

THE ROLE OF ARTIFICIAL INTELLIGENCE IN SHAPING THE FUTURE OF PHARMACY

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ABSTRACT

Artificial Intelligence (AI) is increasingly influencing the field of pharmacy by supporting drug discovery, drug development, pharmacovigilance, medication safety, clinical decision-making, personalized therapy, pharmacy operations, and education. AI techniques such as machine learning, deep learning, natural language processing, and generative AI can analyze large and complex datasets and assist in identifying drug targets, predicting molecular properties, screening potential compounds, optimizing lead molecules, and detecting possible toxicity. AI can also strengthen pharmacovigilance by analyzing adverse drug reactions, electronic health records, drug-drug interactions, and other real-world data. In pharmacy practice, these technologies may improve medication management, treatment personalization, dispensing efficiency, and patient monitoring. However, challenges including poor data quality, privacy and security concerns, algorithmic bias, limited transparency, high implementation costs, lack of trained professionals, and ethical and legal issues must be addressed. AI should therefore be considered a supportive technology rather than a substitute for pharmacists. The future of pharmacy will depend on effective collaboration between AI systems and human expertise, with appropriate professional oversight to ensure safe, ethical, and patient-centered pharmaceutical care.

KEYWORDS: Artificial Intelligence, Pharmacy, Drug Discovery, Pharmacovigilance, Medication Safety, Artificial intelligence (AI) can reduce the overall drug development timeline from the traditional 10 to 15 years down to roughly 5 to 7 years, slashing early-stage discovery phases from years to mere months. Personalized Therapy, Machine Learning, Deep Learning, Clinical Decision-Making, Patient-Centered Care.

INTRODUCTION

Artificial intelligence is a new technology that is growing quickly and it helps in different parts of healthcare. Artificial intelligence in pharmacy field or also called as pharmacointelligence. AI helps for clinical pharmacists, for providing accurate and evidence based on clinical decisions to know the patient data, medical laboratories and medical records and also medication profiles.^[1]

Historically, The new drug development is very long and expensive. However the AI is used to accelerate the discovery of examining data sets and prognostigating efficacy and identifying optimal compounds. Pharmacy artificial intelligence which are also know as pharmacointelligence that refers to using information and technology smartly to improve medicine related work and help in better decisions in pharmacy, according to hatem (2024).^[2]

A key area where pharmacointelligence helps in drug discovery and development. Artificial intelligence (AI) can reduce the overall drug development timeline from the traditional 10 to 15 years down to roughly 5 to 7 years, slashing early-stage discovery phases from years to mere months. Conventional drug development is a lengthy, complex and expensive process it usually takes around 12 years and costs about \$2.6 billion. Due to this delay, patients suffering from complex diseases do not get access to newer and buffer treatments quickly.^[3]

Continuous drug development is crucial for improving patient care, especially for rare & complex diseases that currently have few or no effective treatments. It is mainly needed for rare diseases which do not have proper medicines. As diseases are charging, new problems are coming. So, we need new and advanced treatments for those rare conditions which were earlier not treatable or

had very few options. Idiopathic pulmonary fibrosis (IPF) is one such rare lung disease. It will be explained in detail later in this article. Nowadays pharmacointelligence -that means using a artificial intelligence in pharmacy -is helping to make this drug development faster. It helps to create medicines that are more safe, more effective and more innovative. Before we understood how pharmacointelligence helps in drug development and the future, pharmacy. We should first know about the types of AI.^[4]

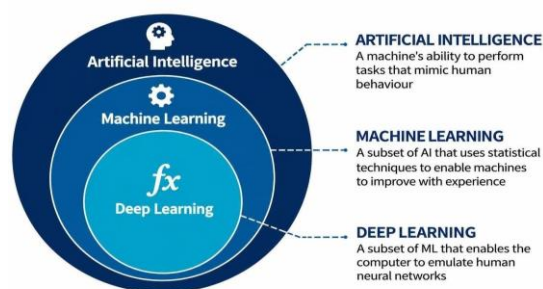


Fig: 1.

MACHINE LEARNING: The important part of AI is machine learning (ML). In machine learning the computer learns by itself using statistical methods, without needing to be programmed for every single step. Machine learning learns in two ways.

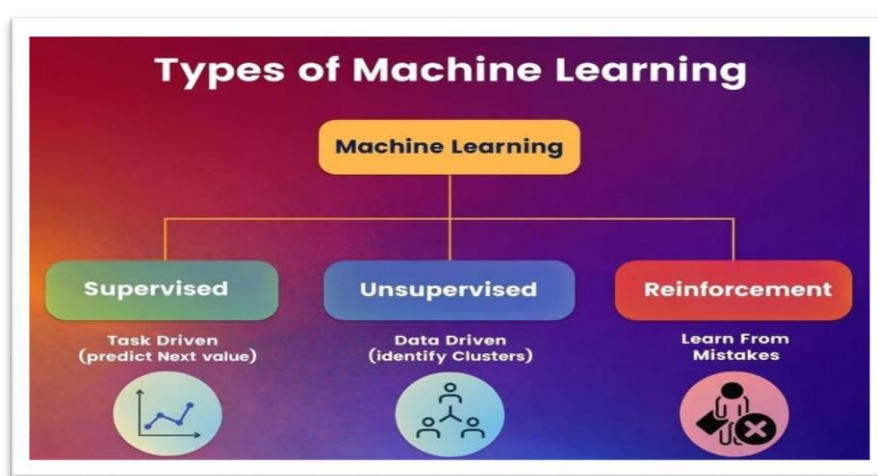


Fig: 2.

