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The Impact of Emerging Technologies on Pharmaceutical Process Design and Optimization in Africa: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors participated in writing, editing, reviewing, and approving the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Emerging technologies present a transformative potential for pharmaceutical process design and optimization, particularly within Africa's evolving pharmaceutical industries. The purpose of this review is to explore the impact of emerging digital technologies, including Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), and Robotics, on pharmaceutical process design and optimization within the African context. Data was collected through a comprehensive literature review of scholarly articles, industry reports, and case studies. By analyzing recent advancements and case studies, this review identifies key areas where technology is reshaping the production processes for pharmaceutical product development. It highlights the benefits, including increased efficiency, improved accuracy, and minimized waste. However, the review also emphasizes significant challenges, including infrastructural limitations, regulatory barriers, and disparities in access to technology that can hinder the adoption of these emerging technologies in Africa. An assessment of their impact on manufacturing efficiency, drug production costs, drug quality, and safety reveals their potential to enhance pharmaceutical manufacturing operations significantly. The findings suggest that while emerging technologies offer substantial opportunities for improving pharmaceutical processes and operations, their successful integration requires a strategic approach that involves stakeholder cooperation, infrastructure improvements, and targeted capacity enhancement initiatives within the continent's pharmaceutical industry. This review offers a broad overview of the current state of technological adoption in the pharmaceutical manufacturing sector in Africa and the impact of leveraging these emerging technologies to drive sustainable improvements in the pharmaceutical product development process.

Keywords: Emerging technologies; artificial intelligence; machine learning; internet of things; robotics; pharmaceutical process.

ABBREVIATIONS

AI : Artificial Intelligence
ANNs : Artificial Neural Networks
ML : Machine Learning
DL : Deep Learning
IoT : Internet of Things
SVM : Support Vector Machines

1. INTRODUCTION

The economic landscape in Africa is marked by an impressive growth rate [1] due to evolving demographics, urbanization, and health system expansions which increase revenue-earning opportunities for pharmaceutical companies [2]. The pharmaceutical industry in Africa has shown significant growth potential with the pharmaceutical manufacturing landscape undergoing noticeable transformations in the digitization of pharmaceutical process design and operations [3,4]. This rapid progression is driven by countries including Nigeria, Ghana, South Africa, and Kenya, with South Africa being among the top five countries globally in pharmaceutical expenditure per capita. As shown in Fig. 1, the LoMMiA research report from the Institute for Economic Justice indicates that South Africa, Egypt, and Nigeria have the largest manufacturing plants, with 122, 120, and 150 facilities each [5].

The African pharmaceutical industry is dominated by privately owned small companies and few major manufacturers [6]. The local production output of the African pharmaceutical industry is 25-30% of pharmaceuticals and below one-tenth of medical supplies available on the African market [7]. Over time, the industry has seen significant improvements in the processing, formulation, and manufacturing of pharmaceutical products from small-scale production using simple hand-operated tools to large-scale production using commercial machinery [8,9]. Also, pharmaceutical process controls have moved from using early machines with limited, pre-determined static settings which required constant monitoring to automated process controls monitored with computers and wireless communication technologies, thereby facilitating continuous manufacturing of pharmaceutical products of high quality [8,10,11].

The relevance of emerging technologies such as Machine Learning (ML), the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and advanced computing on pharmaceutical processes have attracted the focus of researchers and practitioners globally as it has dramatically changed the landscape of manufacturing [8,12]. These advanced

Fig. 1. A map showing African countries with major pharmaceutical companies

manufacturing technologies enable the operation of autonomous, adaptive, self-organizing, and integrated continuous manufacturing processes that are free of any human involvement [13,14]. Performance data can be captured concurrently with the ongoing production process and analyzed by algorithms [15]. The information from the analysis using artificial intelligence can then be used for operational decisions directly impacting production outputs [8].

