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Applications of Artificial Intelligence and Robotics in Pharmaceutical Sciences: Advancing Drug Discovery, Personalized Medicine, and Pharmaceutical Manufacturing

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Abstract

This paper reviews the major contributions made by artificial intelligence (AI) and robotics to pharmaceutical sciences, particularly drug discovery, personalized medicine, and pharmaceutical manufacturing. It demonstrates the speed and cost efficiency of finding therapeutic candidates using large chemical libraries and biological data generated by AI applications that accelerate this process over traditional techniques. Furthermore, AI predictive capabilities to predict the drug's pharmacokinetic and pharmacodynamic profile help to minimize the risks of late-stage clinical trial failure and facilitate the process of developing drugs. In the personalized medicine arena, AI's potential to learn from genetic, environmental, and lifestyle data enables the development of custom-tailored treatment plans to improve patients' outcomes while mitigating negative side effects. These are enhanced by robotics to automate drug synthesis, ensure dosage consistency, and enhance patient safety. It is likely that AI will play a vital role in drug discovery in the future, and cutting-edge machine learning (ML) algorithms will help to dramatically speed up the identification of novel therapeutic targets while saving time and money by delaying or eliminating traditional discovery steps. Also, AI and robotics can be integrated into pharmaceutical manufacturing in order to optimize efficiency by continuously monitoring and optimizing the production processes, enhancing supply chain optimization, and ensuring quality assurance (QA). Overall, this review highlights the impact of AI and robotics in pharmaceutical sciences for creating a more effective and customized healthcare system, which will make patient care and treatment outcomes more efficient.

Keywords: Artificial Intelligence, Robotics, Drug Discovery, Personalized Medicine, Pharmaceutical Manufacturing

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Introduction

AI and robotics have changed industries for the better, and pharmaceutical sciences are one of the biggest winners. This combination of technologies has altered the way drugs are discovered, personalized medicine is provided, and pharma products are manufactured, all to improve productivity and accuracy. AI can be implemented in several ways, such as ML, deep learning, and natural language processing, which allows for automation and process optimization of many functions in pharmaceuticals. Such technologies allow us to perform many tasks, such as mining large data, modeling predictive models, and developing novel drug treatments [1]. AI-based applications in drug discovery, for example, are speeding up the selection of targets to treat through a minefield of chemical and biological information. It has been faster and cheaper than conventional approaches with long trials and errors [2]. In addition, using AI to predict pharmacokinetic and pharmacodynamic characteristics of medications decreases late-stage clinical trial failures and leads to an efficient drug development process [3]. Furthermore, these technologies can also be used to find new drug targets and reuse existing drugs, thereby making old medications even more effective [1].

AI and robotics have pushed the boundaries of personalized medicine, in which treatments are personalized according to patient characteristics. AI algorithms can use the genetic, environmental, and lifestyle data to anticipate the patient's response to specific treatments in order to tailor individual therapies [1]. Robotics assist in this regard as they will automate the formulation of drugs and ensure dose control, which improves patient safety and treatment efficacy [4]. This combination can transform patient care and optimize treatments.

Especially in the pharmaceutical industry, with robotics and AI systems, production lines can be automated, workflows will be efficient, and human error will be minimized [5]. These technologies also allow for real-time monitoring of production, compliance with regulations, and the quality of final products. AI also helps with predictive maintenance of manufacturing machinery to reduce downtime and improve productivity [6].

The use of AI and robotics in the pharmaceutical sciences, overall, is an important step in the field and has the potential not only to transform drug discovery and individual medicine but also to automate manufacturing. Keeping up with the times, pharma executives will need to embrace these technologies if they wish to stay ahead of the fast-moving changes in medicine.

1. Steps to Implement AI and Robotics in Pharmaceutical Sciences

In integrating AI and robotics into pharmaceutical sciences, there are several planned steps for better drug discovery, personalized medicine, and drug manufacturing. This integration will aim to reduce waste, increase accuracy, and eventually help with regulatory compliance while providing better care.

Before implementing AI and robotics, it's essential to understand their roles in the pharmaceutical industry. AI refers to the technologies such as ML, natural language processing, robotics, etc., that can use huge amounts of data to automate processes. Such tools may change drug discovery, manufacturing, and treatment designs based on patient data [7, 8].

1.1 Strategic Framework for Implementation

The way to implement AI and robotics is to first set a strategic roadmap with clear goals and objectives. It needs to be the same kind of framework the pharmaceutical company has, with the focus on the areas where AI and robotics can deliver the most value. Targets can be shortening development times of drugs, improving clinical trial efficacy, and improving patients' outcomes with personalized treatments [9, 10].

Once the goals are established, it's important to check the current infrastructure and data storage systems. This analysis enables gaps to be found, and the technical integration requirements defined. Existing technologies should be able to handle AI, for instance, computational resources, data storage, and algorithms to handle big data effectively [11, 12].

1.2 Data Acquisition and Preparation

Information is the basis of any AI program. Then the next phase would be capturing and preparing the data, which can be preclinical trial data, clinical trial data, patient data, manufacturing data, etc. This data should be of the highest standard, representative and heterogeneous.

Standardization and normalization of data formats across platforms is also required for data interoperability. And, as we know that the pharmaceutical sector is incredibly regulated, compliance with regulations regarding data privacy and security is a must [13, 14].

