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AI in Pharmacy Automation: A Review of Innovations in Robotics, Their Ethical Implications, and Impact on Workflow and Workforce

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Abstract

The pharmacy profession has witnessed a paradigm shift with the integration of robotics and artificial intelligence (AI) in automation. Traditional practices that relied heavily on manual dispensing, paper documentation, and technician labor are now being augmented or replaced by robotic dispensing systems, sterile compounding machines, and predictive AI algorithms. These innovations enhance safety, improve efficiency, and reduce errors, while also raising complex ethical questions related to workforce displacement, liability, and data security. This review explores the historical development of pharmacy automation, its importance in modern healthcare, conventional methods of practice, innovative AI applications, advantages, disadvantages, and ethical concerns. Finally, the article discusses the future scope of AI in pharmacy automation, envisioning a healthcare ecosystem where technology and human expertise complement each other.

Keywords: Artificial intelligence, robotic dispensing units, barcode medication administration, pharmacy automation, bulk dispensing systems

INTRODUCTION

Pharmacy has always played a pivotal role in healthcare, evolving from ancient apothecaries who compounded herbal mixtures to today's complex pharmaceutical industry. Historically, the dispensing of medicines was a manual and highly personalized practice, where pharmacists relied on handwritten prescriptions, compounding skills, and their intimate knowledge of medicinal substances. With industrialization in the 19th century, pharmaceutical manufacturing expanded, and standardized dosage forms emerged, reducing the burden of manual compounding but still leaving the dispensing process largely manual [1]. During the mid-20th century, pharmacies began facing challenges such as increasing prescription volumes, the rising complexity of therapies, and the demand for faster service. Pharmacists and technicians often spent much of their time counting pills, labeling bottles, and performing repetitive tasks, which limited their ability to engage with patients or provide clinical services. Human error in manual dispensing, though unintentional, was a significant cause of medication-related morbidity and mortality worldwide [2]. The 1970s and 1980s marked the early stages of computerization in pharmacies, where electronic systems began replacing paper logs for prescription management. Computerized physician order entry (CPOE) systems and pharmacy information systems introduced digital accuracy into the workflow [3]. Yet, the physical process of dispensing and compounding still relied

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heavily on human effort. By the late 20th century, mechanization slowly gave way to automation. Automated pill counters, label printers, and barcode systems were introduced to support efficiency. Automated dispensing cabinets (ADCs) started appearing in hospitals, providing nurses with controlled access to unit-dose medications [4]. Despite these innovations, true robotics machines capable of performing dispensing, packaging, and even sterile preparations only became more widespread in the late 1990s and early 2000s. The modern era of pharmacy automation is defined by the convergence of robotics, advanced sensors, and machine intelligence. Central fill pharmacies can now process tens of thousands of prescriptions daily using robotic systems. Robots handle tasks such as medication picking, labeling, compounding intravenous admixtures, and even preparing chemotherapy under sterile conditions [5]. It is important to note that automation and AI are not synonymous. Automation refers to machines performing repetitive, rule-based tasks with minimal human intervention, while AI refers to computational systems that learn, adapt, and make data-driven decisions. In pharmacy, automation provides speed and precision, while AI introduces decision-support, predictive analytics, and adaptability to complex scenarios. Their integration represents the next frontier in pharmaceutical practice [6]. Thus, the introduction sets the stage for this review by presenting the historical trajectory of pharmacy automation, its motivations, and its transition from manual practice to intelligent robotics. The sections that follow highlight its importance, conventional approaches, innovative AI applications, benefits, drawbacks, ethical issues, and its role in shaping the pharmacy workforce of the future.

IMPORTANCE

The importance of pharmacy automation is grounded in its ability to address long-standing challenges in healthcare delivery. One of the most pressing concerns in pharmacy practice has been medication errors, which account for a significant portion of preventable adverse drug events [7]. Automated systems improve accuracy by standardizing dispensing and ensuring that the right patient receives the right medication at the right dose and time. Automation is equally crucial for handling the growing prescription volume in both hospital and community pharmacies. With aging populations, chronic diseases, and polypharmacy becoming common, the demand for accurate, efficient dispensing is higher than ever [8]. From a systems perspective, automation enhances inventory management. Traditional stock management is laborious and error-prone, often leading to shortages or overstocking. Automated systems can track expiry dates, predict demand, and reduce wastage [9]. Finally, the importance of pharmacy automation extends to patient safety, efficiency, and economic sustainability. By delegating repetitive tasks to machines, pharmacists can redirect their expertise toward clinical roles such as medication therapy management, patient counseling, and interdisciplinary care ultimately improving health outcomes.

