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Advancing Hospital Pharmacy Automation: Impacts, Challenges, and Future Innovations in AI-Driven Medication Management

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ABSTRACT: The use of automation within hospital pharmacy advances patient care, efficiency, and medication safety. We will review current hospital pharmacy automation technologies (for example; robotic dispensing and AI-enabled clinical support), and the potential benefits of leveraging those systems (such as time savings and reduced medication error). However, data quality challenges, and capacity to integrate legacy technology complicate and hamper the overall benefit of a pharmacy automation system. New technologies, such as digital twins and real time analytics, may offer much more transformational opportunities in pharmacy practice and practice beyond traditional pharmacy roles to engagement and clinical stewardship. All recommended best practices include readiness to implement in phases, data governance, and engaging stakeholders. Pharmacy automation provides the opportunity to transition from current models of care and outcomes determined by technology. Pharmacy automation presents a new way of delivering precision care and technology-enabled analytics; with the pharmacist at the center of health information management, of digital client care, to impact patient outcomes.

KEYWORDS: Robotic Dispensing, AI-driven, Legacy Systems, Predictive Analytics

I. INTRODUCTION

As pharmacies head into thousands of practi-Cal units in 2025, there are increased complexities and intertwined issues being brought about by changes in market factors and operational complexity. Examples of issues arising are medication shortages stemming from fragmented supply chains due to irresponsible manufacturing and geopolitical discord impacting patient and provider access to care; workforce recruitment, retention and burnout with increased challenges to all; high price of medicines associated with increased regulatory burden; closure of pharmacies affecting vulnerable populations dependant on access to care through Medicaid and Medicare; encompassed in the complexity of innovation with integrating various tools and new technology such as artificial intelligence and numerous modifications to drug formularies in the same breath while managing multiple regulations required by the profession to remain compliant; consumer population movement to order mail and through digital health channels while attempting to insert legal frameworks to mitigate consumer choice of care and to protect proprietary information of the pharmacy and or health system. Added pressures in working conditions to provide pharmacy care in addition to market pressures and increased demand in the pharmacy space solely occur in limiting resources and under increasing limitations in both consumer- drift and regulations, and finally, increased demand for pharmacy workforce to be demonstrably resilient in service provision, meanwhile increase in both cybersecurity and quality improvement in manufacturing/supply chain is expected and in some instances preferred. The challenges presented above create a timely opportunity for us to develop innovative and data-driven solutions often through, but not limited to, machine learning and predictive analytics that can support forecasting, inventory management, improving patient and family-centered care through personalized care; as well as in creating systems and processes that help to achieve better outcomes, that are essential to a sustainable pharmacy operation [1].

In the current environment of healthcare operational excellence is of utmost importance and provides a teamwork approach that can achieve a high value of benefit to the experience, quality and safety of specialized care delivered to patients. Operational excellence is adhering to a focus of continuous improvement of the processes involved in the delivery of care to focus on minimizing errors and limiting waste, while ensuring continuance of high quality patient care creating improved patient outcomes and satisfaction. Operational excellence also encompasses design of care processes that facilitate the empowerment of each health professional; creating design processes that simplify and reduce the need for already busy health professionals to take additional work and stress home, creates improvement in job satisfaction and productivity. Operational excellence provides cost savings by eliminating waste from service delivery and creates opportunities for innovation and making it easier to scale the services delivered. Operational

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excellence provides capacity for positioning organizations strategically, for consistent data collection and security, regulatory compliance, and the ability to manage organizational risk in a rapidly changing healthcare marketplace to support meeting changing patient demand and improve workforce resilience.

Operational excellence frameworks that explicitly pertain to hospitals seek to improve patient outcomes, to improve hospital flows, and to help embed an improvement ethos into the workplace culture of healthcare organizations. Examples of operational excellence frameworks include Lean Six Sigma, which focuses on waste elimination and reducing errors; the Toyota Production System, which values the human component of standardizing healthcare practices; the Plan-Do-Study-Adjust Cycle, which establishes the testing and iterating of small process steps; Value Stream Map, which identifies waste in the flow; Root Cause Analysis, which addresses problems identified in organizational processes; and the Shingo Model, which values the humility of leadership and involvement of stakeholders as part of continuous improvement strategies. The successful execution of strategic improvement strategies is contingent on secure leadership buy-in, cross-functional collaboration, data-driven decision-making, workforce training, and on-going tracking and monitoring, making increasing use of predictive analytics, and AI, to further enhance hospital processes [2].

