimensional data analysis and transformation;
3. Natural language processing (NLP) to extract structured information from clinical notes;
4. Reinforcement learning to develop optimal treatment policies; and
5. Hybrid applications combining clinical logic with ML methodologies.

These technologies provide the greatest value to CDSS through their ability to identify potential health risks earlier in the continuum of care, support optimal medication safety, assist with diagnosis, contribute to personalized treatment planning, and automate repetitive clinical workflows, thereby enhancing the efficiency and accuracy of clinical practice [33]. Successful implementation of AI-enabled CDSS requires integration into existing workflows, ongoing involvement of clinical experts, high-quality data input, and continual monitoring of system effectiveness. AI-based systems increasingly employ explainable AI methodologies to help clinicians understand the decision-making process and build trust in these systems. Nevertheless, challenges for AI-enabled CDSS include the potential for amplifying bias, risks to patient safety, and ethical implications of the technology; robust governance and comprehensive validation mechanisms are therefore essential for successful use [34]. Real-world applications demonstrate significant advantages for CDSS, and best practices for successful adoption emphasize aligning AI solutions with clinical needs and engaging end users in the design process.

3.9 Future Prospects and Innovations in AI/ML in Clinical Pharmacy

Clinical pharmacy is undergoing rapid transformation through AI and ML. Over the next 5–10 years, AI/ML is expected to improve medication management, automate repetitive tasks, and enable patient-centred care through personalized dosing [35]. The integration of data and models into AI/ML-based pharmacy systems will significantly redefine pharmacists' capabilities, moving the profession toward pharmacogenomic-based approaches to precision dosing and medication safety, while maximizing therapeutic optimization through evidence-based, individualized strategies—including intelligent digital decision-support systems for predicting adverse drug reactions and automation that reduces operational barriers to clinical service delivery [29].

AI-based agents are also expected to support tele pharmacy, remote clinical services, and the optimization of clinical trial operations. Barriers remain, however, including data quality, the level of acceptance of AI within pharmacy workflows, ethical considerations, and the need for sound governance frameworks aligned with these emerging models of practice. As agentic AI continues to advance, pharmacists are expected to gain greater capacity for proactive risk monitoring and to automate a substantial share of routine pharmacy tasks. Innovations such as 3D-printed medications, digital twins for patient simulation, and hyper-personalized adherence strategies are likely to further enhance the pharmacy profession in the years ahead [36, 37].

Table-1: Impact of AIML on clinical pharmacy practise.

Clinical area	**Traditional approach**	**Ai based approach**	**Improvement (%)**
Medication error detection	Manual review	Automated screening	45(%)
ADR prediction	Spontaneous reporting	Predictive Analytics	88(%)
Drug interaction detection	Database matching	Deep learning models	90(%)
Clinical decision support	Rule based system	Intelligent CDSS	70(%)
Personalised medicine	Standard dosing	Precision dosing	70(%)

Table-2: AI applications in clinical pharmacy.

Application	AI technology used	Clinical benefit
Drug dosing optimization	ML algorithm	Improved efficacy
Prediction	Deep Learning	Enhanced patient safety
Drug interaction detection	Neural network	Reduced toxicity
Clinical decision support	NLP+ ML	Faster decision
Medication adherence monitoring	Predictive Analytics	Better compliance

4. CONCLUSION

Clinical pharmacy is undergoing transformation through the introduction of artificial intelligence (AI) and machine learning (ML), which are having a substantial effect on practice, making it increasingly accurate, efficient, and tailored to individual patients' needs. Pharmacy practice has traditionally relied heavily on clinical judgement in medication-related decision-making; this is now shifting toward more analytical, data-driven approaches that enable clinical pharmacists to analyse large volumes of data from electronic health records (EHRs) and pharmacogenomic databases to select the most appropriate medication and dosage for each patient's unique circumstances while ensuring medication safety. Key advances include the development of AI-based Clinical Decision Support Systems (CDSS), which provide real-time alerts regarding potential drug interactions, and predictive modelling tools that optimize medication therapy. AI-based methods have shown advantages over traditional approaches in predicting the likelihood of adverse drug reactions (ADRs) and in detecting and monitoring drug–drug interactions that threaten patient safety. This review also underscores the importance of educating pharmacists on AI/ML-related issues such as data quality, privacy, and algorithmic bias. In conclusion, although AI/ML will enhance the role of the clinical pharmacist, it cannot replace the pharmacist in delivering personalized, patient-specific pharmaceutical care.

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