1.3 Developing and Training AI Models

After data is sanitized, it's about building and running AI models. From supervised learning for predictive medicine discovery to unsupervised learning for clustering and segmentation of patient data, depending on the goal, different algorithms in ML can be applied.

Training means putting the AI models through training with the preloaded data to learn from. The models are trained over and over again with new data to keep them accurate and performant in the future [10, 15]. Moreover, the continuous model assessment and validation are also important to measure the performance and adjust algorithms as necessary.

1.4 Integrating Robotics into Pharmaceutical Manufacturing

In pharmaceutical production, the application of robotics is of special benefit. Robotics could automate tedious work to eliminate human error and increase manufacturing productivity. The use of robotics systems is a process of designing automation workflows that have robotic arms and automated systems for packaging and quality control.

Combined AI-robotics increases productivity as well. AI will analyze production data in real time, and robotics will make the correction, and then we can have a reactive manufacturing process [11, 7].

1.5 Implementation and Continuous Improvement

With these first steps in place, the real work can start. This is the step of introducing the AI solutions in production and embedding them into the workflows. Having the right people in the right place and having them supported through the transition is essential to success. These technological changes require innovation and flexibility from organizations to get ready for these transformations [16, 15].

Finally, there needs to be a feedback loop on the success of AI and robotics implemented. This iterative improvement process includes keeping track of performance, collecting user insights, and tweaking processes and models. The periodic updates and repair of AI infrastructures keep it in sync with the demands of drug discovery and production [13, 10].

Putting AI and robotics into the pharmaceutical sciences takes some planning, strong data systems, and continuous improvement and adaptation. Such a policy puts pharmaceutical companies in a better position to capitalize on the technology we have at our disposal, and this has the potential to generate new drug technologies and delivery technologies.

2. Benefits and Applications of AI and Robotics in Pharmaceutical Sciences

2.1 Benefits of AI and Robotics in Pharmaceutical Sciences

The application of AI and robotics to pharma science has many benefits that greatly improve the effectiveness and efficiency of drug discovery, personalized medicine, and drug production.

The first advantage of AI in drug discovery is that it can crunch big numbers and find new drug candidates at higher speeds than conventional means. ML and deep learning AI algorithms can pore over bio-dense data, find patterns, and project the effect of different compounds on biological targets. This accelerates the early drug discovery process, thus removing the time and cost of trial and error [17, 18].

Apart from the efficiency of drug discovery, AI helps in personalized medicine as well. AI platforms can read patient information such as genetic data, treatment history, and reaction to previous therapies. This data helps healthcare professionals personalize treatment for individual patients, which makes therapies more effective and the adverse effects smaller. In this way, AI can be leveraged by the pharmaceutical industry to transition away from a generic solution to a more tailored solution with significant improvement in patient outcomes [19, 20].

Even pharma manufacturing can benefit from AI and robots. AI-powered automated systems can also streamline production using predictive maintenance that will identify when the equipment fails in order to prevent downtime and increase savings. Then there is AI's ability to provide better quality control by monitoring production in real-time and finding deviations that might cause product problems. This is not only for regulatory compliance but also for expediting the time of entry of a drug [21, 18].

Overall, the advantages of applying AI and robotics in the pharmaceutical sciences include more efficient, less expensive, more personalized, and more compliant patient care, which is a more effective healthcare system.

2.2 Applications of AI and Robotics in Pharmaceutical Sciences

The pharmaceutical sciences have no limit to how AI and robotics can be employed in drug discovery and manufacturing processes. AI tools in drug discovery are changing the way pharmaceutical firms search for and develop new therapeutics. For example, advanced analytics and AI algorithms are used to scour massive amounts of data from clinical trials and literature to find drug candidates that might work. The new drugs could be forecasted on the basis of the past outcomes by ML models and can inform the decision-makers in the companies, which drug candidates to pursue [17, 22]. 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 [19, 23]. 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 [18, 24]. Another big application is clinical trials, in which AI can design trials and recruit more patients by finding them more effectively. It can quickly speed up pharmaceutical companies' ability to develop new drugs, all the while maintaining high clinical standards [22, 25].

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.

3. Companies Leveraging AI and Robotics in Pharmaceutical Sciences

3.1 Companies Implementing AI in Pharmaceutical Sciences

- *IBM Watson Health*: IBM Watson Health uses AI to conduct many drug discovery and healthcare analytics tasks. Its AI algorithms analyze terabytes of medical information and give recommendations that enhance patient outcomes and clinician decision-making [26]. In recent times, Watson from IBM has been interested in improving clinical processes and drug management leveraging AI intelligence derived from large biological data sets [27].
- *Pfizer*: Pfizer is a leader in using AI/ML in pharma research. The company created an oral antiviral medication, PAXLOVID, for COVID-19 based on AI technology that helped the drug development speed up a considerable deal [28, 29]. Pfizer's AI projects span drug discovery, clinical development reports, and regulatory approval [29]. The AI-powered system opens up the opportunity to learn more about diseases and patients' therapeutic responses [30].
- *Novartis*: Novartis is applying AI and ML to over 150 projects to increase drug discovery performance. The firm works with companies such as Microsoft and NVIDIA to scale AI solutions in the enterprise. Novartis focuses on using AI for accessibility and efficiency in healthcare, although exact results of these initiatives are still being tested [28].

