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Original Article

Transforming Pharmacy Automation: The Role of Robotics and Artificial Intelligence

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ABSTRACT

The rapid evolution of technology has revolutionized pharmacy practice, with robotics and artificial intelligence (AI) emerging as powerful tools in modern pharmacy automation. Robotics has transformed medication dispensing, compounding, and inventory management by enhancing accuracy, efficiency, and safety. Simultaneously, AI systems have enabled intelligent clinical decision support, drug interaction prediction, personalized dosing, and data-driven patient care. Together, these technologies are reshaping hospital, community, and clinical pharmacy workflows, reducing human error, and allowing pharmacists to focus on patient-centered services. Despite challenges related to cost, integration, and ethics, the synergy of robotics and AI holds significant promise for improving healthcare outcomes and operational excellence in pharmacy. This review explores current advancements, applications, limitations, and future directions of robotics and AI in pharmacy automation.

Keywords: Robotics in Pharmacy, Pharmacy Automation, Artificial Intelligence, Smart Pharmacy

INTRODUCTION

The global healthcare system is under increasing pressure to deliver accurate, efficient, and cost-effective services. In this context, pharmacy automation, supported by robotic systems and AI-driven analytics, is gaining momentum. These technologies address key challenges such as medication errors, inventory mismanagement, and pharmacist burnout, allowing pharmacists to focus more on clinical and patient-centered care. Pharmacy automation refers to the use of technology—including robotic systems, software solutions, and artificial intelligence (AI)—to perform and optimize tasks in pharmaceutical operations such as dispensing, compounding, inventory management, and medication tracking. The primary goal is to enhance accuracy, reduce medication errors, improve workflow efficiency, and allow pharmacists to focus more on clinical care and patient counseling. As the global demand for healthcare services grows, the pressure on pharmacy systems to deliver safe, fast, and cost-effective medication management has intensified. Automation has emerged as a key strategy to address these challenges by minimizing human error, ensuring proper dosage and labeling, and improving overall pharmaceutical service delivery (1). Automated pharmacy systems range from unit dose dispensing robots and automated storage systems to intelligent IV compounding units and robotic prescription counters. These systems have been shown to reduce medication errors by up to 50% in hospital settings (2). Furthermore, with the integration of AI algorithms, pharmacies can now support predictive analytics, clinical decision support, and personalized medication therapy, creating a transformative shift toward smart and data-driven pharmacy practice (3).

Evolution of Pharmacy Automation

Pharmacy automation has undergone a significant transformation over the past two decades — evolving from simple pill counters and barcode systems to highly intelligent robotic and AI-integrated platforms.

Key Milestones:

- Early 2000s: Introduction of automated dispensing cabinets (e.g., Pyxis, Omnicell) in hospital settings.
- 2010s: Widespread use of robotic arms for medication dispensing, IV admixture

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compounding, and packaging (e.g., RIVA, ScriptPro).

- 2020s and Beyond: Integration of AI, machine learning, predictive analytics, and cloud-based systems, enabling "smart pharmacies" that are capable of clinical decision support and real-time inventory optimization (4)

Why is Pharmacy Automation Needed?

The need for pharmacy automation is driven by several **systemic, clinical, and operational challenges**:

a. Reducing Medication Errors

- Medication errors affect millions of patients globally and are a leading cause of preventable harm.
- Automation improves **accuracy** in drug dispensing and labeling by minimizing human intervention.

b. Improving Workflow Efficiency

- Manual prescription filling is time-consuming and error-prone.
- Automated systems can handle thousands of prescriptions per day, freeing pharmacists to focus on **clinical roles** and **patient counseling**

c. Supporting Clinical Decision-Making

- **AI integration** allows for real-time alerts about drug interactions, dose adjustments, and therapy optimization.
- Enhances **patient safety** and **treatment efficacy** through data-driven insights.

d. Managing Inventory and Supply Chain (5)

- Automated storage and retrieval systems (ASRS) ensure **accurate stock control**, reduce waste, and streamline the pharmaceutical supply chain.
- Especially valuable in high-volume hospital pharmacies and national-level vaccine distribution.