1. Supervised Learning

In supervised learning, the AI system is trained with labeled data. Labeled data means the input and the correct output are both already given. The system learns the relationship between them and then uses it to predict new results.

For example, in drug development, if we have a large amount of past data showing which medicines and combinations were effective for a particular disease, we can train the AI with that data. After training, when we give a new drug compound, the AI can predict its efficacy and how well it might work for patients.

2. Unsupervised Learning

In unsupervised learning, there is no labeled data. The AI is given only a large set of raw, unlabeled data and it has to find patterns, connections, and relationships on its own. This method is more exploratory in nature. For example, in pharmacy field, unsupervised learning can analyze thousands of patient records without any prim grouping and may identify a new category or pattern of a disease that was previously unknown. In simple words, it helps to discover hidden insights that are not visible to

humans.^[4]

DEEP LEARNING

The next advanced level of AI is deep learning (DL). Deep learning is a part of machine learning itself but it uses deep neural networks to learn from data. It is more powerful than normal ML. Deep learning can understand complex and unstructured data like images, voice and text without extra programming. In drug development DL is very useful. It can study the chemical structure of new compounds and predict whether a new drug will be successful or not. The special advantage of DL is that it can directly analyze and structured data like medical images, x-rays, lab reports and even human speech without needing separate programming for each task. In the context of drug discovery, Deep learning is highly valuable. It can deeply study the chemical structure shape and properties of various compounds and can predict whether a newly designed molecule will be stable, safe and effective as a future medicine.^[4]

In recent years, Artificial Intelligence (AI) has emerged as a cornerstone of industrial advancement, finding extensive and valuable applications across a wide

spectrum of technical and research-oriented domains. Its integration has revolutionized conventional workflows by introducing intelligent automation and data-driven decision-making.

Looking back over the last two and a half decades, the field of pharmacy has demonstrated remarkable resilience and progress in meeting the ever-increasing demand for prescriptions. This achievement is particularly significant considering the persistent challenges such as a shortage of qualified pharmacists, escalating operational expenses, and declining reimbursement rates.^[5]

Pharmacy practice has effectively embraced enabling technological innovations and automation to streamline operational workflows. The adoption of such technologies has not only contributed to a substantial reduction in operating costs but has also elevated the standards of safety, precision, and overall efficiency across all pharmacy environments.

One of the most impactful advancements has been automated dispensing systems. These systems have significantly minimized manual intervention, thereby allowing pharmacists to allocate more time to direct patient interaction and clinical counselling. Consequently, pharmacists are now able to manage a larger patient population while simultaneously improving therapeutic outcomes and enhancing the quality of healthcare delivery.^[5]

It is essential to have a clear understanding of how Artificial Intelligence is used in the pharmacy system and to carefully evaluate both its benefits and drawbacks.

The application of AI in pharmacy offers several significant advantages. It helps to improve accuracy in dispensing and reduces medication errors. AI also enables personalized medication management based on individual patient needs, which leads to better treatment outcomes and improved patient safety.

However, there are certain limitations associated with its use. Unlike humans, AI systems lack empathy and cannot provide the personal interaction and emotional support that patients often need. Furthermore, the effectiveness of AI completely depends on the quality and accuracy of the data provided. Inaccurate or incomplete data may lead to incorrect decisions. In addition, the use of AI also raises several ethical concerns related to privacy, data security, and decision-making responsibility.

Therefore, while AI can be a powerful tool for modern pharmacy, it should be used wisely along with human expertise to achieve the best results.^[6,7,8]

Even though AI technology in pharmacy is becoming more and more advanced day by day, the importance of

pharmacists and pharmacy technicians will never decrease. Instead, their role will become even more valuable.

In the future, pharmacists will not just dispense medicines, but they will become leaders and specialists who provide higher quality patient care with the help of AI. They will be the human heart and brain of the healthcare system. While AI can work fast and handle a large amount of data, it cannot replace the human thinking, experience, and emotional care that a pharmacist gives to a patient.

AI has the power to collect and read huge volumes of data within seconds. But that power has no value unless a human medical expert converts that data into useful information for the patient. For example, AI may suggest many treatment options, but only a qualified pharmacist or doctor on the front line can decide which option is truly best and safe for that particular patient.

So, the future of pharmacy is not AI replacing humans, but AI and humans working together as partners to provide more efficient, accurate, and patient-friendly care.^[9,10]

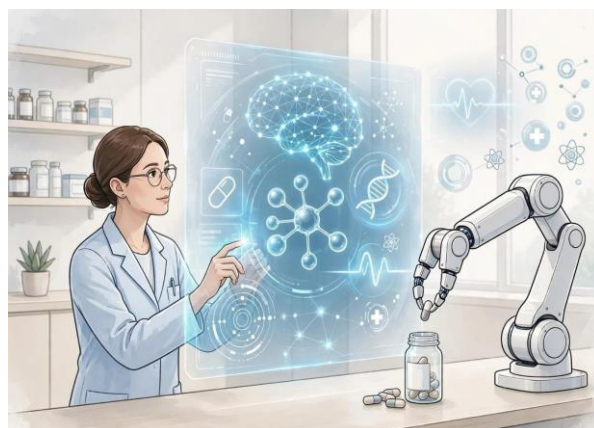


Fig: 3.