- *AstraZeneca*: AstraZeneca also partners with AI companies like BenevolentAI and Oncoshot to leverage AI for clinical trial patient targeting and the discovery of novel drug targets. This collaboration has already led to some new candidates for diseases like chronic kidney disease and pulmonary fibrosis [28]. The use of AI by AstraZeneca is indicative of a strategy that places technology at the heart of its R&D operation in order to bring more productivity and innovation.
- *Bristol Myers Squibb*: Bristol Myers Squibb is working with Exscientia to use AI for the discovery of small molecules. This partnership will accelerate drug candidate discovery and development for diseases such as oncology [28]. AI tools help identify which compounds will make it to later trial stages and thus enable better drug development productivity.
- *Merck*: Merck has been in several joint ventures around AI-enabled drug discovery, such as with BenchSci and Atomwise. Their projects will use ML to analyze biological data to drive the drug development pipeline and target drug candidates more efficiently [28].
- *Exscientia*: Exscientia is known as an entrepreneur in AI-powered precision medicine. The company is using its AI platforms for the discovery of drugs to develop the best drug as fast as possible. Exscientia's AI-engineered small molecules were successful in clinical trials and show how much AI can be applied to the development of drugs today [31].
- *GSK*: GlaxoSmithKline (GSK) teams up with Cloud Pharmaceuticals and Insilico Medicine for target-target and drug design using AI technologies. They work on using AI to build new molecular architectures and pick out good drug candidates to develop [28]. GSK's AI programs show that it aims to move forward with drug development based on current scientific understanding.
- *Roche*: Roche has agreements with some AI companies, such as Recursion Pharmaceuticals, to leverage AI for drug discovery and development. AI integration at Roche is also meant to make the identification of candidates and the identification of possible clinical use cases faster [28]. The AI could help Roche in its R&D work and the drug development process.
- *Lilly*: Eli Lilly plans to scale its AI projects considerably, aiming to do more than 100 AI initiatives [28]. It has understood AI's potential to increase efficiency in different areas of the company, from regulatory affairs to clinical trials. Lilly's move to digital technology shows that it is on a path towards a data-driven pharma sciences strategy.

3.2 Companies Implementing Robotics in Pharmaceutical Sciences

- *Kiro Grifols*: Kiro Grifols has robots for compounding sterile products. Their KIRO Oncology system is built for precise automation of oncology drugs and will provide reliability and safety in critical situations. KIRO Fill is also an automated, non-toxic, compounded sterile preparation machine for high efficiency and patient safety [32].
- *Strateos*: Strateos has a robotic cloud drug discovery lab where drug makers can perform tests from anywhere. This lab scales up and runs faster by automating all aspects of genetic engineering, including sequencing and splicing. With the addition of robotics, scientists are free to ponder results instead of tedious work and therefore speed up science [33].
- *Thermo Fisher Scientific*: Thermo Fisher Scientific is an industrial laboratory robot manufacturer that provides many automations for the lab. They have automated laboratory systems that help them handle complex work for drugs and allow fast development cycles without human oversight. They have technology used in synthetic biology, drug discovery, and bioproducts manufacturing [34, 35].
- *Zipline International*: Zipline is known for their use of drones in drugs as they do logistics and supply chain management. Their self-piloted drones are helping distribute medicine and pharmaceuticals rapidly to rural and underserved areas for faster delivery of medicines and to deliver care in general [36].

- *Getinge*: Getinge specializes in lab automation solutions, i.e., cleaning and transporting lab equipment. Their cage handling devices automate washing and care of cages in the lab to maintain hygienic standards and increase operational efficiencies within the pharmaceutical research lab [37, 38].
- *ABB*: ABB, an industrial robotics company, offers automation solutions for drug manufacturing. They're deploying their robots for sample transfer, equipment maintenance, and medical device assembly. In automating them, ABB improves production and QA in pharmaceutical processes [39, 40].
- *Charles River Laboratories*: Charles River Laboratories is utilizing robotics for cell therapy manufacturing. They are pioneering in the automation of the QA testing and bringing down the final release testing from 14 days to three days. This step makes the development of important cell therapies for patient care very rapid [41].
- *Multiply Labs*: Multiply Labs is committed to robotically automating cell therapies manufacturing. They're one of a consortium looking at industrial-scale gene-technological cell therapies, working with big players such as Cytiva to develop reliable, regulation-compliant robotic production lines. They are developing technology not only for improved reliability in production but also for better access to new treatments [42, 43].
- *Bionaut Labs*: Bionaut Labs uses robotics to address brain diseases precisely. They create remote-controlled micro-robots to bring medicines directly to a problem region of the brain. This new method addresses unmet medical needs in neurology, which highlights robotic therapy in vulnerable settings [44].
- *Insilico Medicine*: Insilico Medicine leverages robotics in its fully automated labs for discovery of drugs. They employ robots with AI that do everything from high-throughput screening to genomic testing. Automating these steps enable Insilico to reduce human bias in drug development and increase precision in the results, all the while reducing the time required to commercialize a new drug [45, 46].

4. Literature Review on Applications of AI and Robotics in Pharmaceutical Sciences

The number of articles covered for the applications of AI and robotics in pharmaceutical sciences in this review are shown in Figure 1 from 2019 through 2024.