Predictive analytics and machine learning are transforming how the pharmaceutical industry develops drugs, conducts clinical trials, manages supply chains, and provides patient care. They allow pharmaceutical companies to lower the costs related to clinical trials and shorten the time to receive a regulatory approvals of new medicines by allowing investigators to estimate drug effectiveness, adverse side impacts, and adherence chances. Machine learning algorithms can process complicated data to find the best drug candidates, personalize medicines, and lessen adverse drug reactions for improved patient safety and drug effectiveness. Machine learning can also optimize how pharmaceutical firms manage their inventories by being able to predict demand for product supply accurately, reduce wastage, and ensure drugs are available on the shelf to meet patient demand. Predictive analytics can also help expedite preparation of clinical trials to determine best patients, approximate patient drop-out rates, and identify the best sites for the clinical trials.

Predictive models can additionally be utilized in commercial opportunities like sales forecasting and targeted marketing strategies. Leading pharmaceutical companies, including Pfizer and Novartis, have already exhibited the promise of predictive modeling and the interventions afforded through predictive modeling technology by dramatically decreasing the time to development for vaccines or matching cancer patients to evidence-based treatment options. While such technologies offer incredible opportunities, significant challenges remain, including data integrity and data quality, model veracity, regulatory issues, and model transparency/explainability. Despite obstacles, predictive modeling and AI have the power to offer a more precise, cost effective, and patient-centered pharmacy practice for tomorrow [3].

Predictive analytics is a methodology by which potential future events are predicted based on historical and current events through statistical modeling, data mining, artificial intelligence, and/or machine learning methodologies. A significant part of predictive analytics is predictive modeling, in which a mathematical algorithm is used to predict the most likely event or occurrence, to assist in making more proactive decisions about the act of healthcare delivery and pharmacy. Predictive modeling uses several machine learning methodologies (e.g. neural networks and classification, regression, and clustering methods) on both structured data (e.g. patient profiles, medication prescribing trends, vaccinations) and unstructured data (e.g. clinical notes, imaging) at scale. Even real-time data (i.e. patient vitals, inventory) is often employed. In a predictive analytics framework, utilizing these methodologies starts with accessing and preparing data and then developing and validating the predictive model before engaging the predictive model into practice. The ultimate objective is to improve patient care and pharmacy operations (e.g. demand forecasting, tailored medication therapy management, early detection of adverse drug responses, and optimized inventory) to enhance patients outcomes and the efficiency /overall operations [4]. Healthcare analytics has a long history and has evolved significantly since it was introduced in the late 1950s, primarily the systematic exploration of health care delivery and clinical data using statistical analyses. In this time, John Tukey, a statistician, was a well-known pioneer of data-centric techniques that continue to influence data-driven healthcare today. In the 1980s and 1990s, the migration of patient health records to Electronic Health Records (EHRs) improved data processing and access. Early implementations of computers for diagnosing patients were limited, such as Medical Diagnostic Decision Support Systems (MDDS), e.g. INTERNIST-1, due to the intricate nature of the data and advances in computing processing. In the 21st century, however, the emergence of big data opened up advanced predictive analytics capabilities that could aid in clinical decision making. Recently, development in artificial intelligence and machine learning have evolved healthcare analytics to improved use of structured and unstructured data for operational workflows, stewardship of a personalized treatment plan, and improved patient health outcomes and modified care from reactive to proactive.

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Clinical decision support systems (CDSS), developed and fostered through advances in deep learning and artificial intelligence (AI), have significantly modified the parameters of the range of typical clinical applications beyond the traditional rules-based. AI-driven clinical decision support systems (CDSS) utilize methodologies such as machine learning, deep neural networks, and natural language processing (NLP) to synthesize large and complex healthcare data, including clinical notes, medical images, and electronic health records. As opposed to earlier expert systems that were reliant on fixed rules, AI-CDSS continuously learn from patterns in data to improve predictive precision. Convolutional neural networks (CNNs), for example, have driven advances in image-based diagnostics in areas, such as radiology and pathology, achieving dermatologist-level performance on classifying skin cancers. AI systems are also facilitating opportunities for precision medicine by integrating genetic, clinical, and demographic data to provide personalized treatment suggestions. These systems are also enhancing early risk evaluations for serious health conditions such as heart failure and sepsis, that then allow for targeted preemptive interventions to reduce avoidable patient mortality. Natural language processing (NLP) may also improve the efficiency of clinician documentation of their observations, while simultaneously accelerating their clinical reasoning by mining unstructured clinical data for information. Due to these recommendations being personalized to the characteristics of the individual patient, AI systems also may reduce clinician alert fatigue, and increase ease and confidence in engaging with the technology—with transparency, bias mitigation, and workflow integration remaining challenges that need to be addressed as well [5].