ARTIFICIAL INTELLIGENCE IN DRUG DISCOVERY AND DEVELOPMENT

The discovery and development of a new drug is a complex, expensive, and time-consuming process involving target identification, hit discovery, lead optimization, preclinical testing, clinical trials, regulatory evaluation, and post-marketing surveillance. Traditionally, researchers have depended heavily on experimental screening and iterative laboratory studies. Although these approaches have produced many successful medicines, they are associated with high costs, long development timelines, and a substantial probability of failure. The increasing availability of genomic, proteomic, chemical, clinical, imaging, and real-world healthcare data has created an opportunity to use artificial intelligence (AI) to improve several stages of pharmaceutical research.

AI, particularly machine learning (ML), deep learning (DL), natural language processing (NLP), and generative AI, can process large and complex datasets much more rapidly than conventional manual approaches. These technologies can identify relationships between biological targets, diseases, genes, proteins, and chemical compounds that may be difficult to recognize through traditional analysis. Consequently, AI is increasingly being investigated as a tool for prioritizing drug targets, predicting molecular interactions, designing novel compounds, estimating toxicity, and improving clinical development.^[11]

Target Identification and Validation

The first important stage of drug discovery is identifying a biological target that can be modified to produce a therapeutic effect. Targets may include receptors, enzymes, ion channels, transporters, signaling proteins, or nucleic acids. Selecting an inappropriate target can result in failure at later stages; therefore, accurate target identification is critical.

For example, AI-based computational approaches can examine disease-associated genetic variations and determine whether particular genes or proteins are likely to contribute to disease development. This can help researchers move from a large list of possible targets toward a smaller group of experimentally testable candidates.

Major contributions of AI in target identification include

- Identification of disease-associated genes and proteins.
- Prediction of gene–disease relationships.
- Identification of previously unknown therapeutic targets.
- Prioritization of targets according to biological relevance.
- Integration of genomic and clinical datasets.
- Prediction of potential target-related adverse effects.
- Identification of biomarkers for patient selection.

Thus, AI can function as a target-prioritization system, reducing the amount of experimental work required during the early stages of drug discovery.^[12,13]

Virtual Screening and Hit Discovery

Once a potential target has been identified, researchers need to find molecules capable of interacting with it. Traditionally, millions of compounds may need to be experimentally screened. This process is expensive and requires considerable laboratory resources.

AI-based virtual screening provides an alternative approach. Computational models can evaluate large chemical libraries and predict which molecules are most likely to interact with a particular biological target. Only the most promising candidates can then be selected for laboratory testing.

Deep-learning systems can learn relationships between molecular structures and experimentally measured biological activities. Structure-based approaches can also

use three-dimensional information about proteins and ligands to estimate binding interactions.

The application of AI in this area has been highlighted by systems such as AtomNet, which uses deep-learning approaches for structure-based.^[14]

Molecular Property Prediction

A potential drug candidate must possess several desirable characteristics. It should demonstrate adequate potency and selectivity while also having acceptable absorption, distribution, metabolism, excretion, and toxicity characteristics.

AI can predict important molecular properties before extensive laboratory testing. Depending on the model and dataset, predictions may include.

Property: Possible AI contribution

Molecular activity: Predicts probability of biological activity

Binding affinity: Estimates interaction between drug

and target Solubility: Predicts aqueous solubility

Lipophilicity: Estimates membrane permeability and distribution.

ADME: Predicts absorption, distribution, metabolism and excretion **Toxicity:** Identifies potential toxic compounds.

Drug–drug interaction: Estimates possible interactions

Selectivity: Predicts activity against related targets

Stability: Estimates chemical or metabolic stability

These predictions do not replace experimental testing. Instead, they can help researchers remove unsuitable candidates earlier, thereby concentrating resources on molecules with a higher probability of success.^[15]

AI-Assisted Lead Optimization

After identification of promising “hit” compounds, researchers modify their chemical structures to improve potency, selectivity, pharmacokinetic properties, and safety. This stage is known as lead optimization.

AI can compare structural characteristics of thousands or millions of molecules and identify modifications associated with improved properties. Machine-learning models can predict how a chemical modification may influence activity or toxicity before the compound is synthesized.

This creates an iterative cycle

Molecular design → AI prediction → compound synthesis → experimental testing → new data → model refinement.

The process can reduce unnecessary synthesis and allow medicinal chemists to focus on modifications with the greatest predicted benefit.^[14]

Generative AI for New Drug Molecules

One of the more recent developments is the use of generative artificial intelligence for molecular design. Instead of merely selecting molecules from an existing chemical library, generative models can propose new molecular structures.

Generative approaches include

Generative adversarial networks (GANs), Variational autoencoders (VAEs), Transformer based models, Reinforcement-learning systems, Graph neural networks (GNNs).

The objective is not simply to generate chemically valid molecules. The generated compounds should ideally satisfy several criteria simultaneously, such as potency, selectivity, solubility, permeability, metabolic stability, and low toxicity.

This concept is particularly important because conventional drug discovery often involves repeated cycles of chemical synthesis and testing. AI-assisted generative design has the potential to shorten these cycles by proposing more focused sets of compounds.^[16]

Prediction of Drug–Target Interactions

Understanding whether a drug molecule interacts with its intended target is fundamental to drug discovery. AI models can learn from experimentally determined drug–target interactions and subsequently predict interactions involving previously untested compounds.