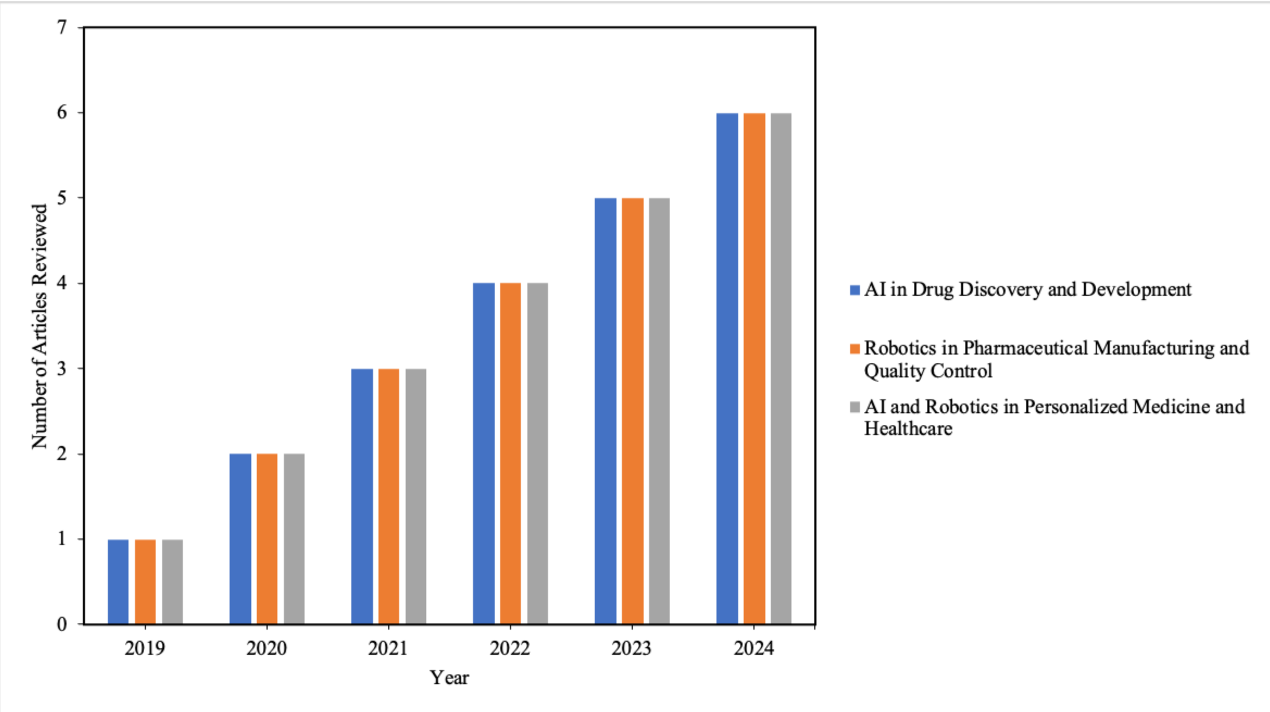

Figure 1: Articles reviewed (2019-2024) for applications of AI and robotics in pharmaceutical sciences

4.1 AI in Drug Discovery and Development

Table 1 below shows a quantitative distribution by publisher of the number of articles related to AI in drug discovery and development.

Table 1 Number of articles from different publishers reviewed for AI in drug discovery and development

Publisher	**Number of Articles Reviewed**
Elsevier	3
MDPI	2
Springer	2
Wiley	2
ACM Digital Library	1
Bentham Science Publishers	1
Cell Press	1
IEEE	1
Indian Journal of Pharmaceutical Education and Research (IJPER)	1
IntechOpen	1
International Journal of Scientific Research in Engineering (IJSREM)	1
Journal of Chemical Health Risks (JCHR)	1
Journal of Drug Delivery and Therapeutics (JDDT)	1
Scientific Temper	1
Technoscience Academy	1
Wolters Kluwer Health	1
Total	**21**

Wang et al. (2019) focused on using AI to read large datasets, predict drug-target interactions, target lead compounds, and accelerate clinical trials. Their study showed the way AI could transform drug design in the big data era while solving data quality and inter-disciplinary collaboration issues [47]. Sethuraman (2020) went further by pointing to AI's application in formulation development, using ML, neural networks, genetic algorithms, and others for drug-process optimization and economic efficiency, and the cost savings are projected to be tremendous [48]. In contrast, Jiménez-Luna et al. (2020) used explainable AI (XAI) to boost the model transparency in deep learning models of prediction of molecular structures and new compound generation. They studied the ills of interpretation in AI models and suggested XAI methods to make chemists and data scientists work together [49]. Archer and Germain (2021) pointed out that AI could expedite time and money by enabling virtual screening, preclinical optimization, and clinical trials. Their results showed AI's potential to be used in patient selection, adherence, and post-marketing surveillance in the face of data quality and regulatory hurdles [50]. Tang et al. (2021) also found AI's role in solving some of the most fundamental

problems in molecular property prediction, de novo design, and retrosynthesis. They pointed to the potential of AI in mining massive biomedical datasets for drug reuse and for optimizing drug discovery [51]. Moingeon (2021) took this even further, talking about AI's application of multimodal data to disease modeling, therapeutic target selection, and biomarker discovery. It backed computational precision medicine and allowed for customization of treatments and new clinical trials such as virtual placebo groups [52].
Borkotoky et al. (2022) targeted ML and AI applications to the drug life cycle, focusing on in silico predictive absorption, distribution, metabolism, excretion, and toxicity (ADMET) models to optimize therapeutic compound efficacy, safety, and dosage. They emphasized AI's ability to model drug targets, 3D protein structures, and small molecule behavior, which in turn streamlined drug discovery [53]. So too, Lluka and Stokes (2022) applied AI to discover antibiotics by solving antibiotic resistance by leveraging ML to study antibacterial systems biology, drug interaction, and mechanism of action. They focused on restoring the old approaches like natural product discovery using AI tools and proposed open-access datasets to move faster [54]. Sharma (2022) meanwhile sketched out the general use of AI in the drug industry by providing examples of the application of AI in clinical data analysis, diagnosis, and selection of patients for clinical trials using artificial neural networks (ANNs) and natural language processing [55].

