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Review Article

AI, Automation, and Robotics in Pharmaceutical Industry

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ABSTRACT

A significant change is taking place in the pharmaceutical industry, driven by the integration of advanced technologies such as Artificial Intelligence, Robotics, and Automation. This review explores the historical evolution of these technologies, beginning from their origins in the 11th century through their rapid development during the Industrial Revolution and subsequent adoption in the 1980s. The application of AI in drug discovery and development enhances data analysis, predicts drug-target interactions, and streamlines clinical trial processes, while also facilitating personalized medicine through tailored treatment plans. Robotics, including various specialized designs, significantly improves manufacturing efficiency and safety in sterile environments. Moreover, automation is pivotal in optimizing production processes, maintaining compliance with good manufacturing practices, and enhancing operational efficiency. The potential of nanorobots for innovative drug delivery and therapeutic interventions presents exciting opportunities, albeit with challenges such as safety and cost. Looking ahead, the convergence of these technologies leads to advancements in autonomous systems and personalized healthcare, underscoring the importance of developing a skilled workforce capable of navigating the complexities of digital systems in the pharmaceutical landscape. Collaborative efforts with educational institutions will be essential for fostering the expertise.

INTRODUCTION

The pharmaceutical industry has been utilizing computers since the 1980s for collecting data, conducting research, and drug development.(1) Recently, AI automation and robotics have emerged as rapidly growing sectors, especially within this industry. These technologies involve

machinery that minimizes the need for human intervention. By enhancing efficacy, accuracy, and safety in drug production and discovery, they significantly improve outcomes. Additionally, they are advantageous for data storage and managing documentation records. Algorithms are being used to analyze vast datasets, including molecular structures, biological data, and clinical

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trial outcomes, to identify potential drug candidates and predict their effectiveness. Machine learning models can help streamline the early stages of drug development, reducing both time and costs. The use of AI in clinical trials streamlines patient recruitment by analyzing electronic health records and identifying suitable candidates. AI can also help in monitoring trial progress and outcomes, ensuring compliance, and assessing data for safety and efficacy more effectively than traditional methods. Magnetic small-scale robots show great potential in medicine due to their movement advantages. Recent research highlights improvements in their design and use, aiming for clinical applications.

The studies emphasize the need for better functionality and reliability and suggest further development for commercialization.(2)The pharmaceutical industry is undergoing a significant change due to the implementation of innovative technologies. AI acts as a highly advanced machine learning system, constantly analyzing a massive amount of data. This capability significantly enhances researchers' ability to gather insights more efficiently. In the world of pharmaceutical innovation, robots are transforming the way we develop new medications, making the process faster, safer, and more efficient than ever before.(2)



Figure 1: Technical use in Pharmaceutical Industry

In our modern era of rapid technological growth, the advancement of software and manufacturing innovations is reshaping healthcare and industries alike. Along with this growth, 3D printing or additive manufacturing (AM) continues to expand as a specialized technology. Although it originated in the 1980s, 3D printing has developed into an important tool for producing layered objects from a material or ink based on computer-aided design (CAD) models, which are sliced in software for manufacturing.(3)

3D printing is increasingly favored over traditional manufacturing methods, which often have

limitations. It is becoming widely adopted in healthcare sectors, including therapeutics, orthodontics, and the production of medical devices. As this technology continues to progress, it holds the promise of enhancing efficiency and generating innovative medical solutions.(3)

Nano robots are tiny machines engineered at the nanometer scale, offering groundbreaking potential in the pharmaceutical industry. Built with knowledge from physics, chemistry, biology, and engineering, these devices can operate inside the human body to deliver drugs, assist in diagnosis, and support therapeutic treatments. By detecting

abnormal signals or cells, evaluating cellular health, and releasing targeted chemicals, Nano robots can precisely eliminate harmful cells, such as cancerous tissues. Nano robots are being used more and more for diagnosis, prevention, and treatment, especially for delivering drugs. They can help monitor glucose in people with diabetes, treat heart attacks, rebuild tissues, repair nerves, fight cancer, and deliver drugs directly to the brain or bones. New developments in robotics, nanotechnology, medicine, bioinformatics, and computing are making these drug delivery systems possible. Notable examples include respirocyte, microbivore, surgical, and cellular repair Nano robots, which typically have diameters of 0.5-3 microns and are constructed from components measuring between 1-100 nanometers.(4–8)

Even though Nano-robots have many benefits, there are some drawbacks. For example, if several types are used at once, they might form clusters inside the body. Also, using and setting up Nano-robots can be very expensive. This technology would change healthcare by making treatments more personal, effective, and with fewer side effects. It may also help doctors perform less invasive surgeries and catch serious diseases earlier. Researchers are even looking into how Nano-robots might slow down aging.(1) Nanorobotics is defined as the technology focused on creating machines or robots that operate at or close to the nanometer scale (10^{-9} meters). These devices are also referred to as Nano machines.(9)