Drug–target interaction models may combine Molecular fingerprints, Chemical structures, Protein sequences, Three-dimensional protein structures, Binding-site characteristics, Gene-expression data, Pharmacological data.

These approaches can help researchers identify potential binding partners and investigate whether a molecule might interact with unintended proteins.^[17]

Drug Repurposing

Drug repurposing involves identifying new therapeutic applications for medicines that have already been investigated or approved for another condition. This strategy can be advantageous because information regarding pharmacology, safety, formulation, and clinical use may already be available.

AI can analyze relationships among drugs, diseases, genes, proteins, pathways, and clinical outcomes to identify possible new drug–disease association.

For example

Existing drug → known molecular targets → biological pathway → disease mechanism → predicted new indication → experimental/clinical validation.

Drug repurposing is particularly valuable for diseases in which conventional drug development is difficult or

where there is an urgent unmet medical need.^[1]

AI in ADME and Pharmacokinetic Prediction

A major reason for drug-development failure is inadequate pharmacokinetic performance. A compound may demonstrate strong activity in vitro but fail because it is poorly absorbed, rapidly metabolized, unable to reach the required tissue, or eliminated too quickly.

AI models can estimate pharmacokinetic characteristics during the early development stage. Prediction of ADME properties allows researchers to identify compounds that may have poor clinical potential before investing heavily in their development.

AI may assist in predicting

Oral absorption, Plasma protein binding, Blood–brain barrier penetration, Metabolic stability, Clearance, Half-life, Volume of distribution, Enzyme-mediated metabolism.

These predictions can support the selection and optimization of candidates with more favorable pharmacokinetic profiles.^[15]

AI-Based Toxicity Prediction

Safety is one of the most important considerations in pharmaceutical development. Conventional toxicity assessment generally requires multiple experimental approaches, including cell-based, animal, and later clinical investigations.

AI can identify structural and biological patterns associated with toxicity. Models can potentially predict hepatotoxicity, cardiotoxicity, genotoxicity, cytotoxicity, and other adverse effects.

Early toxicity prediction allows researchers to eliminate high-risk candidates before expensive later-stage studies.^[15]

AI in Clinical Drug Development

The role of AI extends beyond laboratory-based discovery into clinical development. Clinical trials generate large quantities of data from patient characteristics, laboratory measurements, imaging, treatment responses, adverse events, and other clinical variables.

AI can support

Patient recruitment, Identification of suitable clinical-trial participants, Patient stratification, Selection of clinical endpoints, Prediction of treatment response, Identification of biomarker, Detection of adverse events, Clinical trial monitoring, Analysis of clinical-trial datasets.

AI-based patient selection can potentially identify individuals who meet specific inclusion criteria more efficiently, reducing delays in recruitment.^[19]

AI and Precision Medicine

Drug response varies considerably between individuals. Genetic differences, age, disease characteristics, environmental factors, concomitant medications, and lifestyle can influence therapeutic outcomes.

AI can combine molecular and clinical information to support precision medicine, in which treatment decisions are increasingly tailored to individual patient characteristics.

For example

Patient genomic data + clinical characteristics + disease phenotype + previous treatment response → AI analysis → predicted therapeutic response → individualized treatment strategy.

This approach is particularly relevant in oncology, rare diseases, and other areas in which molecular heterogeneity strongly influences treatment response.^[20]

AI in Formulation and Drug Delivery

AI is also useful after the active pharmaceutical ingredient has been identified. Developing an appropriate dosage form requires optimization of numerous formulation variables.

Machine-learning and artificial-neural-network approaches can be used to investigate relationships between.

Drug concentration, Polymer concentration, Excipients, Particle size, Manufacturing conditions, Dissolution rate, Drug-release profile, Stability.^[21]