Applications of AI and Robotics in Pharmaceutical Sciences:

It's not only in pharma manufacturing that robots are taking a deep dive. Packing, labeling, and quality control are done by automated systems with higher throughput and fewer human mistakes. Such automation increases overall production efficiency and helps to meet high-level regulatory requirements. Also, robots may cooperate with human workers, providing more power and accuracy in difficult processes [6,7]. The individualization of medicine is also supported by AI applications that use clinical evidence to inform treatment decision-making. AI, for example, can read a patient's medical history and genomic information and recommend the most efficient regimens that will fit the patient's profile. Such personalization not only makes treatment more effective but also increases patients' satisfaction and compliance with therapy [8, 9]. Overall, AI and robotics used in pharmaceutical science improve drug discovery, personalized medicine, and pharmaceutical manufacturing efficiency that ultimately leads to improved patient outcomes and care.

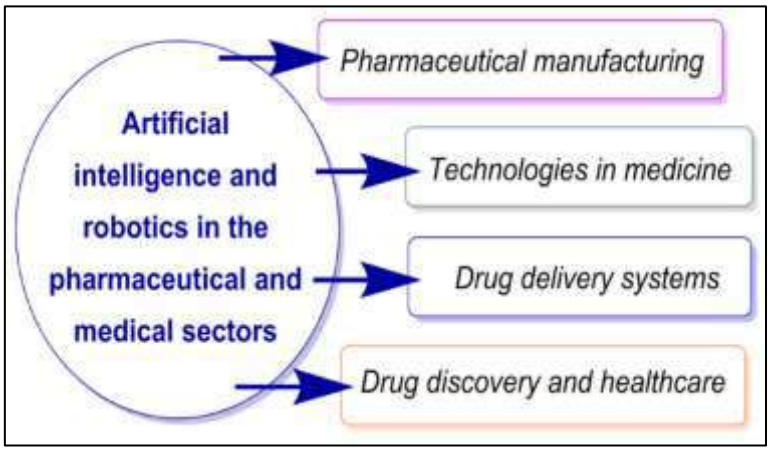

Fig 1 AI and Robotics in Pharmacy Sector

Top Pharmaceutical Automation Solutions

Here is the some of the top pharmaceutical automation solutions adopted by leading firms:

Table 1 Top Pharmaceutical Automation Solutions

Solution	Functionality	Benefits
ABB IRB 1200	Robotic arms in pharma for material handling	Compact, fast, and clean-room compliant
Siemens SIMATIC	AI-driven pharmaceutical automation technologies	Real-time monitoring and control
Omnicell XT	Pharmacy automation systems for automated pill dispensing	Increases medication accuracy in hospitals
FANUC Robots	Used in drug packaging and labeling	Handles small to large batch operations with precision

How Are Robotic Systems Used in Drug Packaging?

Robotic systems work in medicine shop as shown in fig 2 and also have revolutionized drug packaging processes in the pharmaceutical industry by increasing efficiency, accuracy, and safety. They are used in various stages of packaging, from filling and labeling to sealing and palletizing.

1. Primary Packaging

Robotic systems are used in **primary packaging**, where the drug comes into direct contact with the packaging material, such as blister packs, vials, ampoules, and syringes.

- **Blister Packing**: Robots ensure accurate placement of tablets or capsules into blister cavities using high-speed vision-guided systems.
- **Vial/Syringe Filling**: Robotic arms with sterile handling mechanisms are employed in aseptic environments to fill and cap vials and pre-filled syringes. (10,11)

2. Secondary Packaging

This includes the packaging that groups primary packages together, such as boxes, cartons, and shrink-wrapping.

- Robots are used for **cartoning**, **case packing**, and **tray loading**.
- They perform precise movements to handle delicate pharmaceutical items with care, avoiding damage or contamination. (12)

3. Labeling and Inspection

Robotic systems equipped with machine vision automatically **inspect labels**, **verify barcodes**, and ensure **label placement accuracy**.

- **Vision-guided robots** detect mislabels, smudges, or missing information.
- They are also used to apply tamper-evident seals.