CONVENTIONAL METHODS

Before robotics and AI, pharmacy relied on conventional approaches

- *Manual Dispensing:* In most hospital and community pharmacies, pharmacists or technicians manually counted tablets, capsules, or powders, filled them into containers, and affixed labels. This method relied heavily on the attentiveness of staff. Errors such as wrong drug selection, incorrect dosage, or mislabeling were frequent sources of medication errors. Compounding of sterile and non-sterile preparations (ointments, IV admixtures, and chemotherapy) was also performed by hand under laminar airflow hoods. Although effective, this exposed workers to occupational hazards, especially when dealing with cytotoxic drugs [10].
- *Unit Dose and Bulk Dispensing Systems:* Hospitals traditionally adopted bulk dispensing, in which medications were supplied in large containers and distributed to wards. Later, the unit dose dispensing system was introduced, where individual patient doses were packaged and delivered daily. While unit dose reduced wastage and improved safety, the preparation was still largely manual, requiring significant technician labor [11].
- *Paper-based Prescription Management:* For decades, prescriptions were handwritten by physicians and transcribed manually by pharmacists. Patient records, inventory logs, and billing

details were also maintained on paper. Illegible handwriting, transcription errors, and incomplete information were frequent problems, often contributing to medication-related adverse events [12].

- *Barcode Medication Administration (BCMA):* To reduce human errors, barcode medication administration (BCMA) and labeling systems were introduced. Pharmacists printed barcodes for medications, which nurses scanned at the bedside to ensure the “Five Rights” (right patient, right drug, right dose, right route, right time). However, the process still relied on human scanning, documentation, and system compliance, meaning errors were not fully eliminated [13].
- *Inventory Control:* Manual tracking with stock cards or spreadsheets, vulnerable to delays and inaccuracies. Pharmacies maintained stock levels using ledgers, Kardex cards, or spreadsheets. Reordering decisions were made based on staff judgment rather than real-time data. Stock-outs, overstocking, and drug expiry wastage were common in this method. These methods, while essential in their time, could not meet the demands of modern healthcare where accuracy, efficiency, and traceability are paramount [14] (Table 1).

Table 1. Limitations and Risks of Conventional Methods [10–14].

Method	**Common Errors / Risks**	**Impact on Workflow / Safety**
Manual Dispensing	Wrong drug selection, incorrect dosage, mislabeling, exposure to cytotoxic drugs	Medication errors, occupational hazards, workflow delays
Unit Dose & Bulk Dispensing	Manual preparation, labor-intensive	Time-consuming; risk of errors during packaging and distribution
Paper-based Prescription Management	Illegible handwriting, transcription errors, incomplete records	Increased risk of adverse events, inefficient record-keeping
BCMA	Human scanning errors, system non-compliance	Errors not fully eliminated; requires staff vigilance
Inventory Control	Stock-outs, overstocking, expired drugs	Disruptions in patient care; financial losses due to wastage

INNOVATIVE APPLICATIONS/OPPORTUNITIES OF AI IN PHARMACY AUTOMATION

- *Robotic Dispensing Units:* Central fill robots can automatically store, pick, count, and label thousands of medications daily. These systems minimize manual handling, reduce human error, and improve workflow efficiency. By using intelligent storage algorithms and barcode verification, robotic dispensing units ensure accuracy in high-volume environments while freeing pharmacists to engage in clinical and patient-centered activities [15].
- *Sterile Compounding Robots:* Robotics has advanced sterile compounding practices, particularly in preparing intravenous admixtures and chemotherapy drugs. Sterile compounding robots integrate AI-assisted sensors and machine vision to maintain aseptic conditions, optimize dosing precision, and comply with standards such as USP <797> and <800>. These innovations reduce variability, improve safety, and protect staff from occupational hazards [16].
- *AI-driven Inventory Optimization:* Predictive analytics supported by AI are increasingly used to forecast medication demand and manage expiry tracking. By analyzing historical consumption data, prescription trends, and seasonal variations, AI models recommend optimal reorder points, minimize stock-outs, and reduce wastage. AI-enabled systems can also identify slow-moving drugs and facilitate redistribution before expiry, improving supply chain efficiency [4].
- *Telepharmacy & Automated Kiosks:* AI-enabled telepharmacy platforms and automated kiosks extend access to pharmaceutical services in rural and underserved regions. Patients can consult pharmacists remotely through video calls, while AI verifies prescriptions and supports safe dispensing. Automated kiosks linked to centralized systems ensure timely and accurate medication delivery, bridging healthcare gaps in remote areas [17].
- *Pharmacovigilance Tools:* AI-based pharmacovigilance platforms such as VigiRank and Bayesian neural networks enable early detection of adverse drug reactions. These systems process