Craig et al. (2022) focused on the promise of AI to revolutionize research, drug development, and personalized medicine. They were particularly interested in experts' advice on AI's capacity to speed up clinical trials and predict molecular interactions but noted shortcomings such as data quality and interdisciplinary communication [56]. Mhatre (2023) similarly discussed AI's capacity to speed up drug discovery by discovering new targets and streamlining drug development for virtual screening, binding affinity prediction, and drug formulation. The study underlined AI's predictive ability for physicochemical analysis and dosage optimization, although at the early stages of deployment [57]. Acharjee et al. (2023) added to the debate the idea of AI-inspired innovation in drug reuse, molecular structure prediction, and data visualization techniques. Their paper addressed such fundamental issues as ethical data use, model usability, and the necessity of a context-based AI algorithm selection [58].

Parvathaneni et al. (2023) focused on AI and ML to improve drug discovery workflows, such as target discovery, lead optimization, and ADMET prediction. They had shown that software such as AlphaFold and Deep Docking helped significantly to predict protein structure and screen compounds with much lower cost and quicker time to development [59]. Patnaik et al. (2023) developed these advantages further and focused on how AI would help solve age-old bottlenecks (e.g., cost and trial inefficiencies). They highlighted AI's role in drug repurposing and toxicology prediction, with examples of how natural language processing and patient data analysis improved trial outcomes [60]. In contrast, Nguyen et al. (2023) focused on AI in the field of G protein-coupled receptor (GPCR)-based drug discovery and outlined its capability to explain GPCR mechanism, identify ligands, and predict therapeutic response [61].

Sahgal and Sundarasekar (2024) wrote about the use of AI and ML for accelerating drug pipelines, molecular design, and solving hard-to-solve preclinical research challenges. They also found that AI can lower costs and drug development times while facilitating disease understanding [62]. Huanbutta et al. (2024) took this one step further and gave a view of AI's use in the pharmaceutical life cycle, from drug discovery, formulation development, manufacturing, quality control, and post-market surveillance. They focused on predictive modeling and data analytics to ensure stable drugs and production at the same time that tight quality control and patient safety are maintained [63]. In contrast, Ujjwal (2024) looked at AI as a drug-development revolution and the efficiency with which it solved the problems faced by the standard drug discovery processes. The research also talked about AI's potential to decrease failure rates, improve formulations, and accelerate innovation but mentioned issues with data quality and ethics [64].

Chakravarthi et al. (2024) referred to AI and bioinformatics as complementary tools for computer-aided drug design (CADD) via data analysis, prediction, and optimization. They showed how AI could help with problems such as data integration and visualization and improve drug design time [65]. Patne et al. (2024) focused on AI's potential to revolutionize target-based drug discovery utilizing ML. They showed the usefulness of techniques such as Simplified Molecular Input Line Entry System (SMILES), deep learning, and generative adversarial networks (GANs) to optimize target finding, binding affinities, and lead compound discovery [66]. In contrast, Serrano et al. (2024) discussed the possibilities of AI's wider use, specifically in re-engineering individualized medicine and delivery of drugs. Their paper reported AI's potential in the optimization of treatment, drug safety, and regulatory problems [67].

4.2 Robotics in Pharmaceutical Manufacturing and Quality Control

Table 2 below shows a quantitative distribution by publisher of the number of articles related to robotics in pharmaceutical manufacturing and quality control.

Table 2 Number of articles from different publishers reviewed for robotics in pharmaceutical manufacturing and quality control

Publisher	**Number of Articles Reviewed**
IEEE	6
MDPI	3
Royal Society of Chemistry	2
Springer	2
American Association for the Advancement of Science (AAAS)	1
arXiv (Cornell University)	1
BMJ Group	1
Elsevier	1
International Journal of Pharmaceutical Quality Assurance (IJPQA)	1
SLAS Technology	1
Wiley	1
ΛΌΓΟΣ: Collection of Scientific Papers	1
Total	**21**

Rosso et al. (2019) focused on laboratory automation for pharmaceutical process development using Highly Automated DoE (HAD) workflows and robotic systems for chemical processes optimization. They described improved experimental reproducibility, yield, and reduced impurities in synthetic active pharmaceutical ingredient (API) fabrication [68]. In contrast, Palamattathkuttiyil et al. (2020) examined how automation might affect all QA functions more generally, from increased efficiency, compliance, and robotics-based monitoring of quality to customization of medicine. They pointed out issues like cost and skill requirement but highlighted how automation in QA could revolutionize processes [69]. Kujau et al. (2020) specifically tested the APOTECAchemo robotic system for compounding cytotoxic medications with high dosage precision (97.5% within ±3%) and a low error rate (~1%), improving patient safety and decreasing toxic-drug exposure in the workplace [70].