This study aims to analyze how emerging technologies impact pharmaceutical industries in Africa, particularly with their process design and optimization. The challenges to the effective optimization of pharmaceutical processes are considered and the adoption of emerging technologies into pharmaceutical process designs is proposed as recommendations to significantly improve the efficiency, capacity, flexibility, safety, and quality of medicines produced industrially [8].

2. OVERVIEW OF THE AFRICAN PHARMACEUTICAL INDUSTRY

Africa's pharmaceutical industry is critical to improving public health outcomes, promoting economic development, and lowering the continent's reliance on imports [7,16]. Despite significant challenges such as budgetary limitations, inadequate infrastructure, skilled labor shortages, and regulatory limitations, the industry has ample growth opportunities due to the rising demand for pharmaceuticals.

The pharmaceutical industry in Africa, valued at over $30 billion, is projected to expand to $70 billion by 2030 due to the rising prevalence of chronic illnesses and population growth. Africa imports 95% of its medications and 99% of its vaccines [16,17], relying heavily on international support. Many African nations have inadequate pharmaceutical manufacturing and regulatory frameworks, limiting access to quality, safe, effective, and affordable medical products [7]. Domestic manufacturing capabilities are limited, and the industry heavily depends on imports from China and India. However, the United Nations Industrial Development Organization (UNIDO) and McKinsey & Company report that South Africa, Nigeria, and Kenya have more sizable pharmaceutical industries than other African countries [18,19].

To address these challenges and enhance the pharmaceutical industry's self-sufficiency, African nations must prioritize developing and enforcing digitalized and resilient manufacturing processes [20]. Due to competition and regulations, African pharmaceutical industries are behind in technological advancements and are constantly under pressure to improve their capabilities [20,21]. Some countries in the continent, like South Africa and Nigeria, have adopted certain emerging technologies while several countries have yet to adopt any of these emerging technologies [1]. Automating production processes with emerging technologies will ensure the quality, safety, and efficacy of locally produced medicines and vaccines, reduce Africa's dependence on imports, improve healthcare outcomes, and contribute to global health security [22,23,24].

3. EMERGING TECHNOLOGIES IN THE PHARMACEUTICAL INDUSTRY

3.1 Overview of the Emerging Technologies

The principles of artificial intelligence (AI) and machine learning (ML) were introduced in the mid-20th century [25,26]. Significant growth has been observed in their applications across various fields, including healthcare and drug development [27]. The global pharmaceutical industry has leveraged these emerging technologies to enhance processing output, reduce operating costs, and improve safety, accuracy, and efficiency in production settings [28]. AI and ML can be applied to pharmaceutical process design and optimization. From developing formulations to enhancing the quality-by-design frameworks, these powerful automation tools have provided insights into pharmaceutical formulations and their respective processing methods [29,30]. This review focuses on four of these technologies, namely: Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), and Robotics. Together these technologies optimize the various aspects of pharmaceutical manufacturing processes as observed in Fig. 2 which shows their interconnectedness.

3.1.1 Artificial intelligence

The processes for manufacturing pharmaceutical products in Africa can be made more efficient to match global standards by harnessing the potential of artificial intelligence. Artificially intelligent systems are created using algorithms trained with data to process information with the ability to learn, adapt, and make decisions or predictions based on patterns and insights derived from the data [31,32,33]. Artificially intelligent machinery handles the most complex functionality, maximizing production. It guarantees that production processes will be completed with extreme precision. in addition to producing excellent work, it can assess ongoing processes, identify weak points, enhance decision-making, and identify possibilities for process simplification [29]. Artificial intelligence (AI) emulates or enhances human performance by simulating human intelligence in computer models [34,35]. in the pharmaceutical sector, drug development is costly, time-consuming, and governed by numerous regulations. However, the introduction of artificial intelligence (AI), deep learning (DL), machine learning (ML), and other computational scientific methods has significantly improved the success rate of the drug development process [30].