II. KEY APPLICATIONS IN PHARMACY OPERATIONS

In pharmacies, demand forecasting uses statistical and machine learning methods to improve inventory management by predicting prescriptions, patterns, and seasonal variations to reduce shortages. Time series modeling methods, like Moving Average, Exponential Smoothing, and ARIMA, all utilize historical sales data to detect trends and seasonality. Holt-Winters methods can provide additional accuracy to time series forecasts by including seasonality into demand predictions. Causal models, which can also come from econometrics or regressions, organize demand based on prognosticators outside of demand, like demographics and economic conditions, to predict longer-term demand forecasting. Machine learning models, including an example of using neural networks or random forests, analyze complex datasets to detect nonlinearities in time and in their response to demand, while at the same time being cognizant of the nuanced changes in market dynamics (e.g. demand related to treatment rationale, persistence, adherence, and curative response). Hybrid demand forecasting approaches incorporate a mix of methods in the demand forecasting efforts on behalf of suppliers to improve precision in physical inventory forecasting. Furthermore, methods of consensus and judgment, such as the Delphi methodology, are utilized for items that are new and do not have any historical data. Sophisticated platforms integrate all available information sources, such as public health data, epidemiologic data, and data concerning treatment persistence to improve forecast precision and ultimately access to medications, as well as improve operation efficiency in preparation for demand changes.

In health care, supply chain and inventory management focus on improving productivity, reducing costs and ensuring timely delivery of needed medications and supplies. Some main efforts for all suppliers to consider, occur as a result of bringing automation to supply chain and inventory management and monitoring of medications and supplies to generate demand information to ensure avoidance of stock outs or stocking too much to finally ensure health care facilities have what they need, when they need it, all while ensuring less administrative burden and eliminating errors. Analytics based on data apply artificial intelligence and other predictive technologies to improve demand forecasting and procurement planning by assessing and validating the effective use of historical consumption habits and external demand indicators. Strategic partnerships and consolidation of health systems promote economies of scale, a limited surplus of inventory, and standardized practices that provide an opportunity for improved productivity. The "force of technology" will result in improved transparency and faster operational efficiencies by sharing data among different stakeholders Supply chains that are sustainable and resilient will start to develop service models to incorporate variables of patient safety and environmental impact into their risk mitigation principles. Supply chain performance will be further advanced with more sophisticated technologies (artificial intelligence, robotics, block chain technology, deep reinforcement learning, etc.) being embedded into the supply chain practices. Together, these initiatives are more likely to develop a response to the demands of healthcare service delivery, eliminate wasted space, maintain patient care delivery, and support fiscal sustainability [6].

Workflow automation will enhance productivity in a changing healthcare landscape, particularly in pharmacy operations as it looks to automate pre-existing manual functions such as prescription verification and claims processing for insurance. The verification uses less human review, and reduces errors by review of the prescription (for checking drug interactions and whether the prescribed medication is an insurance panel) through interactions with EHR's and

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through pharmacy workflow programs. Robotic process automation (RPA) carries out standard administrative tasks such as data entry or claims submission, speeds up reimbursements, and decreases the need for human intervention. As noted, the functions can also utilize optical character recognition (OCR) and natural language programming (NLP) to review data for multiple types of documents and initiate an automated process. The processes can also provide increased accountability and transparency through audits of compliance, real-time analysis, and alerts for any exceptions. Automated refill reminders and communication devices for patients will also increase engagement, including reminders for refills which can decrease no-show rates, and develop adherence to medication therapy. Ultimately, end-to-end workflow automation will improve the speed of the process, reduce total costs of the process, lighten and relieve the burden of administrative work, and allow healthcare providers to do more of what they want to do; focusing more on patient care than documenting it. Each of these workflows is made increasingly more effective using AI and other automation technologies, and providing organizations a low-code/no-code way to enhance digital transformation efforts both workflow and in customizing the workflows in health care [7].