Technological evolution: The history of automation dates back to the 11th century, when machines and equipment for automation were first developed. In the 1800s, during the Industrial Revolution, modern automation emerged with mechanized methods and advanced tools, significantly boosting factory productivity. By the 1920s, the introduction of electricity further sped

up manufacturing processes. The progress continued in the 1930s and 1940s with the development of feedback controllers, which improved automation capabilities. By the 1980s, automation technology was widely adopted across sectors such as manufacturing, retail, pharmaceuticals, and consumer goods.(1)

Types Of Robots Used in the Pharmaceutical Industry.

➤ Scara Robots: -

SCARA, which stands for Selective Compliance Articulated Robot Arm, robots are defined by their ability to move freely within a single horizontal plane. While they typically have four axes, there are variations that feature three or five axes as well. The first two links can swivel horizontally, while the third link, known as the quill, moves vertically and can also rotate horizontally, though it does not tilt. Some SCARA robots are equipped with a hollow air balance cylinder, which is a metal shaft that offsets the weight of the end effector and payload. This feature helps reduce “Settling time” is the delay a robot experiences after it moves to a position before it can perform its next action. SCARA robots offer several advantages, such as a fixed swing arm design that allows for very fast cycle times. Their small footprint and lightweight construction make them well-suited for tight spaces. However, their primary limitation is their restricted ability to maneuver around obstacles.(10) As these robots are high-speed robots in the pharmaceutical industry, they can perform quick pick-and-place tasks with a high level of precision. SCARA robots are precisely utilized in advanced pharmaceutical processes, including 3D printing of pharmaceuticals, CNC milling, and drilling of medical devices. This capability meets the quality control and demands of companies.(11)





Figure 2: Scara robot arm.

➤ **Cartesian Robots: -**

The system's structure comprises two linear slides positioned at a 90-degree angle. A motorized unit travels horizontally along these slides, which correspond to the X and Y axes, while also being capable of vertical movement along the Z-axis. A quill holds the robot's end effector, such as a gripper, and a fourth axis (θ) enables the quill to rotate in the horizontal plane. One of the main advantages of this robotic configuration is that it is generally less expensive compared to other types of robots.

However, it does have some disadvantages, notably a restricted range of motion. In terms of applications, this system is frequently utilized in automated systems designed for specific tasks and is commonly found in devices that specialize in tasks like assay testing.(10)

Cartesian robots are designed for linear movements and are commonly used for precise pick-and-place operations along fixed paths. They are especially effective for accurate motions within a defined plane and are often employed in tasks such as liquid handling and plate manipulation.(11) As items progress through production and their weight, including boxes, cartons, and pallets, increases, simpler robotic systems like Cartesian robots may be used in early stages. These robots are well-suited for straightforward, linear tasks such as assembly and pick-and-place operations. However, as production demands rise and items become heavier, more powerful robotic arms may be required. While Cartesian robots are efficient for specific applications, articulated robotic arms are better for tasks needing flexibility and complex movements. Understanding the strengths of Cartesian robots is crucial for optimizing production efficiency.(12)



Figure 3: Cartesian robot arm.

➤ **Articulated Robots: -**

Articulated robots are known for their enhanced mobility, which is attributed to their vertical and horizontal joints. They typically have more joints than SCARA robots. The work envelope for articulated robots is spherical, demonstrating enhanced flexibility in their movements, and they can execute tasks that resemble those performed by a human hand or arm. The most common type of articulated robot features six axes. The first link rotates in the horizontal plane, similar to a SCARA robot, while the second link rotates in a vertical plane. These six-axis articulated robots mimic the movements of a human arm, including the forearm and wrist. This similarity is due to the inclusion of

a vertically rotating wrist joint and a vertically rotating forearm, which enables increased maneuverability (ability to move).

This similarity is due to the inclusion of a vertically rotating wrist joint and a vertically rotating forearm, which enables increased maneuverability. With their human-like forearm and wrist joints, six-axis articulated robots can pick up various materials and objects from the horizontal plane, regardless of their orientation. They can not only pick up objects but also place them at any required angle. Additionally, articulated robots are capable of performing a wide range of other tasks.(10)



Figure 4: Articulated robot arm.

Application Of AI, Automation, And Robotics in the Pharmaceutical Industry.

- **Emerging Technologies in Drug Discovery:**

- AI in drug Discovery: AI enhances the identification of drug candidates by analyzing biological and chemical datasets. It predicts drug target interactions, toxicity, and efficacy, while also enabling drug repurposing during emergencies. Tools such as DeepDTA and PADME are utilized to predict drug-binding affinities.