4. Serialization and Track-and-Trace

Modern robotic packaging lines integrate serialization technology to comply with global regulations (like the **US Drug Supply Chain Security Act**).

- Robots print unique identifiers (barcodes, QR codes) and manage data logging for **track-and-trace** systems. (13)

5. End-of-Line Automation

Robotic systems are used at the end of the packaging line for:

- **Palletizing** finished products onto shipping pallets.
- **Wrapping and labeling** pallets for distribution.

These systems reduce human fatigue and the risk of repetitive strain injuries while increasing throughput. (14)

Fig 2 AI generated Robot pharmacist dispenses medicines

Synergy Between Robotics and AI: Toward Smart Pharmacies

he convergence of **robotics** and **artificial intelligence (AI)** is transforming conventional pharmacies into **"smart pharmacies"**, where intelligent systems not only automate routine tasks but also enable advanced decision-making. This synergy enhances speed, accuracy, safety, and personalization in pharmaceutical services.

How Robotics and AI Work Together

- **Robotics** excels at performing **precise, repetitive physical tasks** such as dispensing, packaging, labeling, and compounding medications.
- **AI** analyzes **data patterns**, supports **clinical decision-making**, predicts inventory needs, and enhances patient care through tailored recommendations.
- When integrated, these systems form an **autonomous and intelligent pharmacy infrastructure**, often capable of **real-time optimization** and **error detection**.
- Here is the Benefits of AI and its Description in a tabular form:

Table 2 Benefits of AI and its Description

Benefit	Description
Improved Safety	Reduces human errors and improves drug verification processes
Operational Efficiency	Robots execute repetitive tasks; AI optimizes workflows
Enhanced Decision Support	AI algorithms assist pharmacists with clinical decisions
Personalized Care	AI helps tailor medication regimens based on patient-specific data

AI in diagnosis and Targeted Genomic Treatments:

- **Treatment plan designing:** The designing of effective treatment plans is possible with the help of AI technology. When any critical condition of a patient arises and the selection of a suitable treatment plan becomes difficult, then the AI system is necessary to control the situation. All the previous data and reports, clinical expertise, etc., are considered in the designing of the treatment plan as suggested by this technology. IBM Watson for Oncology, the software as a service, is a cognitive computing decision support system that analyzes patient data against thousands of historical cases and insights gleaned from working thousands of hours with Memorial Sloan Kettering Cancer Center physicians and provides treatment options to help oncology clinicians make informed decisions. These treatment options are supported by literature curated by Memorial Sloan Kettering, and over 300 medical journals and 200 textbooks, resulting in almost 15 million pages of text.

- **Assisting in repetitive tasks:** AI technology also assists in some repetitive tasks, such as examining the X-ray imaging, radiology, ECHO, ECG, etc., for the detection and identification of diseases or

disorders. Medical Sieve (an algorithm launched by IBM) is a "cognitive assistant" having good analytical and reasoning abilities. A medical start-up is necessary for the improvement of the patient's condition by combining deep learning with medical data. A specialized computer program is available for each body part and used in specific disease conditions. Deep learning can be employed for almost all types of imaging analyses, such as X-ray, CT scan, ECHO, ECG, etc (15)

- **Health support and medication assistance:** In recent years, the uses of AI technology are recognized as efficient in health support services and also, for medication assistance. Molly (a start-up-designed virtual nurse) receives a pleasant voice along with a cordial face. Its aim of it is for helping patients to guide the treatment of patients as well as support them with their chronic conditions during doctor's visits. Ai Cure is an app existing in a Smartphone webcam, which monitors patients and assists them to control their conditions. This app is useful to patients with severe medication situations and for patients who participate in clinical trials. (16)

- **Accuracy of medicine:** AI shows a good impact on genomics and genetic development. Deep Genomics, an AI system is useful for observing patterns in the genetic information and medical records to identify the mutations and linkages to diseases. This system informs doctors about the events happening within a cell when DNA is altered by genetic variation. An algorithm is designed by the father of the human genome project, Craig Venter, that gives information on patients' physical characteristics based on their DNA. "Human Longevity" AI technology is useful to identify the exact location of cancer and vascular diseases in their early stage.