The automation of pharmacy workflow is improving medication administration and promoting patient-centered care in multiple tasks that pharmacy technicians and pharmacists perform such as prescription verification or insurance claims processing. As a result, the pharmacist has more time to involve in clinical activities such as individualized consultations and services. As the repetitive tasks of processing insurance claims and medication and security checks are handled by streamlined processes through automation; automation use is utilized to produce personalized medicine or drug dosages through carefully defined guidelines or protocols in order to promote quality and accuracy in medication therapy which is especially important for treatment. Using automation to connect to the patient for prescription history and adherence facilitates pharmacists' timely interactions with the patient and promotes a more individualized counseling. In addition, automation will also enhance patient engagement workflows through everything from refill reminders, easy two-way communication to support medication schedule changes to patients, while decreasing wait times and further developing the patient-pharmacist relationship, and increasing adherence to medication therapy. In summary, advanced workflow automation improves patient experiences and patient outcomes through increased efficiency and safety which complements the level of accuracy and personalization delivered by the pharmacist as an integral part of patient centered care.

In the hospital setting, automation improves personalized medicine by combining disparate patient data sets with predictive AI models that ultimately build personalized treatment protocols to support advanced care. The automation of clinical documentation, genetic (genomic) information, pharmacy records, and real time evaluations enable healthcare professionals to construct patient-specific treatment packages closer to personalized medicine by matching protocols to the individual patient's preferred treatment patterns vs a traditional patient treatment model, the "one size fits all" approach. Automation allows for more time by health professionals to provide medical care of patients (including in-home telehealth, remote monitoring, etc.). In fact, AI-based diagnostic tools promote improved diagnoses and treatment adjustments with better fidelity analysis of the patient laboratory or diagnostics test results. Automation will also rely on dynamic clinical decision support systems that continuously update recommendations based on new diagnostic information, as well as input from patients about their response to medical therapy, which has the potential to enhance study outcomes, adherence to medication therapy, and medication safety and effectiveness. Overall, automating high-stakes hospital care in an even more proactive and efficient patient-centered way addresses the goals of precision medicine. [8]

Automation plays an important role in the healthcare risk management process by standardizing, being efficient, and ensuring the accuracy of important protocols to reduce human error when verifying prescriptions and clinical documentation costs. The processes of mitigating, eliminating or removing, risk, are done in an automated mode, have technical standards and are progressively validated, which means that errors are reduced significantly. Real-time monitoring technologies rapidly detect unusual occurrences, i.e., harmful medication interactions, and allow time to intervene prior to the unforeseen occurrence becoming a more alarming situation. Automation promotes regulatory compliance and electronically generates audits for accountability. Automation provides the capacity for time-intensive tasks before the healthcare professional was possible to reallocate time to spend with patient care and reflective strategic thinking within the workflow. Predictive analytics in automated systems also advance risk management protocols addressing conseqwuences of care in patients with evolving risk and operational delays. Automation mitigates operational risks, advances patient safety, mitigates the occurrence of medication errors, and increases efficiency in the claims process, thus providing a safer healthcare community, advancing operational accountability and promoting quality patient-centered care

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III. USE CASES AND MEASURABLE OUTCOMES

The value of automation and artificial intelligence in pharmacy operations and individualized care has been observed in many case demonstrations and pilot programs. For example, one hospital in Brazil noted that prior to the implementation of robotic dispensing devices there was a substantial reduction in prescribing errors and dispensing errors, improving pharmaceutical safety and the speed of medication to patients, especially in emergencies. Robotic dispensing devices that utilize AI applications will interface with 3-D printing, machine learning, and other technologies to develop individualized dosages that are precise, and will allow for real-time monitoring of patients to improve adherence and identify problems with medication dosing early. In the hospital supply chain, blockchain technology works with AI to increase supply chain visibility to prevent counterfeit drugs and improve inventory management and medication access and availability. On the whole, all of these projects show how automation increases "safety, efficiency, and individualized care" in hospitals [9].