- Clinical trials: AI enhances patient recruitment, monitors trial data in real-time, and employs predictive analytics to design more efficient trials. Robotics systems are also used to manage trial data effectively.

- Customized Healthcare solutions: AI insights into individual Patient data to develop tailored treatment plans, predict individual drug responses, and minimize side effects.(13)

1) Manufacturing and Production: -

- Automation in manufacturing: automated systems optimize processes such as mixing,

granulation, tablet pressing, and capsule filling. This ensures consistency and reduces waste.(14)

- Robotics in production: robots handle high-precision tasks, including weighing, dispensing, and liquid handling.(15) Collaborative robots aid in packaging and inspection, while automated guided vehicles (AGVs) transport materials throughout the facility.(14)

- Sterile Environment: robots function in aseptic conditions, particularly for vaccine production and injectable drugs. This helps to minimize contamination risks and ensure product safety.(16)

2) Quality Control and Assurance: -

- AI in Quality Control: AI-powered vision systems are used to inspect products for defects, analyze production data to identify anomalies, and optimize manufacturing processes.(11)

- Automation in quality Assurance: Automated systems ensure accurate documentation for

regulatory compliance and enable real-time monitoring of critical parameters.(16)

3) Medical applications: -

- Physicians are currently using AI to evaluate patients and analyze health risks.
- AI programs are also being utilized to educate physicians about different medications and their potential side effects.(17)

4) Advanced Diagnostics and Monitoring: -

- AI in Diagnostics: AI analyzes medical data for the early identification of health conditions, which is crucial for effective treatment, and provides treatment recommendations.(11) Wearable devices, integrated with AI, monitor patient health in real-time.(13)

5) Packaging and Labeling: -

- Robotics in Packaging: Blister packaging, bottle packing, and labeling tasks are automated by robots.

- AI in labeling: AI makes sure that labels include correct regulatory information and dosage guidelines.(12)

6) Regulatory compliance: -

- Automation for compliance: good manufacturing practices (GMP) are followed, and accurate paperwork for regulatory submission is kept by automated systems.(15)

7) Medicine supply and patient monitoring by Automated guided vehicles AGVs: -

- The vehicle's main purpose is to: Deliver medications to patients.
- Monitor key body parameters, including temperature.(18)



Figure 5: Nasopharyngeal swabs

Role Of 3D Printing in Modern Pharmaceuticals.

3D printing is becoming increasingly utilized in the medical field, with various applications

demonstrating significant value in enhancing clinical decision-making and improving patient care.(19)

- 1) 3D Printed nasopharyngeal swabs: - During the COVID-19 pandemic, it was crucial to focus on testing to enable early diagnosis of the disease. Nasopharyngeal (NP) swabs were used as the gold standard for testing, which is essential for identifying and isolating infected individuals to prevent further person-to-person spread. However, the effectiveness of widespread testing depends on test quality and treatment impact. Rapid increases in cases can

overwhelm current medical equipment, disrupting supply chains for items like swabs, ventilators, and personal protective equipment. Because it allows for the rapid and cost-effective production of complex and customized products, 3D printing offers a promising solution to these shortages. Additionally, open source design sharing via 3D printing facilities, global prototyping, effectively meeting the rising demand.(20)



Figure 6: 3D printing of personalized medicines

- 2) 3D printing for personalized medicine: - 3D printing is a versatile technology that allows for the creation of customized medications by adjusting factors such as size, shape, and fill rate. This capability directly addresses the unique needs of specific patient populations. It improves medication for children to produce low-dose, personalized medications specifically for pediatric patients. It also enhances the taste and appearance of drugs for patient compliance. This technology can prepare loose and porous formulations, making medications easier for elderly patients who have difficulty swallowing.(21)
- 3) 3D printing in pharmaceutical production: - 3D printing technologies mainly utilize inkjet-

based or inkjet powder-based methods. Inkjet-based drug fabrication involves spraying precise droplets of drug formulations and binders onto substrates like paper, cellulose, or glass. A variation of this method encapsulates droplets in a liquid film, creating microparticles and nanoparticles for targeted molecule delivery.(22)

- In powder-based printing, an inkjet printer applies an “ink” containing active ingredients onto a powder bed, solidifying it layer by layer. These technologies allow for innovative dosage forms like microcapsules and multilayered drug delivery systems, incorporating ingredients such as

acetaminophen, vancomycin, and various polymers.(22)

- 4) 3D printing in pharmaceutical research and drug development: - 3D printing, especially through the use of 3D bioprinters, is transforming pharmaceutical research and drug development. It facilitates the creation of customized medications, moving away from the traditional “one-size-fits-all” model. This innovative technology enables on-demand drug printing in various environments, such as clinics and even patients’ homes. As it becomes increasingly affordable and sophisticated, it also addresses safety and regulatory challenges. These advancements present a competitive edge for companies that integrate 3D printing into their supply chains, as it promises to deliver better, more personalized pharmaceuticals. (23)