- **Drug creation:** The development or creation of pharmaceuticals takes more than a decade and consumes billions of rupees. "Atom wise", an AI technology that uses supercomputers, is useful to find out the therapies from the database of molecular structure. It hurled a virtual search program for safe and effective therapy for the Ebola virus with the existing drugs. The technology identified two drugs that caused Ebola infection. This analysis was completed within one day compared to months to years with manual analysis. A Biopharma company in Boston developed big data for the management of patients. It reserves data to find the reasons why some patients survive diseases. They used patients' biological data and AI technology to find out the difference between healthy and disease-friendly atmospheric conditions. It helps in the discovery and design of drugs, healthcare, and problem-solving applications.

- **AI helps people in the health care system:** The "open AI ecosystem" was one of the top 10 promising technologies in 2016. It is useful to collect and compare the data from social awareness algorithms. In the healthcare system, vast information is recorded which includes patient medical history and treatment data from childhood to that age. This enormous data can be analyzed by the ecosystems and gives suggestions about the lifestyle and habits of the patient.

- **Healthcare system analysis**: In the healthcare system, if all the data is computerized then retrieval of data is easy. Netherland maintains 97% of invoices in digital format, which contain treatment data, physician names, and hospital names. Hence, these can be retrieved easily. Zorgprisma Publiek, a local company analyses the invoices with the help of IBM Watson cloud technology. If any mishap occurs, it recognizes it immediately and takes the correct action. Because of this, it improves and avoids patient hospitalization. (17)

- **Prediction of toxicity:** Drug toxicity prediction has been determined by various computational models such as ML, structural warnings, read-across, and molecular modeling. Based on the physicochemical and structural properties of the drug, a computational model helps predict the drug's toxicity even before that drug is synthesized. The prediction of various types of toxicity such as carcinogenicity, mutagenicity, hepatotoxicity, acute oral toxicity, and hERG inhibition was determined using the ML model. (18,19)

- **AI in research and development:** In research and development, AI technology is used to identify and solve complex problems related to drug development.[61] Nowadays several companies like Novartis, Qrativ, and BioXcel are merging with AI-based technology in research and development. In pharmaceutical research, various computational approaches such as Quantitative Structure–Activity Relationship (QSAR), QSPR, pharmacokinetic and pharmacodynamics mathematical models have been used as *in silico* methods to generate new identity chemical entities, as well as various formulation design areas such as porosity, dissolution, and stability issues. (20-23).

Challenges and Future Prospects:

Pharmacy automation has the potential to revolutionize the healthcare sector by enhancing accuracy, efficiency, and patient safety. However, its widespread adoption faces several challenges. One major hurdle is the high initial investment cost, including procurement, installation, and maintenance of sophisticated robotic systems and AI software. Smaller and rural pharmacies often lack the financial resources and technical infrastructure to support such transitions. Additionally, integration with existing pharmacy management systems and electronic health records can be complex, requiring significant IT support and staff training. Concerns about data privacy and cybersecurity also arise, especially when handling sensitive patient information in cloud-based or AI-driven systems. Moreover, the resistance to change among pharmacy staff, who may fear job displacement or feel overwhelmed by new technologies, can slow down adoption. Despite these challenges, the future of pharmacy automation looks promising. Advancements in artificial intelligence, machine learning, and Internet of Things (IoT) are making automation smarter and more adaptable. Automated dispensing systems, AI-driven drug interaction alerts, and robotic medication storage and retrieval units are increasingly streamlining operations. As technology becomes more affordable and user-friendly, even smaller pharmacies will be able to participate in this digital transformation. The integration of personalized medicine and pharmacogenomics with automated systems could lead to highly tailored patient care. Furthermore, the role of pharmacists is expected to shift from manual dispensing to more clinical and consultative roles, enhancing their impact on patient outcomes. In the long term, pharmacy automation will not only improve workflow and safety but also enable a more proactive and patient-centered approach to healthcare.

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