When looking at trials for pharmacy automated care in hospitals, they generally demonstrate improved patient care, operational efficiency, and pharmaceutical safety. Implementing these systems results in lower pharmaceutical errors related to medication, typically with decreasing dispensing errors as well. For instance, in a Brazilian hospital, the rate of mistakes made in prescriptions dropped from 26% to 15% and the rate of dispensing errors dropped from 36% to 33%. The intensive care units experienced a decrease in prescription errors, and the automated dispensing cabinets (ADCs) resulted in a marked drop in the number of errors related to the selection and preparation of a drug. In terms of operations, automation has improved medication delivery and decreased the time patients waited to receive essential treatments from 45 minutes to 1 minute, and decreased general prescription processing time by 88% overall. This increased efficiency has also resulted in a large labor savings, providing more than 35 hours a week of released staff time.

Patient safety has improved as a result of securing the medication supply along with a tenfold increase in accuracy of administration (9). This improvement meant patients were taking their medications more correctly and timely administration of medications significantly improved. For instance, the percentage of timely administration of medication increased from 59% to 77%, which benefited outcomes for some of the most critically ill patients, for example, sepsis patients. Although it initially seems costly (to purchase and install) and a somewhat burdensome point of disruption, the long-term benefits are compelling, such as the reduction of labor, reduction of medication waste, and reduction in medication related issues, affording pharmacists to spend less time doing mechanical work and more time on clinical monitoring. Overall, results of the trials align with those of prior studies documenting the clear benefits of the use of automation in hospital pharmacy in the areas of effectiveness, safety, cost-savings, and patient outcomes, thus, providing health care providers with a clear strategy for implementing automation in their approach to modern health care delivery [10].

Hospital pharmacy operations have advanced considerably with the adoption of automation, resulting in reduced wait times for patients, fewer dispensing errors, and significantly improved clinical safety. For example, patient wait times were reduced by an average of 53%, and there was a reduction of greater than forty-five minutes in the time to first dose in a highly complex case in emergency care, from forty-five minutes to only one-minute wait time. While there has been a significant increase in operational efficiency, healthcare leaders should focus on eliminating bottlenecks in the pharmacy process and addressing pharmacist shortage issues to receive the full benefit. Next, automated inventory management resulted in an 88% improvement in prescription processing time, improved availability of medication, a reduced stock-out rate and decreased waste. The implementation of automation in the process resulted in significantly reduced rates of administration, dose and selection errors, improving the safety of dispensing medication due to the scanner and validation process. Lastly, the productivity of the pharmacists and pharmacy technicians increased by 33–40%, allowing them to participate in more patient-focused activities. Along with greater productivity, there was also an increase in patient satisfaction with pharmacy services by anywhere between 20-22%. In conclusion, adoption of pharmacy automation does improve operational performance, safety, affordability, and patient experience.

IV. SYSTEM ARCHITECTURE

An integrated system for hospital pharmacy automation consists of both hardware and software to improve drug administration processes. Important hardware components include automated dispensing robots and cabinets that use arm robots, RFID tags, and barcode readers to handle medications. The integrated system may have centralized pharmacy and decentralized pharmacy methods, which allow ease of access to medications and easy preparation of unit-doses. The integrated system permits reliable data exchange through Electronic Health Records and Hospital

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Information Systems so clinician decision-making can occur in real-time for personalized medication dosing and prescription validation. The software platform manages work flow and links various other modules, such as clinical decision support and inventory management and often uses AI and machine learning technologies to identify potential errors. Communication networks allow for safe and efficient information transport in clinical workstations and with automated systems. Real-time dashboards include analytics of demand forecasting and monitoring compliance from a safety perspective. Additional technologies, such as optical character recognition, telepharmacy, and autonomous robots, contribute to the level of operations. An example of systems integrated for hospital pharmacy automation from a university hospital is St. Olavs University Hospital. Systems approach design to safety and efficiency concerns for all patient care and care that routinely personalizes care to patients and families while supporting scalable operations [11]. A depiction of an integrated system for hospital pharmacy automation, that is both hardware and software, is shown in below Figure 1:

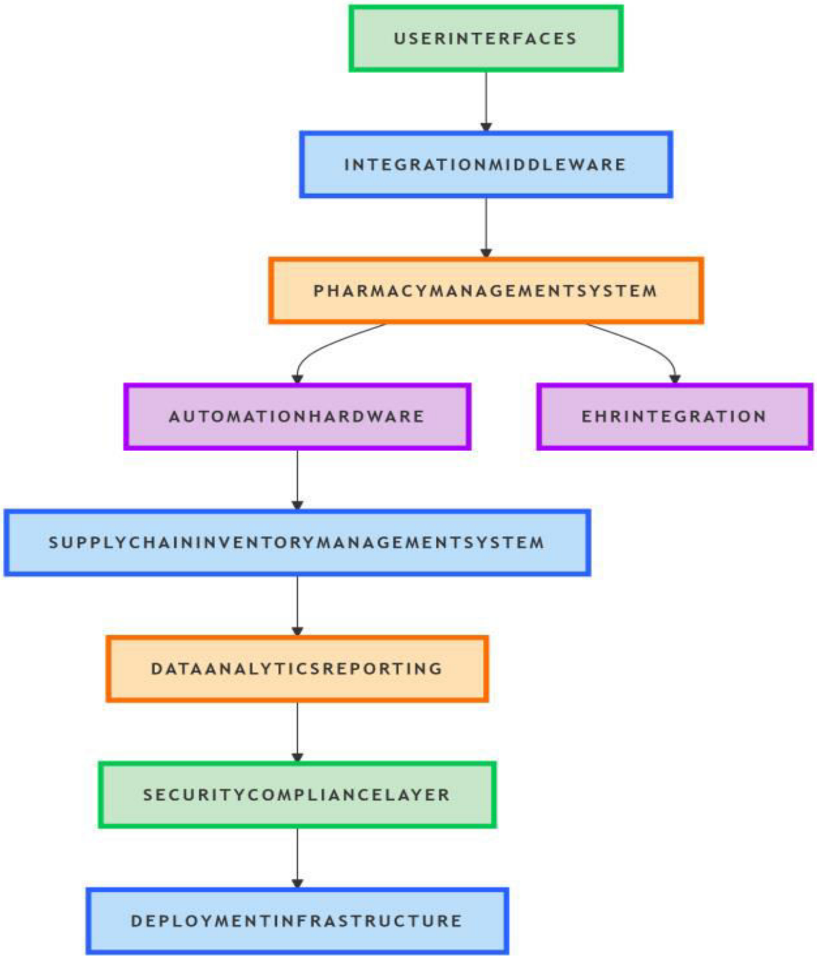

Figure 1: Hospital Pharmacy Automation System Architecture

- **Automated Dispensing Robots and Cabinets:** Automated systems and robotic arms dispense pharmaceuticals through technologies such as RFID tags and bar code scanners.
- **Centralized vs. Decentralized Pharmacy Systems:** Decentralized smart cabinets provide fast access to medications, while centralized pharmacy performs sterile compounding and dispensing of multi-dose medications.
- **Electronic Health Records (EHR) and Hospital Information Systems (HIS) Integration:** Real-time data exchange between EHR, HIS, patient records, and dispensing data streams enables personalized dose recommendation and confirmation.

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- **Software Platforms and Middleware:** Medication dispensing, preparation, and delivery workflows are managed by automation control software that may have modules for the utilization of AI, and other advanced data/information management solutions, to identify potential mistakes.
- Communication Networks: Secure connection for workstations, and automated equipment used in clinical care team location, wired (ex. ethernet) and wireless (e.g. Wi-Fi) physical connectivity, are integrated into the pharmacy automation system to simplify connectivity and functional capability.
- Real-time Dashboards and Analytic Capabilities: Identifying demand forecasts, process performance and compliance audits; through advanced data software and resource management.

While reflecting on hospital pharmacy automation there are some important issues related to interoperability, and data integration, However, most important has to do with data not retaining clinical context when transitioning data, and or systems and there are implications with accuracy in the clinical narrative, and patient safety is first and foremost. Many of the existing solutions are still utilising batch, transfer of data and/or information to simply show data elements, and have not implemented full integration when data is in motion. Decisions that are emergent, urgent, or timely, carry a level of risk when making conclusions based batch or distributed data/information environments. Added to the decreasing credibility of data, is the issue of tracing provenance of data to/from different systems, while conducting compliance audits. Data silos or different formats also complicates, and duplicate data entry, along with an incomplete patient story, and limited data governance erodes trust in reliable data, and undermines efficiency and analytics. Technical debt arises from dependence on outdated systems which limits modern integration options. Hospital IT teams in turn experience burnout from keeping up with many integrations simultaneously. To overcome these obstacles and fulfill the mission of pharmacy automation will require a people-centered approach, that aligns technological solutions to clinical processes, governance and to the user. [12].