- 5) 3D printing for Kidney-on-a-chip platform: - 3D printing is essential for developing advanced research tools like “kidney on a chip” platforms. These systems mimic human organs and serve various functions, including drug screening, toxicity testing, and disease modeling.(24)

- 6) 3D printing in the manufacturing of solid oral dosage forms: 3D printing (3DP) is revolutionizing the production of solid oral dosage forms (SODFs). All 3DP technologies commence with a design crafted using computer-aided design (CAD) software. This design is subsequently transmitted to the printer’s software, which slices the model into individual layers that the printer constructs sequentially to produce the final object. Additionally, some 3D printing processes may require post-processing steps, such as removing excess materials, polishing, or sintering.(25)

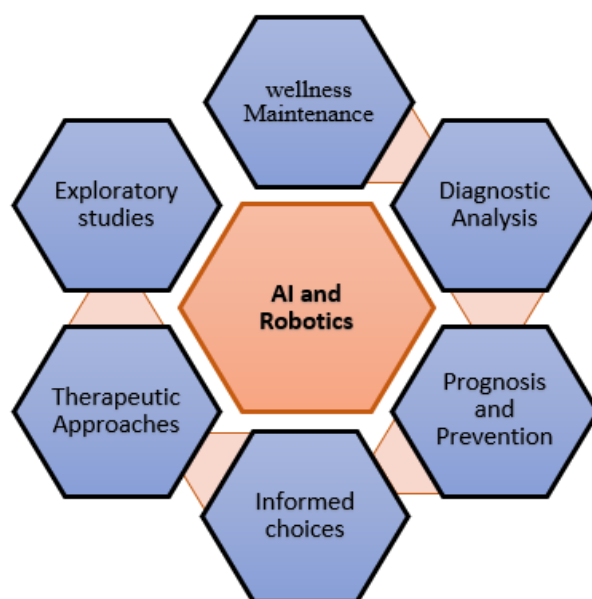


Figure 7:- Technological roles

- 7) **Nano robots** Richard Feynman coined the term “nanorobots” in 1959, while Robert Freitas was the first to investigate nanorobots.

Norio Taniguchi helped create the term “nanotechnology” in 1974. Dr. Eric Drexler authored publications on nanoscale and

nanodevices in the 1980s. Fullerenes and carbon nanotubes were invented in 1985 and 1991, respectively. Atomic force microscopy (AFM) was invented in 1991. In 2000, a

company and a Nano manufacturing facility collaborated to create nanorobots for clinical use.(5)



Figure 8: Nano Robots

➤ **Manufacturing approaches: -**

- Biochips: Utilize the joint approach of nanoelectronics, photolithography, and new biomaterials for manufacturing nanorobots. Applicable in surgical instrumentation, diagnosis, and drug delivery.(4)
- This manufacturing method has been in use in the electronics industry since 2008.
- Practical nanorobots may be integrated as nanoelectronics devices for teleoperation and advanced medical instrumentation capabilities.(4)
- Nubots: Nubots are organic molecular machines at the nanoscale, constructed from DNA structures. They can assemble 2D and 3D nanochemical devices and be activated by small molecules, proteins, or other DNA molecules.(4)
- Engineered biological circuit gates based on DNA allow for in-vitro drug delivery targeted at specific health issues.
- However, these systems do not permit precise in-vitro teleoperation of the engineered prototypes.(4)
- Surface-bound systems: Synthetic molecular motors can attach to surfaces and demonstrate machine-like motions when confined to microscope materials.
- These motors can potentially move and position nanoscale materials similarly to a conveyor belt.(4)
- Bio-hybrids: Bio-hybrid systems merge biological and synthetic elements for biomedical or robotics applications.
- Components include nanoscale DNA, proteins, or mechanical, with techniques like thiol-ene-e-beams for nanoscale feature writing and functionalization.(4)

- Bacteria-based systems: This method utilizes microorganisms such as *Escherichia coli* and *Salmonella typhimurium*, employing their flagella for propulsion.
- Electromagnetic fields typically regulate the movement of these biological devices.(4)
- Virus-based: Retroviral gene therapy involves retrained retroviruses that attach to cells and replace DNA through reverse transcription. These vectors, typically pol-gag genes, are used in retroviral, adenoviral, and lentiviral gene delivery systems. These vectors have been used in cats to send genes into genetically modified organisms (GMOs), enabling them to display a specific trait.(4)