large datasets from clinical notes, health records, and patient reports, identifying potential safety signals much faster than manual methods. Automating pharmacovigilance reduces workload for regulatory bodies and enhances global drug safety [18].

- *Collaborative Robots (Cobots):* Cobots are designed to work alongside pharmacy staff in tasks such as packaging, labeling, and sorting. Unlike traditional robots, they have adaptive programming and safety sensors that allow safe human–robot interaction. By handling repetitive and ergonomically challenging tasks, cobots reduce staff strain, improve consistency, and support higher productivity in pharmacy operations [19] (Table 2) (Figure 1).

Table 2. Comparative Impact – Conventional vs AI-Driven Methods [15–19].

Aspect	Conventional Methods	AI / Robotic Innovations	Impact
Dispensing	Manual counting, labeling, packaging	Robotic dispensing units	Reduces human errors, improves speed and efficiency
Compounding	Manual sterile compounding	Sterile compounding robots	Ensures aseptic conditions, dosing precision, staff safety
Inventory Management	Manual tracking, stock cards, spreadsheets	AI-driven predictive inventory	Minimizes stock-outs/wastage, optimizes supply chain
Patient Access	In-person consultation only	Telepharmacy & kiosks	Expands reach, improves patient convenience
Safety Monitoring	Manual pharmacovigilance	AI pharmacovigilance platforms	Faster ADR detection, reduces regulatory workload
Repetitive Tasks	Performed manually by staff	Collaborative robots (Cobots)	Reduces ergonomic strain, improves productivity

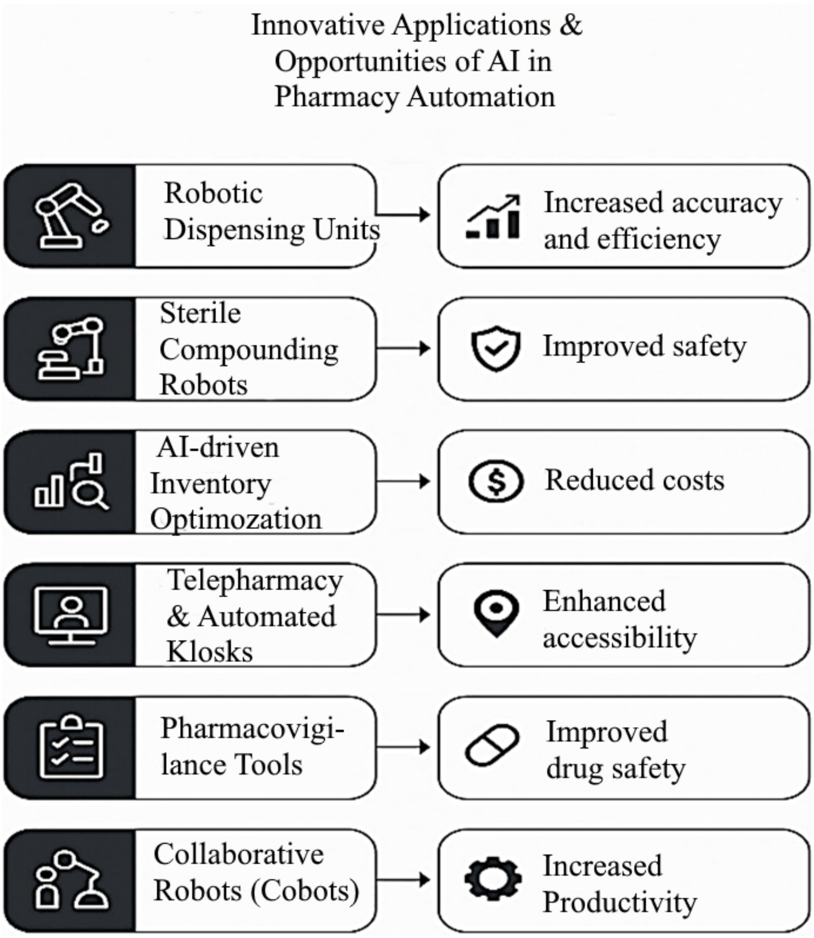

Figure 1. Flow chart of Innovative Application [15–19].