Opaspilai et al. (2021) designed a robotic system using Selective Compliance Assembly Robot Arm (SCARA) robots, a vision system, and convolutional neural networks (CNNs) to depalletize hospital beds with a focus on better logistics and lower labor costs [71]. Hole et al. (2021) focused on the full digitalization of the pharmaceutical industry, specifically robotics' contribution to Good Manufacturing Practice (GMP) compliance, operational efficiency, and change-resistant resistance in Contract Development Manufacture Organizations (CDMOs) [72]. Courtney and Royall (2021) summarized the robotics in the lab during COVID-19 with a focus on diagnostic testing and biobanking, as well as barriers to adoption such as integration with workflows and reliability [73].

Ochs et al. (2022) invented the AUTOSTEM platform, a robot-controlled automated system for producing mesenchymal stem cells (MSCs) for cell therapies. The platform proved to be more efficient, with proliferation of cells faster and quality controlled as compared to the traditional approaches, while maintaining sterility and GMP compliance [74]. In contrast, Mathew et al. (2022) explored mobile collaborative robots as bioprocessing facilities for customized drug production and environmental monitoring. They described how the pliability and effectiveness of these robots in daily tasks such as tube transport, bag manipulation of infusion bags, and Petri dish scanning reduced human error and streamlined manufacturing [75]. Alahmari et al. (2022) analyzed robots applied to pharmacy, in this case drug dispensing. Robotic systems, they discovered, could reduce the medication error rate, speed dispensing, and improve patient safety by replacing human tasks with machine-readable activities. But they did note that even mechanical malfunctions needed human supervision, and there was no automation for that [76].

Saharan (2022) spoke about robotic systems' overall benefits in accuracy, speed, and reproducibility in the pharma and life sciences sectors. His studies called attention to robot technology and, in particular, to the development of collaborative robots and humanoids, which lessen human interference in such fundamental tasks as drug discovery and biotechnology. The adoption of AI and Internet of Things (IoT) made work more efficient and safer in these environments too [77]. In contrast, Borkar et al. (2023) focused on the production and development of Delta robots for pharmaceutical manufacture. They took on the technical issues of material selection, kinematic design, and control system integration and thereby improved efficiency, accuracy, and safety in pharma manufacturing. What they discovered was that customized design and testing is critical to ensure that the robots perform as expected in the industry [78]. Arce et al. (2023), on the other hand, focused on the development of a robot palletizer and visual algorithms for drug packaging quality control. Their work pioneered a dual method of computer vision and joint robotics to detect more defects and correctly label and weight. Its early validation tests showed that the system can be easily operated for palletizing work and is an excellent productivity and quality control solution [79].

Yu et al. (2023) explored image processing for laboratory robots with the integration of the Opentrons industrial robot with the YOLOv5 object recognition framework. Their work showed that the system can greatly increase accuracy in processes such as tip detection and liquid measurement of pipettes and liquids, leading to higher quality control and more efficient lab processes [80]. Borkar et al. (2023) reviewed pick-and-place robots in pharma that are also getting used because of labor shortages and higher safety and quality requirements. The paper focused on the robots' effectiveness in repetitive tasks, like pill counting, fluid handling, and quality-control inspections. It also reported that automation of the pharmaceutical industry eliminates human error and ensures compliance with regulations [81]. Stasevych and Zvarych (2023), on the other hand, gave a much more general description of robotics and AI in pharmacy and medicine and how these technologies could change medicine. Their studies pointed to the possibility of using AI and robotics to improve pharmacokinetics, personalized medicine, and precision in treatment [82].

Thieme et al. (2024) was designed to use cost-effective liquid handling robots in a drug development lab, using the Opentrons OT-2 robot with AutoLab software for lab automation. The integration, they showed, was more efficient and accessible to users, had a lower learning curve for the new users, and solved the cost and complexity challenges in lab workflow [83]. Klymenko (2024) wrote about how dynamic programming algorithms were used to balance the load on a pharmaceutical manufacturing conveyor line and how robotics plays an integral part in increasing production efficiency, reducing mistakes, and adhering to tight quality control. The dynamic programming style provided for continual improvement stumbling blocks, keeping up with changing demands of the pharmaceutical industry [84]. Bao et al. (2024) showed an automated chemical synthesis system for drugs that had a robotic chemistry system coupled to special software that made complicated synthesis more automated. Their system was both precise and efficient in generating therapeutic compounds, with promise of lower manufacturing times and costs in drug production [85].

The study by Tang et al. (2024) focused on automating drug delivery in smart pharmacies through a multi-stage grasping network and adaptive robotics system. They used sophisticated image-processing and drug segmentation techniques to precisely robotically handle drugs of different shapes. The system was tested in a pilot setting and showed great efficacy and flexibility of drug delivery in a smart pharmacy environment [86]. In contrast, Slattery et al. (2024) built RoboChem, a robot system for automated photocatalytic processing. This system also used various robotic elements to perform closed-loop Bayesian optimization, resulting in higher yields for reactions and scale-up photocatalysis in continuous flow reactors. These findings showed the platform’s versatility and effectiveness in maximizing photochemical reactions, which led to pharmaceutical use cases in chemical synthesis [87]. Topelius et al. (2024) conducted a multi-site evaluation of automated non-sterile pharmacy compounding for children’s propranolol tablets. They went from 90% to 100% dosing accuracy through iterative stages with a 3D printing-like process and quality control instruments like NIR spectroscopy. They focused on how automation could help with better dosage accuracy and overall quality in pharmaceutical compounding, especially for pediatric formulations [88].

4.3 AI and Robotics in Personalized Medicine and Healthcare

Table 3 below shows a quantitative distribution by publisher of the number of articles related to AI and robotics in personalized medicine and healthcare.