➤ Applications of Nanorobots: -

- Nanorobotics dentifrices: It is delivered by mouthwash or toothpaste. It covers the subgingival surface and metabolizes organic matter into harmless vapour. Identify and destroy pathogenic bacteria in plaque. Mechanical devices that deactivate when swallowed.(7)
- Maintenance of oral hygiene: Mouthwash with smart nanorobots targets and eliminates harmful bacteria. Supports harmless oral flora for a healthy ecosystem. Identifies and lifts food particles, plaque, and tartar for rinsing. It can reach areas beyond toothbrush and floss.(7)

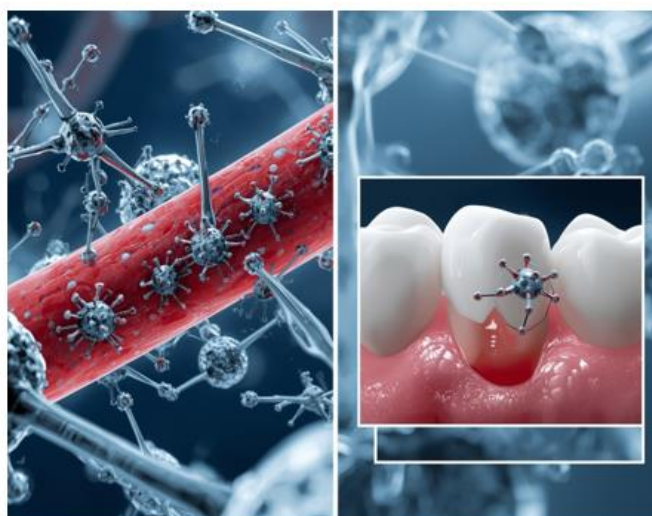


Figure 9: Treatment of Diabetes, Tooth repair

- Treatment of Diabetics: Nanorobots represents a promising advancement in the healthcare sector, offering the potential to enhance medical instrumentation, diagnostics, and therapeutic treatments. For patients with diabetes, frequent blood sampling is necessary to monitor glucose levels, which can be uncomfortable and inconvenient. To address this issue, continuous glucose monitoring through medical nanorobotics can be

employed. This technology allows for automatic tracking of sugar levels in the body, enabling doctors, specialists, and healthcare professionals to provide real-time health care, improving the patient's medication regimen.(6)

- Tooth Repair: Techniques involve genetic engineering, tissue engineering, and regeneration. Nanorobots enable complete

dentition replacement, covering mineral and cellular needs.(7)

- Treatment of cancer: Modern medical technology and treatments can be used to treat cancer effectively, with early diagnosis being crucial for improving a patient's chances of survival, so it is important to detect cancer before it begins spreading. To minimize the side effects of chemotherapy, targeted drug delivery must be effective. Nano robots can move through the body and use chemical biosensors to detect early-stage tumors.(7)
- Cavity preparation and Restoration: Multiple nanorobots work together for cavity preparation and restoration. Precise focus on demineralized enamel and dentin to conserve tooth structure.(7)
- Nanorobots in surgery: Large surgical tools do not have similar small-scale tools. This makes it difficult to perform surgeries on a tiny scale, and it limits how deeply they can reach into tissues.(26) Surgical nanorobots can be introduced into the body through blood vessels or catheters. These robots are controlled by a

surgeon and can act as semi-independent surgeons inside the body. They can find and diagnose problems and fix lesions using tiny manipulations, all while communicating with the surgeon through ultrasound signals. Early forms of cellular nanotechnology are already being tested, such as using a vibrating micropipette to cut dendrites from neurons without harming them, and using a femtosecond laser for precise tissue surgery.(8)

- Nanorobots in medicine and targeted drug delivery: Nanorobots can be used for drug delivery in medicine. Unlike traditional methods where drugs spread throughout the body, nanobots can target specific areas, making treatment more effective and reducing side effects. These nanobots require movement, control, and the ability to penetrate tissue to ensure that drugs reach the right places. They could enhance treatment effectiveness while minimizing risks from strong medications.(27) This process uses two main technologies: one that requires external energy sources and another that relies on the body's own energy.(28)

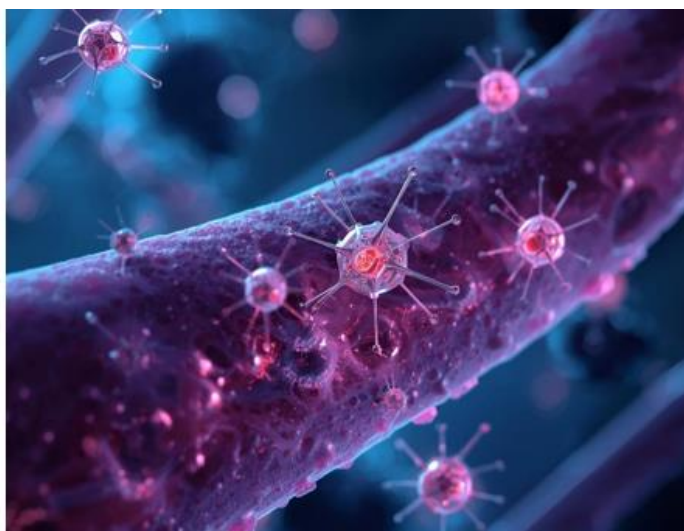


Figure 11: Nanorobots in medicine and Targeted Drug Delivery.