Hospital pharmacy automation will need an expanded infrastructure that is both software and hardware focused. The software infrastructure involves Pharmacy Management or Inventory systems for controlling inventory and processing prescription orders, integration middleware that supports the interoperability of Clinical and Supply Chain systems, Workflow Automation Systems to manage prescription processes and order management, data analytic computing tools that support compliance monitoring and forecasting, in addition, data security to protect data and support regulatory compliance. The hardware infrastructure includes; automated dispensing robots and cabinets to store and dispense medications, RFID and barcode scanners to manage inventory, reliable network connectivity to support connectivity, and servers or cloud services to store and scale data.

Data platforms serve as a critical component to ensure accurate medication histories through electronic health records (EHRs), automation of the supply-chain functions, and improved patient engagement through telepharmacy and adherence monitoring services. Workforce needs include pharmacy technicians and pharmacists to operate the automations, clinical informatics specialists to oversee the governance of data, IT engineers to manage the technology infrastructure, data scientists to analyze data, and professionals skilled in change management to train and facilitate staff acceptance of the automation services. Overall success in deploying pharmacy automation solutions will depend on multidisciplinary teams supporting important discussions and decisions involving clinical and technical and operational knowledge to maximize workflows and preserve patient safety and regulatory compliance. A summary of pharmacy automation solutions and their core feature set is shown in Table 1 below. Pharmacy automation is typically defined as solutions that can drive efficiency, accuracy, and workflow in medication management. Each automating solution category will have specific features designed to meet pharmacy practice needs, from medication dispensing solution systems to inventory management solutions. The goal of pharmacy automation solutions is to improve workflow, decrease human error, and indirectly improve patients care through more effective management of resources and delivery of care. Identifying the most relevant category of pharmacy automation solution is summarized in Table 1 below:

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Table 1: Major Pharmacy Automation Solution Types and Features

Solution Type	Key Features	Primary Use Cases
Automated Dispensing Systems	Automate medication counting, sorting, dispensing; ensure inventory accuracy; error reduction	Retail pharmacies, hospitals, long-term care, outpatient clinics
Automated Packaging & Labeling	Precise medication packaging, labeling for dosing accuracy; compliance with regulatory standards	Centralized pharmacies, mail-order, repackaging facilities
Automated Table-top Counters	High-speed, accurate pill counting and dispensing, reduces manual errors	Retail, hospital, compounding pharmacies
Automated Storage & Retrieval	Robotic inventory storage, retrieval; space optimization; real-time tracking and error minimization	Hospitals, large pharmacies
Medication Compounding Robots	Automated drug mixing, sterile compounding; precision and safety	Hospital pharmacies, specialty compounding
Prescription Verification Systems	Electronic checks for prescription accuracy, drug interactions, contraindications	Integrated in pharmacy management systems
Prescription Filling Robots	Automate filling of prescriptions from bulk stock, reduces labor demand	High-volume pharmacies, retail chains
Medication Management Software	Inventory management, e-prescribing, refill management, patient profiles, billing integration	All pharmacy types across retail and healthcare
AI & Machine Learning	Drug dispensing accuracy, predictive analytics, patient adherence monitoring, chatbot assistance	Decision support, patient engagement
Blockchain Integration	Drug traceability, counterfeit prevention, supply chain transparency	Medication safety, regulatory compliance
Robotic Process Automation (RPA)	Automate administrative tasks like claims, order placement, and returns processing	Workflow efficiency in pharmacy operations