ADVANTAGES/IMPACT OF AI IN PHARMACY AUTOMATION

- *Error Reduction:* AI reduces manual dispensing errors significantly.
- *Time Efficiency:* Robots can dispense faster, allowing pharmacists to focus on clinical roles.
- *Cost Savings:* Though initial costs are high, long-term efficiency offsets investment
- *Workforce Enhancement:* Automation frees pharmacists for patient-centered care.
- *Data-driven Insights:* AI provides real-time analytics for supply chain and patient safety [20].

DISADVANTAGES/ETHICAL ISSUES OF AI IN PHARMACY AUTOMATION

- *Job Displacement:* Routine technician tasks risk being automated.
- *Privacy Concerns:* AI-driven systems handle sensitive health data.
- *Algorithmic Bias:* Predictive models may reproduce inequities in drug distribution.
- *Liability:* Responsibility for robot-related errors remains unclear.
- *Cost Barriers:* High investment restricts access for smaller pharmacies [4].

FUTURE SCOPE (RESEARCH SCOPE)

The future of pharmacy automation driven by artificial intelligence (AI) and robotics is expected to expand across multiple dimensions of healthcare. As technology advances, pharmacy will not only serve as a point of medicine distribution but also as an intelligent hub integrating patient care, data analytics, and personalized medicine. One major direction is the development of autonomous pharmacies, capable of performing end-to-end tasks with minimal human intervention. These systems will integrate robotic dispensing, AI-driven inventory optimization, automated billing, and real-time regulatory compliance. The vision of a "lights-out pharmacy," where prescriptions are received electronically, verified by AI, and fulfilled entirely by robotic systems, is becoming more realistic as technology matures [21]. Another emerging area is personalized medicine. With the growing role of pharmacogenomics and precision medicine, AI-powered pharmacy systems will be able to design tailored medication regimens based on genetic profiles, lifestyle factors, and comorbidities. This will ensure optimized dosing, minimize adverse effects, and improve therapeutic outcomes. Integration of AI with wearable health devices and electronic health records will allow dynamic dose adjustments in real time, representing a shift from static prescriptions to adaptive therapy [22]. The global pharmaceutical supply chain will also benefit from AI-driven solutions. Predictive models can identify risks such as shortages, manufacturing delays, or distribution bottlenecks, allowing proactive interventions. Blockchain-enabled platforms combined with AI will ensure transparent and tamper-proof tracking of medicines from manufacturer to patient, reducing counterfeit risks and improving trust in pharmaceutical logistics [23]. In the field of pharmacovigilance, future AI systems will utilize deep learning and natural language processing to analyze massive volumes of real-world data, including social media posts, patient forums, and wearable device outputs, to detect adverse drug reactions earlier than current systems allow [18]. This will enhance patient safety and speed up regulatory decision-making. Telepharmacy and digital health integration are likely to expand significantly. Automated kiosks, supported by AI verification, will become more common in rural and underserved regions, ensuring equitable access to medications. Remote consultations using AI-assisted platforms will support pharmacists in monitoring adherence, counseling patients, and making dose adjustments [24]. Finally, the ethical and workforce dimensions will continue to be central to research. The impact of automation on employment, data privacy, and liability must be studied with long-term evidence. Future frameworks will need to balance technological efficiency with workforce sustainability and patient trust [25].

CONCLUSION

Pharmacy automation represents one of the most transformative innovations in healthcare. From manual dispensing to AI-integrated robotics, the journey reflects a constant pursuit of safety, efficiency, and better patient outcomes. While automation brings significant advantages, it also raises ethical and workforce concerns that require thoughtful governance. The future of pharmacy will likely be a partnership between advanced technology and human expertise, ensuring both efficiency and compassion in healthcare delivery.

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