- Gene therapy using nanorobots: Nanorobots can treat genetics by comparing cell protein and DNA structures to known standards. They can correct mistakes and make adjustments. Chromosomal replacement therapy sometimes works better than conventional methods. A small repair vessel operates inside the cell's nucleus, inspecting DNA and removing regulatory proteins for analysis. Information is compared to a larger nanocomputer outside the nucleus. The repair vessel, only 50 nanometers wide, can perform advanced treatments that current medical professionals cannot. Once corrected, proteins are reattached, allowing DNA to return to its original shape. If these devices circulate in a patient's body, it could revolutionize internal medicine, potentially eliminating diseases like viral infections, cancer, and arteriosclerosis (29)
- Dental implants: Successful osseointegration relies on critical factors like surface contact area, topography, bone bonding, and stability. Utilizing nanotechnology, nanoscale deposits of hydroxyapatite and calcium phosphate can enhance implant surfaces, promoting better bone growth.(30)

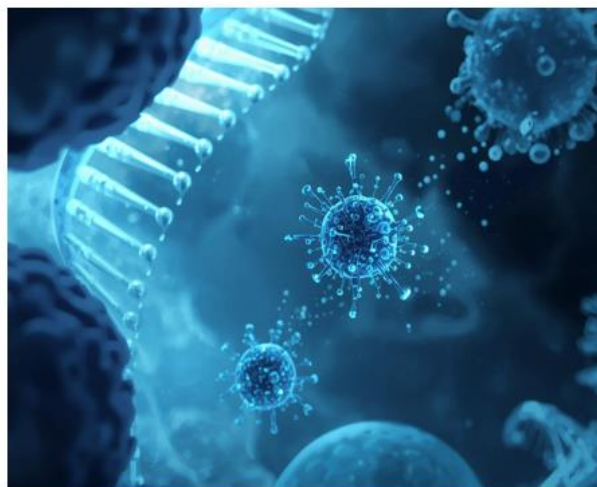


Figure 10: Gene therapy using Nanorobots

Automated Devices



Figure 12: Automated Devices

Automation, which involves using machines to perform repetitive and critical tasks, is playing a vital role in the rapidly growing pharmaceutical industry. As regulatory standards become stricter, automated systems help companies meet these demands more effectively. It provides significant benefits. It increases productivity and ensures consistent product quality at various stages of manufacturing, from handling raw materials to inspecting final products. Thanks to advancements in computer hardware and software, these systems

are now more flexible, reliable, and cost-effective, enabling plants to increase output without sacrificing quality. Additionally, these technologies are being integrated to facilitate real-time quality control.(31)

Automated Drug Distribution System

Automated dispensing devices (ADDs) are robotics systems designed to streamline medication management in healthcare settings, including pharmacies, hospitals, and healthcare

facilities. They enhance accuracy, efficiency, and safety in dispensing processes. Key features include high precision, inventory management, integration with pharmacy systems, barcode scanning, customizable settings, and security controls like biometric authentication.(32) The medication-use process in hospitals is notably susceptible to errors, particularly during the dispensing and administration phases, which pose significant risks to patient safety. To address these issues, various automated and semi-automated drug distribution systems (DDS) have been implemented. These systems aim to mitigate risks, reduce costs, and allow healthcare professionals to allocate more time to clinical work.(33)

➤ **There are three main types of automated DDS:**

- Decentralized systems: They utilize automated dispensing cabinets (ADCs) located in the wards.
- Centralized systems: They rely on the hospital pharmacy-based technologies, including carousel dispensing technology (CDT) and robotic medication picking systems.
- Hybrid system: A combination of centralized and decentralized features.(33)



Figure 13: Automated drug distribution device

➤ **Benefits of automated DDS:**

- Increased Efficiency: Automated systems enhance the organization of medication, monitor expiration dates, and streamline the preparation of prescriptions. Automatic stock control and reorder processes minimize the time pharmacy staff spend on supply chain tasks.
- Reduced errors: Automation significantly lowers the risk of medication errors.
- Improved safety: Advanced systems utilize technologies such as barcode scanning and electronic medical records to boost patient safety.
- Time saving: Automation decreases the time needed for nurses and pharmacists to complete

tasks, enabling them to concentrate more on patient care.(34)

Automated dispensing cabinet: An automated dispensing cabinet (ADC) system was implemented in a French hospital's intensive care unit (ICU) to enhance the management of sterile medical devices (SMDs). This initiative was a direct outcome of a successful earlier trial that utilized a similar system for managing medications. The study aimed to assess two primary areas:

1. **Impact on staff and logistics:** The main objective was to evaluate how the new system influenced the workload of both pharmacy and ICU staff and to determine if it improved the availability of sterile medical devices.
2. **Economic impact:** The secondary goal was to measure the system's effect to financial operations, specifically looking for reductions in the value of SMD stock and the costs associated with restocking.(32)

Automated Guided Vehicles

Today, self-driving load transportation is essential for the timely provision and disposal of operational units such as machines, plants, and workspaces. Material supply shortage can occur when material flows are not properly managed.