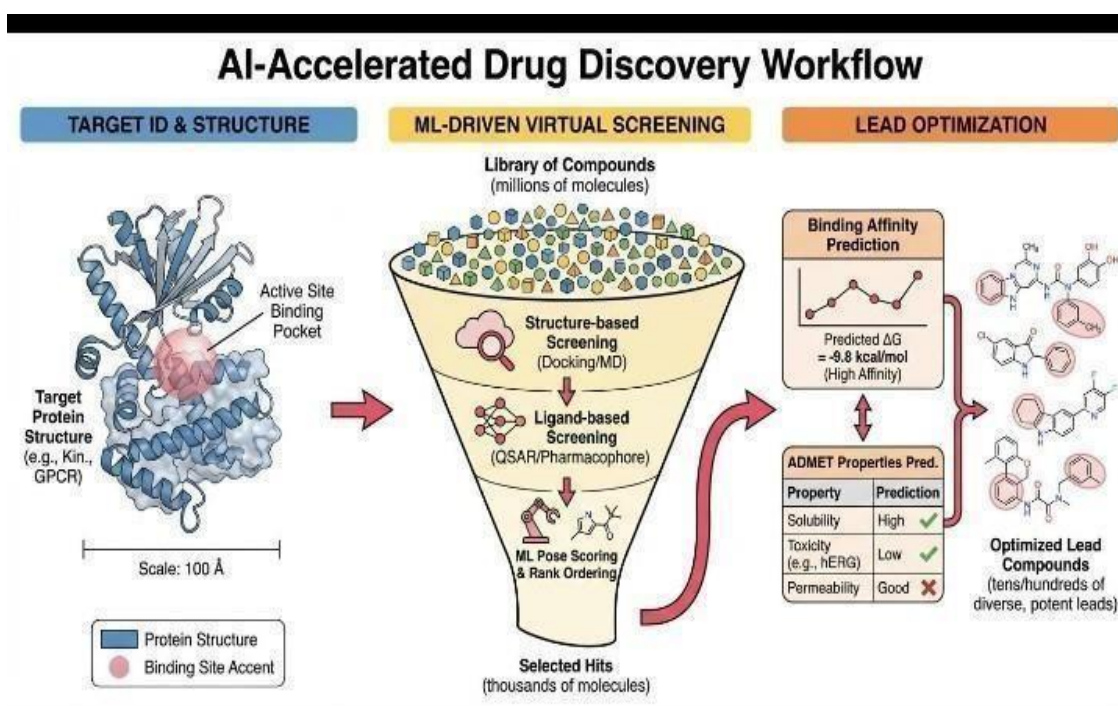


Fig: 4.

Artificial Intelligence For Drug Safety And Pharmacointelligence

Artificial intelligence (AI) is becoming an important tool for improving drug safety and strengthening pharmacovigilance. Drug safety assessment traditionally depends on laboratory experiments, animal studies, clinical trials, and post-marketing adverse drug reaction (ADR) monitoring. Although these approaches are essential, they may not identify every possible toxicity because clinical trials involve limited numbers of patients and may not adequately represent rare diseases, elderly patients, polypharmacy, or complex drug-drug interactions. AI can complement these conventional methods by analyzing large and heterogeneous datasets to identify safety patterns that may be difficult to detect through manual assessment.^[22]

AI in Preclinical Drug Safety

One of the important applications of AI is the prediction of toxicity before a drug candidate reaches advanced clinical development. Machine-learning algorithms can analyse chemical structures, molecular properties, biological targets, pathways, and previously reported toxicity information to estimate the potential safety profile of new compounds.

AI-Based Prediction of Organ Toxicity

AI can also be applied to predict toxicity affecting specific organs. Drug-induced liver injury (DILI) is a particularly important safety problem because liver toxicity can limit the clinical development or use of medicines. Xu et al. developed deep-learning models for DILI prediction using molecular information. Their best model achieved an accuracy of 86.9% on an external

validation set, demonstrating the potential of deep learning as an additional tool for identifying compounds with hepatotoxicity risk.

Similar computational strategies can potentially be applied to other safety endpoints, including cardiotoxicity, nephrotoxicity, neurotoxicity and reproductive toxicity. Therefore, AI-based toxicity prediction may help researchers prioritize safer candidates for experimental testing rather than relying entirely on conventional trial-and-error approaches.^[22]

AI in Pharmacovigilance and Pharmacointelligence

Pharmacovigilance involves the detection, assessment, understanding, and prevention of adverse effects associated with medicines. AI can strengthen this process by transforming large volumes of pharmacological and clinical information into useful safety signals. The term pharmacointelligence can be used to describe this broader data-driven approach, in which information from adverse-event databases, electronic health records (EHRs), biomedical literature, drug databases, and other real-world sources is integrated to support medication-safety decisions.

Identification of Drug–Drug Interactions

Polypharmacy increases the possibility of drug–drug interactions (DDIs), particularly among patients receiving multiple medicines for chronic diseases. AI can combine information about drug structures, targets, metabolic pathways, pharmacokinetic properties, and observed clinical outcomes to predict possible interactions.

Machine-learning and network-based methods can identify relationships between drugs, genes, proteins, pathways, and adverse events. This provides an opportunity to detect potential interactions that may not be obvious when each medicine is evaluated

independently. Consequently, AI-assisted DDI prediction can support safer prescribing and help pharmacists and clinicians evaluate medication combinations more efficiently.^[23]

Electronic Health Records and Real-World Data

EHRs provide another important source for AI-based pharmacovigilance. Unlike spontaneous adverse-event reports, EHRs may contain longitudinal information such as diagnoses, prescriptions, laboratory measurements, procedures, and clinical notes.

Natural Language Processing in Drug Safety

A significant amount of safety information is available in unstructured text, including clinical notes, case reports, biomedical publications, and online health discussions. Natural language processing (NLP) allows AI systems to extract relevant information from these textual sources.

NLP models can identify drug names, adverse events, symptoms, diseases, and relationships between medicines and adverse outcomes. Modern deep-learning techniques, including word embeddings, recurrent neural networks and attention-based models, have expanded the ability of computers to interpret biomedical language. These technologies can reduce the manual workload involved in reviewing large numbers of safety reports and can help identify potential ADR signals more rapidly.^[24]

Role of AI in Continuous Drug Safety Monitoring

AI has the potential to make drug safety monitoring a more continuous process. Instead of depending only on periodic manual review, computational systems can repeatedly analyses newly available clinical and pharmacological information. This may support earlier identification of emerging safety concerns, particularly when information is distributed across multiple databases.^[25]