Table 3 Number of articles from different publishers reviewed for AI and robotics in personalized medicine and healthcare

Publisher	**Number of Articles Reviewed**
Elsevier	3
Springer	3
Taylor & Francis Group	3
Frontiers	2
IGI Global Scientific Publishing	2
Bentham Science Publishers	1
Cell Press	1
IEEE	1
Institute for Systems and Computer Engineering, Technology and Science (INESC TEC)	1
IOP Publishing	1
IOS Press Ebooks	1
Journal of Obstetric, Gynecologic, & Neonatal Nursing (JOGNN)	1
MDPI	1
Total	**21**

Fang et al. (2019) focused on collaborative task assignment of connected, affective robots acting as autonomous healthcare helpdesks. Their work showed that emotionally receptive robots could collaboratively work to better treat patients by changing their workload based on the instantaneous emotional and situational judgments of patients. Such a dynamic system improved work performance and patient happiness, which indicates large-scale opportunities for AI-powered robots in healthcare [89]. In contrast, Bauer et al. (2020) used AI and infrared thermography to create an automated system for determining stages of cellulite. These findings demonstrated that Histogram of Oriented Gradients (HOG) combined with ANNs was more than 80% accurate at the stage of cellulite detection, particularly in the early stage of cellulite detection, which allowed for diagnosing and treating patients as per their specific needs [90]. Instead, Ghita et al. (2020) looked at AI and automation in anesthesia (closed-loop drug delivery systems). The paper reviewed automation progress and challenges to develop truly integrated systems for anesthesia control. In spite of the technology deficiencies, these studies focused on the possibility of patient safety, cost-effectiveness, and clinician effectiveness to make it easier to manage anesthetics more dynamically and personalized [91].

De La Vega et al. (2021) demonstrated how important AI is in genome analysis, particularly for rare genetic disorders. They developed GEM, an AI tool that would automate the search for candidate genes, speeding up and saving money. GEM ranked more than 90% of causal genes in the top candidate set and was superior to other variant prioritization systems with a recall rate of 97% for true positive diagnoses. This also brought the tool's capability to work with complicated genetic variants, including structural variants, and to rework previously unresolved cases [92]. In contrast, Tsopra et al. (2021) were centered on AI validation in precision medicine and the prediction of treatment response in triple-negative breast cancer (TNBC). Their framework focused on hard-to-explain validation, such as data safety, metrics, and explainability of AI. The purpose of this study was to establish AI in oncology to be safe, efficacious, and open before bringing it to the clinic [93]. Gasteiger and Broadbent (2021) talked about more general applications of AI and robots in medicine, reporting developments in neural networks, wearable computing, and companion robots. They pointed to AI's potential for diagnostic enhancement, personalized care, and health monitoring in real time. The research also recognized barriers, including ethical and the risk of technological hegemony overtaking the human side of care [94].

Kumar et al. (2022) created the DeepBoT system, a deep learning robotic system with live monitoring sensors for elderly patients, and it is focused on scaling and affordable IoT and AI healthcare. It focused on robot medical support and ultrafast data transmission to set the bar for e-healthcare [95]. Sorrentino et al. (2022) devised a cognitive system for socially assistive robots (SARs) with individualized care via AI-based representation of knowledge, reasoning, and human-in-the-loop decision-making. In tests with the assistive robot ASTRO, the system tailored cognitive testing and treatment to elderly residents and was more efficient in handling larger patient groups [96]. Jain and Jain (2022) referred to the potential of AI, IoT, and robotics combined in order to improve medical operations and patient care through profiling of individual trends and facilitating oversight. There were also barriers such as lack of evidence for actual implementation according to the research [97].

Similarly, Ahmad et al. (2023) focused on AI and home-based diagnostics, highlighting their potential to enable real-time health monitoring and personalized treatment plans. They observed that such technologies foster patient engagement and reduce hospital dependency but acknowledged challenges like data privacy and infrastructure needs [99]. In contrast, Edmonds (2023) explored AI's application in women's health and nursing care, emphasizing predictive analytics, personalized care, and improved decision-making. Her research highlighted enhanced nursing workflows and patient outcomes while noting the importance of user-friendly implementations and addressing training gaps [100].

Costa et al. (2022) examined computer vision, robotics, and AI to improve the delivery of care, especially for diabetes care. Their research focused on how automation can support better diagnosis, monitoring, and utilization to provide better patient care and lower healthcare system burden [98]. Similarly, Ahmad et al. (2023) was all about AI and home diagnostics and how they can provide live monitoring of health and individualized care. They noted that these types of technologies enable patient engagement and hospital independence but noted data privacy and infrastructure requirements [99]. Instead, Edmonds (2023) looked at AI for women's health and nursing, with the focus on predictive analytics, personalized care, and decision-making. Her study also outlined improved nursing processes and outcomes along with easy-to-use implementations and gaps in training [100].

Kumar et al. (2023) reviewed AI uses in healthcare in a detailed way that highlighted the ways in which AI can be used to improve diagnostics, therapy recommendations, and clinical management systems. The research noted important obstacles such as ethics and trust issues and called for cross-sectoral collaboration to break down those obstacles [101]. D'Silva and Gatti (2023) were devoted to AI-based robotics and explained how they were used in surgery, rehabilitation, telemedicine, and diagnostics. Their study highlighted the accuracy and efficacy of these technologies in healthcare as well as regulatory and ethical limitations [102]. Vardhanabhuti et al. (2023) provided much more comprehensive coverage of AI and robotics, ranging from diagnosis of disease, drug discovery, treatment tailoring, and surgical assistive robotics. They reported real-world usage and new technology, including wearable health monitors in real time [103].