Automated guided vehicles (AGVS) are driverless systems designed for rapid and safe transportation of materials. AGVs have been utilized since 1955, and their adoption has significantly increased, with tens of thousands now in operation across various industrial applications.

However, despite their advantages, AGV systems have notable limitations in terms of adaptability, reconfigurability, and scalability. These limitations are primarily attributed to two main issues:

- A centralized control structure.
- Vehicle movement is restricted to a fixed network of predefined paths.(35)



Figure 14: Drug Distribution in hospital via AGVs

As per the study published in the year 2024, the implementation of automated guided vehicles (AGVs) in a company's warehouse to automate specific processes, increase safety, and eliminate

collisions. The demand for AGVs is projected to increase by up to 17% between 2019 and 2024, which supports the company's interest in implementing them at multiple locations.



Figure 15: Drug Distribution in industry via AGVs

In that study, a company replaced three manual workers who transported materials with two automated guided vehicles. It outlines specific processes for the AGVs, including their designated routes, loading and unloading points, and charging stations. The study indicates that the company will save a significant amount on employee wages by adopting new technology. The study also provides insights into AGVs and autonomous mobile robots (AMR) technology, highlighting their capability to operate continuously for 24 hours a day. AGVs utilize sensors and scanners to detect obstacles and avoid collisions, which is essential for safety. Additionally, AGVs are equipped with an integrated display that provides diagnostics, battery status, and destination information.(36)

Automated guided vehicles (AGVs) are essential for movement in various industries due to their efficiency and reliability.

In the pharmaceutical industry, AGVs support process validation and compliance with good manufacturing practices (GMP). Their ability to track all movements provides a verifiable record for demonstrating process control, reduces human error, minimizes contamination risks, and ensures robust automated documentation and traceability.

In the chemical sector, AGVs are utilized for delivering raw materials, transporting materials to curing storage warehouses, and facilitating movement between processing cells and stations.

In general manufacturing, AGVs are instrumental in delivering raw materials, transporting work-in-progress items, moving finished goods, removing scrap materials, and supplying packaging materials.

Overall, AGVs enhance operational efficiency, safety, and compliance across the industry.(37)

In hospitals, the implementation of an automated system for delivering medicine and monitoring patients is revolutionizing patient care. This innovative approach utilizes a mobile app, "Hospital 4.0," which allows nurses to control a specialized vehicle designed for efficient medication delivery. The process begins with a nurse preparing the vehicle, placing the necessary medicine inside, and selecting the desired travel mode through the app. Once initiated, the vehicle employs advanced obstacle detection sensors to navigate its surroundings. If the pathway is clear, it expertly follows a pre-defined route marked by infrared (IR) sensors. Upon reaching its destination, the vehicle halts automatically when a proximity sensor identifies the patient's bed. At this point, the patient, possibly with assistance, can retrieve the medicine from the vehicle's secure compartment. This system not only automates the supply of medication but also enhances basic patient monitoring, ultimately streamlining operations and improving efficiency within the hospital environment.(37)

Future Prospects

The future of AI and automation in healthcare looks bright and promising. The text highlights that upcoming trends and advancements will prioritize enhancing the capabilities, accessibility, and ethical application of these technologies, ensuring their widespread and effective adoption.(38) Future research should prioritize comprehensive studies on collaboration between humans and robots in dynamic, multi-task environments, as current investigations are limited to a fixed set of tasks. For true collaboration to be realized, robots need to become more cognitive and less dependent on human supervision. The integration of sophisticated machine-vision techniques with deep learning will provide cobots with a heightened sense of perception, allowing

them to operate more safely and effectively across a variety of workplaces.(39) The future of robotics is projected to see a substantial rise in the number of robots, particularly within industrial settings. Additionally, robots and autonomous systems are anticipated to become prevalent in society, making their way into areas such as self-driving vehicles and service robots for both home and workplace use.(40) The advancement of AI technologies will pave the way for new breakthroughs in quantum computing, reinforcement learning, and personalized medicine.(41) As the pharmaceutical landscape evolves, AI will take on a pivotal role in fostering innovation, enhancing patient care, and ultimately transforming the future of healthcare.(42) The integration of digital technologies in the pharmaceutical production sector will yield significant future benefits for patients.(43)