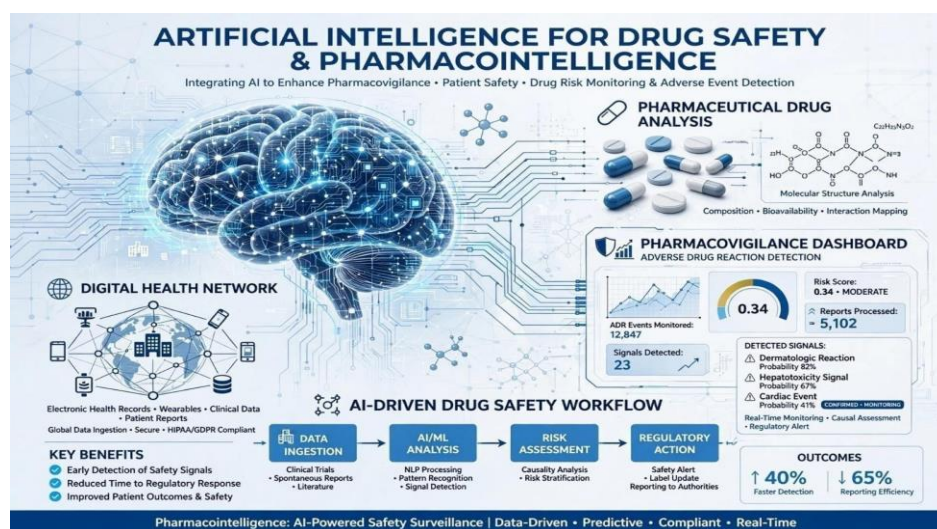


Fig: 5.

BENEFITS OF ARTIFICIAL INTELLIGENCE IN PHARMACY

Artificial Intelligence (AI) is becoming an important technology in pharmaceutical sciences and pharmacy practice. By combining machine learning, predictive analytics, natural language processing, and automation with large healthcare datasets, AI can support activities ranging from drug discovery to medication management and patient care. Current literature describes applications in clinical decision support, medication safety, personalized therapy, dispensing, adherence monitoring, and pharmacy operations.

1. Faster Drug Discovery and Development

One of the major advantages of AI in pharmacy is its ability to accelerate the early stages of drug discovery. Conventional drug development involves screening large numbers of chemical compounds and experimentally evaluating their biological activity, pharmacological properties, and toxicity. These processes can require considerable time and resources.

AI-based models can analyze large chemical, biological, genomic, and pharmacological datasets to identify patterns that may not be easily recognized through conventional approaches. AI is therefore being investigated as a tool for virtual screening, drug repurposing, molecular optimization, and prediction of drug properties.^[26]

2. Improved Medication Safety

AI can contribute to medication safety by identifying potentially harmful medication-related problems. Pharmacy systems may use AI to analyze patient records, prescriptions, laboratory results, and medication histories to identify possible drug–drug interactions, inappropriate prescriptions, adverse drug reactions, or other medication-related risks.^[27]

3. Better Clinical Decision-Making

Pharmacists routinely need to consider several factors

when making medication-related decisions, including the patient's diagnosis, age, laboratory values, existing medicines, allergies, and treatment response. AI can process these diverse data sources and provide decision-support information.^[27]

4. Personalized and Precision Pharmacotherapy

Patients can respond differently to the same medicine because of variations in genetics, age, disease characteristics, lifestyle, previous treatment, and other biological factors. AI can integrate these different types of information to support more individualized treatment decisions.^[28]

5. Increased Pharmacy Operational Efficiency

AI and automation can reduce the amount of repetitive work involved in pharmacy operations. Applications include prescription screening, medication identification, dispensing support, inventory monitoring, demand prediction, medication reconciliation, and workflow prioritization.^[27]

6. Reduction in Healthcare and Pharmaceutical Costs

AI may contribute to cost reduction by improving efficiency and reducing avoidable resource use. In pharmaceutical research, faster identification and prioritization of promising compounds can reduce unnecessary experimental work. In pharmacy practice, automation and predictive systems can potentially decrease medication errors, improve inventory management, reduce wastage, and optimization techniques.^[26,27]

7. Improved Medication Adherence and Patient Monitoring

AI can also support patients after medicines have been prescribed. Digital systems can analyze medication taking patterns and identify patients who may be at risk of poor adherence. These systems can support reminders, monitoring, and targeted interventions.^[27]

Figure: Benefits of Artificial Intelligence in Pharmacy



Note: AI integration supports pharmacists, enhances patient outcomes, and promotes safer, more efficient, and cost-effective pharmacy care.

Fig:6.

Challenges and limitations of AI in pharmacy

Artificial intelligence (AI) is increasingly being used in pharmacy for drug discovery, medication management, pharmacovigilance, clinical decision support, and personalized therapy. Despite these developments, several challenges limit its effective and safe implementation. Addressing these limitations is essential for ensuring that AI improves pharmaceutical care without compromising patient safety or professional responsibility.

1. Data Quality and Availability

AI systems depend heavily on large amounts of high-quality data. In pharmacy and healthcare, data may be incomplete, inconsistent, outdated, or recorded in different formats. Poor-quality data can affect the performance of AI models and may result in inaccurate predictions or recommendations. Access to sufficiently large and representative datasets can also be difficult because healthcare information is often distributed across different institutions and systems.^[29]

2. Data Privacy and Security

Pharmacy-related AI applications may process sensitive information such as patient medical histories, laboratory results, prescriptions, medication use, and treatment outcomes. Improper handling of such information can create risks related to privacy breaches and unauthorized access. Strong cybersecurity measures, secure data storage, controlled access, and compliance with applicable data-protection regulations are therefore necessary.^[30]

3. Algorithmic Bias

AI systems can reproduce or amplify biases present in their training data. If certain patient groups are poorly represented in the dataset, the system may produce less accurate results for those populations. Such bias could affect areas such as drug-response prediction, clinical decision support, and identification of patients at risk of adverse drug reactions. Using diverse and representative datasets and regularly evaluating model performance can help reduce this problem.^[31]