Although leveraging pharmacy automation is beneficial, there are many considerations of pharmacy automation that fall into several areas of challenges. The first area is explainability, bias, and quality of the data. There is a desire for reliable and consistent data, bias mitigation in the AI models, and explainability or reasoning of the AI so the clinician can create trust. The second area is the challenge of integrating those automating system with pharmacy, especially pharmacy operations and pharmacy IT, which are legacy systems that may not be FHIR compatible or lack APIs for interoperability with automated pharmacy services. The third area is change management. Employee resistance from uncertainty may require continued training and involvement, which may improve acceptance. There are also budget constraints for smaller hospitals that can lead to hesitance to adopt automation. Budget constraints are often tied to implementation and maintenance. There are real risks to medication availability and patient safety when dealing with technical errors and outages, which is why robust power systems and vendor tech support is needed. Often debated in automation is that while certain roles and responsibilities can be automated, the human aspect of clinical judgment and personalized care will require human involvement, suggesting that not all responsibilities in the pharmacy will be able to be automated. Addressing each of these challenges can be done through thoughtful planning, engaging multiple stakeholders, various training levels, and a focus on patient safety and interoperability, utilizing a systems-thinking approach as the basis to improve the chances of success for automation is shown in below Figure 2:

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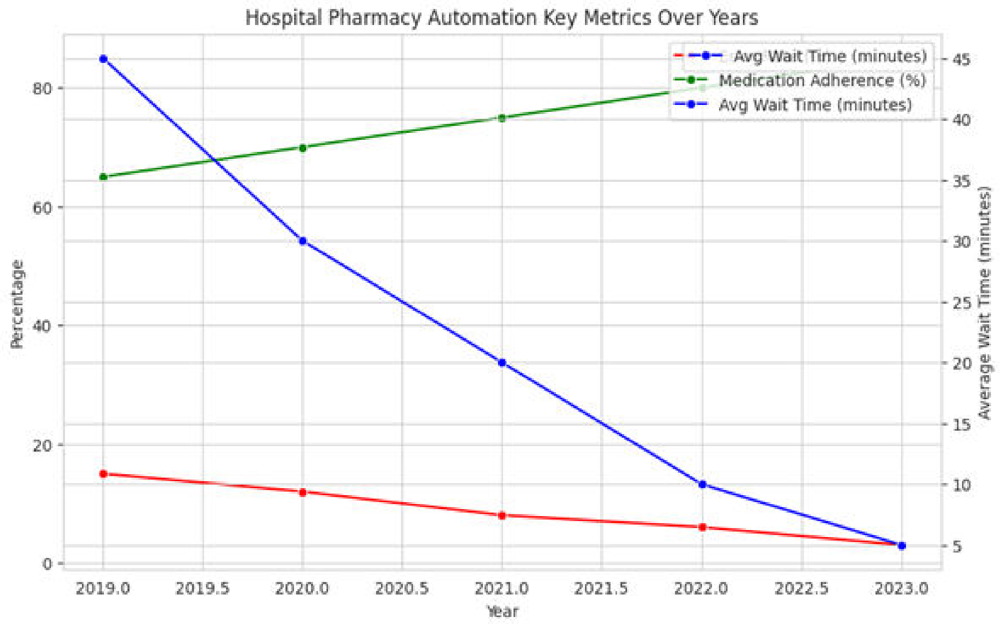

Figure 2: Hospital Pharmacy Automation Key Metrics Over Years

V. CONCLUSION

Recent developments in pharmacy systems emphasize the incorporation of technology to enhance decision support, patient safety, and operational efficiency while reducing error. Realtime analytics make it easier to improve demand planning and identify issues through a variety of data sources. The utilization of digital twin technology is on the rise in simulating and optimizing pharmaceutical operations for increased resilience and throughput. With the increased automation of more routine repetitive work, pharmacists and technicians will shift to more clinical decision making, AI oversight, and patient engagement roles with an increased need for upskilling in data analytics and collaboration. By introducing AI and digital technologies to organizations, they benefit from efficiencies, lower error rates, and less waste. Likewise, AI and digital technologies are defining personalization and prediction into pharmacy operations. There are challenges with change management and integration that pharmacy leaders need to plan on investing in. Pharmacy leaders need to make plans to invest in data governance, employee training workflows in AI integrations, engage those technology vendors that share in this investment in workforce development with safety as a primary focus, and create key performing indicators (KPIs) to assess and evaluate the performance of the pharmacy continuously. Further, as we look further ahead as AI and digital twin technologies evolve, these technologies will lead to pharmacy operating in much higher levels of automation, which will allow pharmacists to further enhance clinical activities that improve, manage, and triage better patient health; especially in the area of sustainability with predictive analytics and AI. Additionally, when considering existing literature and business visibility that looks through 2025 and beyond, the supporting consensus using best practice will exist as well.

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