- Accelerated drug discovery: AI will streamline virtual screening of chemical libraries, rapidly identifying drug candidates.(44)
- Personalized medicine: AI will analyze patient data to tailor treatments and predict responses.
- Innovative compounds: Scientists will use deep learning to design more effective compounds with fewer side effects.
- Patient care: Future AI monitoring will use wearables to improve remote care and medication adherence.
- Clinical trial design: AI will efficiently recruit suitable participants using health records and biomarkers.(44)
- Smart hospitals: The integration of AI, machine learning (ML), and big data sets to revolutionize smart hospitals and healthcare



facilities, defining the future of the healthcare landscape.

- Cost and time efficiency: AI presents a significant opportunity for the pharmaceutical industry to reduce both the cost and time involved in drug development.(45)
- Digital surgeons: surgeons will need to become “digital surgeons,” which means they should embrace new training methods and guide machines that can enhance their thinking abilities.
- Autonomous surgery: Surgeons will eventually manage autonomous surgeries while still maintaining and practicing their operating skills.(46)
- AI and Drug discovery market: AI reasoning plays a crucial role in medication research by identifying diseases, suggesting treatments, and predicting infection spread. It enhances drug discovery by aiding scientists in finding new treatment methods. In pharmacology and biotechnology, drug development involves formulating and arranging medications by targeting natural components, such as proteins or molecules. Recently, new drugs have been discovered by analyzing the dynamic elements of existing therapies.(47)
- 3D printing: Medical 3D printing has advanced in creating organ models, implants, and personalized scaffolds. While direct printing of tissues is still developing, challenges remain in materials and building the extracellular matrix (ECM). Future efforts will focus on improving equipment, materials, standards, and collaboration to enhance tissue engineering scaffolds.(48)

- AI advancing automated drug dispensing system (ADDS): AI enhances automated dispensing systems by improving accuracy and efficiency. These systems sort and dispense medications, predict maintenance needs, and integrate with inventory management and electronic health records (EHRs). They also alert pharmacists to potential drug interactions or allergies, enhancing patient safety.(49)
- Need for a skilled workforce: To adopt Industry 4.0 technologies, the pharmaceutical industry requires a skilled workforce to handle complex digital systems. There is a shortage of professionals in data analytics, AI, and robotics. Companies must invest in training and collaborate with universities to develop these skills.(50)

CONCLUSION

The pharmaceutical industry is currently undergoing a significant transformation, driven by the strategic integration of advanced technologies such as AI, Robotics, 3D printing, and nanorobots. This review has explored how these innovations are fundamentally reshaping the entire drug development lifecycle, from initial discovery to final patient care. AI plays a vital role in transformation by significantly speeding up research and development. It analyzes large datasets to identify promising drug candidates and predict their effectiveness, while also streamlining clinical trials through better patient recruitment and data monitoring. Simultaneously, robotics and automation are revolutionizing manufacturing processes, ensuring high precision in tasks such as weighing, dispensing, and packaging. These automated systems not only maintain regulatory compliance but also significantly reduce the risks of human error and contamination. Additionally, advancements like 3D printing are paving the way for personalized medicine, enabling the creation of



tailored medications that fit the unique needs of various patient groups, including children and the elderly. Likewise, nanorobots are emerging as innovative tools for precision medicine, capable of delivering drugs directly to specific areas and assisting in diagnostics and surgical procedures. Looking ahead, the future of healthcare will be defined by the continued evolution and collaboration of these technologies. We can expect substantial advancements in areas such as autonomous surgery, personalized treatments, and the establishment of smart hospitals. However, this digital transformation also presents new challenges, particularly through automation, holds the promise of not only streamlining operations and improve efficiency while leading to more effective, personalized, and safer patient care. As the pharmaceutical sector continues to embrace these innovations, it is essential to ensure that the workforce is adequately prepared to navigate and thrive in this evolving landscape, ultimately benefiting patients and the healthcare system as a whole.

Abbreviations:- AI: Artificial intelligence, GMP: good Manufacturing practices, 3DP: Three-Dimensional printing, CAD: Computer-aided design, AM: Additive manufacturing, AGVs: Automated guided vehicles, NP: Nasopharyngeal, SODFs: Solid oral dosage forms, AFM: Atomic force microscopy, GMOs: Genetically modified organisms, ADDS: Automated dispensing devices, DDS: Drug distribution systems, ADCs: Automated dispensing cabinets, CDT: Carousel dispensing technology, SMDs: sterile medical devices, ICU: Intensive care unit, AMR: Autonomous mobile robots, IR: Infrared, ML: Machine learning, ECM: Extracellular matrix, EHRs: Electronic health records.

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