De Micco et al. (2024) discussed the legal challenges of robotics and AI in health care, with a focus on how they will help revolutionize patient care through accurate diagnosis, individualized care, and improved data collection. But the research also noted medico-legal issues, including unclear liabilities in malpractice claims involving self-aware technologies, and proposed dedicated legal structures to solve them [104]. In contrast, Trezza et al. (2024) was about unsupervised learning for precision medicine, how the AI can mine big data to detect new patterns in disease and stratify patients. They discussed how unsupervised learning could provide unintentional information for targeted treatments but acknowledged issues such as data privacy and clinical validation [105]. Gupta and Jha (2024) also talked about AI use in medical robots with the success in surgical accuracy, diagnosis, and telemedicine. Their paper highlighted the healthcare-transforming power of AI-powered robots while solving problems around data availability and ethical issues [106].

Shafik et al. (2024) pointed out that AI and medical robotics transformed smart healthcare, streamlining patient data and medical care and responding to labor shortages and epidemics worldwide. But these advances did not sate the data security and patient safety fears, so effective measures are required to ensure sustainability [107]. Sudha et al. (2024) focused on AI-powered diagnostics and robotics and their potential in cardiovascular disease diagnosis, medical imaging, and elderly care. Their study highlighted ML and IoT in the mix to improve diagnosis accuracy and performance while recognizing the cybersecurity and data management problems [108]. Maglogiannis et al. (2024) launched the first-ever digital twin technology in healthcare, which provided mental and physical health monitoring in real time at a hospital for early identification of burnout and sustainability of the workplace. The AI4Work project specifically focused on healthcare workforce well-being in a way that the other studies had focused almost entirely on patients [109].

6 Challenges and Future Scope of AI and Robotics in Pharmaceutical Sciences

6.1 Challenges

Bringing AI and robotics to the pharmaceutical sciences has a multitude of difficulties. A main fear is that of AI regulations. Current regulation is in no place to accommodate a new technology and slows AI-powered drug development and manufacturing. Good systems will have to be created to ensure safety, efficacy, and data quality while correcting AI algorithm biases [110].

Data integration and maintenance is another big problem. Healthcare companies tend to parse huge data sets from multiple data sources, all siloed and hard to aggregate. Good AI systems need data analytics techniques

that can combine data to provide the right insights [111]. Data interoperability can be a hindrance in leveraging AI's full capabilities in drug interaction prediction, patient response prediction, and clinical trial efficiency.
There's also the issue of clinical evidence and practical use. Not only do AI algorithms need to work efficiently in controlled conditions, but they need to be usable in clinical contexts. Problems of ethics in AI implementation, such as patient privacy, informed consent, and algorithmic bias, will become even more challenging as they are incorporated into healthcare [110].

6.2 Future Scope

Despite the challenges, the future scope of AI and robotics in pharmaceutical sciences is promising. AI for drug discovery will only accelerate due to high-accuracy ML algorithms to forecast molecular interactions and drug efficacy. The ability of computational models based on AI could potentially be applied to find novel therapeutic targets in a very short time and with minimal expense compared to traditional discovery strategies[3].
Customized medicine is where AI's opportunities lie. AI could parse genetic, environmental, and lifestyle information to formulate individualized therapy plans for specific patients. The predictive capabilities of AI can be utilized by clinicians to tailor treatment regimens and drug treatments to achieve better patient outcomes with fewer side effects [112].
When it comes to pharmaceutical manufacturing, robotics and AI can reduce waste by providing automated machinery that monitors and reconfigures production in real time. Using AI robots will streamline supply chain management and strict QA and result in the creation of smart manufacturing processes to meet market demands without any compromise on regulatory compliance [21].
In the future, AI and robotics combined with new technologies like quantum computers and low-code systems will be able to create even more possibilities in pharmaceutical sciences. These partnerships can give elasticity for future continuous improvement and scalable solutions in drug development and manufacturing, and ultimately better care [113].

Conclusion

The convergence of AI and robotics in pharmaceutical sciences marks a revolution in drug discovery, personalized medicine, and pharmaceutical manufacturing. The use of these technologies improves the process efficiency and effectiveness, which improves the care and health outcomes for patients. AI helps to discover therapeutic candidates quicker and cheaper than traditional approaches by rapidly parsing big datasets to detect them. This is not only shortening the development cycle of a drug but also cutting down on late-stage clinical trial loss through better predictive analytics. It is important that AI tailor treatment programs accordingly. Through individualized patient information, such as genetics and lifestyle, AI could enable the creation of personalized treatments that achieve the best possible outcomes and have minimum side effects. Drug manufacturing is streamlined, drug formulation is precise, and the overall process is optimized by robotics. It frees researchers to work on something new, instead of on the same thing, and speeds up science. There are bright prospects for AI and robotics in the pharma sciences, and they could potentially change drug discovery and patient care further. These technologies are going to keep evolving and leading to more and better healthcare innovations. Finally, with AI and robotics in the field of pharmaceutical sciences, we are not only making advances in drug discovery and personalized medicine but also in the manufacturing chain, which is leading to better patient outcomes and a better healthcare system.

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