4. Lack of Transparency

Some advanced AI models operate as complex systems in which it is difficult to understand how a particular prediction was produced. This is often referred to as the “black-box” problem. Pharmacists and other healthcare professionals may be hesitant to rely on recommendations that cannot be adequately explained. Greater transparency and explainable AI methods are important for building confidence in AI-supported decisions.^[32]

5. Accuracy and Reliability

AI-generated information is not automatically correct. Errors may occur because of poor-quality training data, inappropriate model design, unusual patient

characteristics, or situations that were not represented during model development. AI recommendations should therefore be evaluated against reliable clinical evidence and reviewed by qualified professionals before being used for important patient-care decisions.^[29]

6. High Cost and Technical Requirements

Developing, implementing, and maintaining AI systems can require considerable financial and technical resources. Healthcare organizations may need specialized software, computing infrastructure, secure data systems, and trained personnel. Smaller hospitals, pharmacies, and institutions may find it difficult to adopt sophisticated AI technologies because of these requirements.^[33]

7. Lack of Skilled Professionals

Successful implementation of AI requires professionals who understand both pharmacy and digital technologies. Many pharmacists may have limited training in areas such as machine learning, data analysis, and AI-based decision systems. Incorporating AI-related education into pharmacy curricula and providing continuing professional training can help pharmacists use these technologies more effectively.^[33]

8. Ethical and Legal Concerns

The use of AI raises important questions regarding responsibility, informed decision-making, patient autonomy, and professional accountability. If an AI-supported recommendation results in an error, determining responsibility among the pharmacist, healthcare institution, software developer, and AI provider may be complicated. Clear ethical and legal frameworks are therefore needed.^[30]

9. Limited Human Interaction

AI can efficiently analyse information and identify patterns, but it cannot fully replace the empathy, communication, and professional judgment of a pharmacist. Patients may require explanations, reassurance, counselling, and consideration of personal circumstances that cannot always be captured by an algorithm. AI should therefore support rather than completely replace pharmacist–patient interaction.^[30]

10. Integration with Existing Healthcare Systems

Another challenge is integrating AI applications with existing pharmacy and hospital information systems. Differences in software, data formats, and communication standards can make implementation difficult. Poor integration may increase workload rather than reduce it. Interoperability and user-friendly system design are therefore important for successful adoption.^[29]



Fig: 7.

Ethical and Privacy Considerations of AI in Pharmacy

Artificial intelligence is increasingly being applied in pharmacy for drug discovery, clinical decision-making, medication management, and pharmacovigilance. However, its use involves important ethical and privacy concerns that must be addressed to protect patients and maintain trust in healthcare.

Patient Privacy and Data Protection

AI systems often require patient information such as medical history, laboratory results, prescriptions, medication records, and treatment outcomes. Improper collection, storage, or sharing of such information may expose patients to privacy and cybersecurity risks. Therefore, sensitive health data should be securely stored, access should be restricted to authorized users, and information should only be collected when necessary.^[34]

Transparency and Explainability

Some AI systems can produce recommendations without clearly showing how the conclusion was reached. In pharmacy practice, lack of transparency may make it difficult for pharmacists to evaluate an AI-generated recommendation. AI tools should therefore provide sufficient information about their purpose, limitations, validation, and appropriate use.

Bias and Fairness

AI systems may reflect biases present in the data used to develop them. If certain patient populations are underrepresented, AI-based predictions may not perform equally across different groups. Diverse datasets and continuous evaluation are important to promote equitable

use of AI in pharmacy.

Accountability and Professional Responsibility

AI should support, rather than completely replace, the professional judgment of pharmacists. Clear responsibility is necessary when AI-assisted decisions contribute to an incorrect recommendation or patient harm. Appropriate human oversight, professional training, and mechanisms for reviewing AI decisions are therefore essential.

Patient Autonomy and Human-Centered Care

Pharmacy care involves communication, counselling, empathy, and consideration of individual patient preferences. AI should not remove the patient's role in healthcare decisions or replace meaningful interaction with healthcare professionals. Human oversight should remain central when AI is used in patient care.^[34]

Impact of AI on Pharmacy Education

Artificial intelligence (AI) is gradually changing pharmacy education by introducing new approaches to teaching, learning, assessment, and professional training. Recent reviews indicate that AI can support personalized learning, problem-based learning, communication skills, assessment, and other educational activities, while also creating challenges related to faculty preparation, academic integrity, ethics, and reliability.

Personalized Learning

AI-based educational tools can provide students with learning support according to their individual needs and learning pace. Students can use AI applications to obtain explanations of difficult pharmaceutical concepts,

generate practice questions, and receive immediate feedback. This may help learners identify areas where they need additional study and encourage more independent learning.^[35]

Improved Teaching and Learning

AI can assist teachers in preparing educational materials, case studies, quizzes, and problem based learning activities. Generative AI tools can also act as tutors or learning assistants, allowing students to explore clinical and pharmaceutical topics interactively. Recent pharmacy-education literature has described applications including personalized learning, communication activities, and problem-based learning.^[35,36]

Development of Clinical and Decision-Making Skills

AI can be incorporated into simulated clinical scenarios where pharmacy students analyses patient information, identify medication-related problems, and consider possible interventions. Such activities can provide opportunities to practice clinical reasoning before students encounter similar situations during experiential training.^[36]

Support for Research and Information Retrieval

Pharmacy students can use AI-assisted tools to organize information, summarize scientific literature, generate research ideas, and assist with data analysis. However, students need to verify AI-generated information against reliable scientific sources because AI systems can produce inaccurate or unsupported information.^[37]

Changes in Assessment Method

The availability of generative AI has encouraged pharmacy educators to reconsider traditional assignments and assessments. Instead of relying only on essays or

factual questions, educators may incorporate oral examinations, case-based activities, practical assessments, and tasks that require students to explain and critically evaluate AI-generated responses. This can help assess genuine understanding and critical-thinking skills.^[36,37]

Challenges in Pharmacy Education

The integration of AI is not without difficulties. Faculty members may require additional training, institutions may need clear policies, and curricula may already be heavily loaded. Concerns also include academic integrity, overdependence on AI, inaccurate information, privacy, and unequal access to technology. A recent scoping review specifically identified faculty expertise, limited outcomes data, legal and ethical issues, and generalizability as challenges to AI implementation in pharmacy education.^[38]

The Future of Pharmacy: Where AI Meets Human Expertise

Artificial intelligence is gradually transforming pharmacy from a traditional medicine focused profession into a more data-driven, intelligent, and patient-centered field. Its applications extend from drug discovery and development to pharmacovigilance, medication safety, personalized therapy, clinical decision-making, pharmacy operations, and education. By analyzing large and complex datasets, AI can help pharmacists and researchers identify useful patterns, support faster decision-making, and improve the efficiency of pharmaceutical services. However, the future of pharmacy should not be viewed as a replacement of pharmacists by technology. AI can process information rapidly.

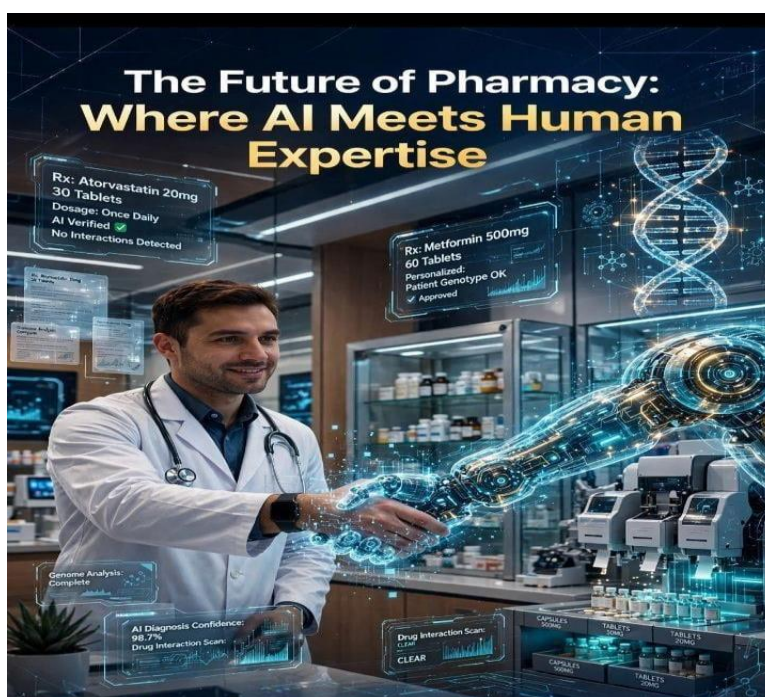


Fig: 8.

and provide predictions or recommendations, but pharmacists contribute to professional judgement, clinical experience, communication, empathy, and an understanding of individual patient needs. Therefore, the greatest potential of AI lies in combining computational intelligence with human expertise.^[39]

The successful integration of AI will also require attention to data quality, privacy, transparency, bias, ethical responsibility, professional training, and proper validation. AI generated outputs should be carefully evaluated and used as supportive information rather than accepted without professional review. Pharmacists will therefore need to develop AI literacy while maintaining their core clinical and ethical responsibilities.

In the coming years, collaboration between pharmacists, researchers, healthcare professionals, and AI technologies may create a more efficient and personalized healthcare system. The pharmacy of tomorrow will not simply be automated; it will be intelligent, evidence-driven, and human-centered. Ultimately, the future of pharmacy lies not in choosing between AI and human expertise, but in bringing both together to achieve safer medicines, better therapeutic decisions, and improved patient care.^[40]

CONCLUSION

Artificial Intelligence is emerging as an important technology with the potential to transform both pharmaceutical research and pharmacy practice. Its applications extend across drug discovery and development, toxicity prediction, pharmacovigilance, medication safety, precision pharmacotherapy, clinical decision-making, pharmacy operations, and education. By processing large amounts of information and identifying patterns rapidly, AI can support researchers and pharmacists in making more informed and efficient decisions.

Despite these opportunities, successful implementation requires careful attention to data quality, privacy, security, transparency, bias, ethical responsibility, validation, and professional training. AI-generated predictions should be critically assessed and should not replace clinical expertise or professional judgement.

Pharmacists will continue to play an essential role because patient care also requires communication, empathy, ethical reasoning, and an understanding of individual needs.

The future of pharmacy therefore lies in a collaborative approach in which AI provides computational support while pharmacists provide clinical knowledge and human-centered care. With responsible implementation and appropriate human oversight, the integration of AI can contribute to safer medicines, improved therapeutic decisions, efficient pharmaceutical services, and more personalized patient care.

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