3.1.2 Machine learning

Machine Learning, a branch of artificial intelligence, has a fundamental framework that uses several algorithms to understand data patterns [30]. Various automation-based methods utilize Machine Learning and deep learning. Deep learning is an aspect of Machine Learning that interconnects computing elements [31]. Machine learning (ML) encompasses a variety of mathematical techniques, including support vector machines (SVM), decision trees, artificial neural networks (ANNs), and deep learning, which can be leveraged to optimize pharmaceutical processes by improving data analysis, predictive modeling, and decision-making capabilities [36]. Artificial neural networks (ANNs) have attracted attention because of their versatility in characterizing intricate linear or non-linear relationships for various applications, including regression, pattern detection, and time-series forecasting [37,38]. By leveraging ANNs, pharmaceutical companies can achieve more accurate predictions, identify hidden process patterns, and improve decision-making processes, thereby optimizing drug production processes [39].

3.1.3 Internet of things (IoT)

The Internet of Things (IoT) is a complex system of interconnected devices enabling data exchange and interaction with other devices,

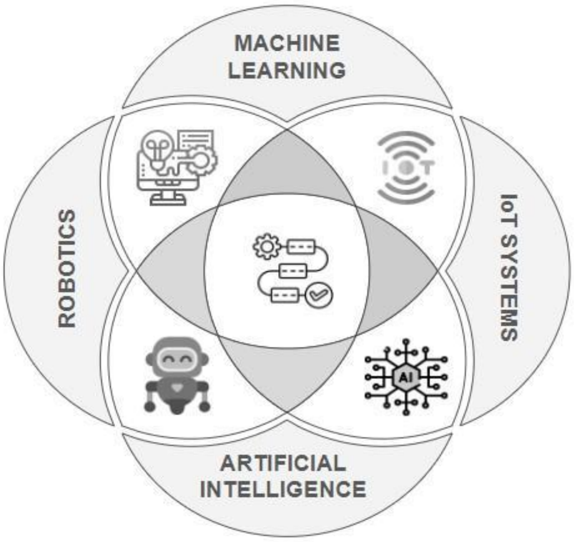

Fig. 2. The Intersection of Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and Robotics for Pharmaceutical Process Optimization

systems, and the cloud [40]. Sensors and processors with large and heavy chips have been added to computers since the 1990s, however, in recent times, Radio Frequency Identification (RFID) tags, which use low-power computer chips, are used for tracking processes and can provide solutions for optimizing production efficiently [41]. Smart IoT devices used in manufacturing to improve efficiency are called industrial IoTs [42]. Industrial equipment and sensors provide industries with comprehensive, real-time data that may be leveraged to enhance production processes [41,43]. IoT systems offer insights into manufacturing processes by providing a more thorough view of the production environment, including resource tracking, quality control, process monitoring, energy optimization, and potential hazard identification, thereby enhancing the production of safe and quality drugs [41]. Recently, researchers have found prevailing issues with IoT systems resulting from their integration such as those surrounding big data analytics, data sharing, security breaches, privacy, and energy efficiency [44]. Hence, effective measures and policies should be established during adoption to mitigate the vulnerability of IoT systems to these risks.

3.1.4 Robotics

Robots execute tasks with minimal human involvement, thus reducing the need for manual labor in the pharmaceutical industry [45]. They streamline processes, optimize workflows, reduce production times, and substantially increase the efficiency of the drug manufacturing process. Integrating robotics into the different stages of drug production has brought about a range of benefits, including raw materials handling, packaging, labeling, and quality inspection of products, to ensure consistency and reduce the risk of contamination in the production process [29,46,47]. Pharmaceutical robots equipped with hyperspectral imaging techniques are an advancement in the quality control process for medical products [46,48]. This emerging trend enhances the precision and reliability of product inspections, enabling the detection of minute defects and contaminants in the production process that traditional methods might miss [46]. By adopting this technology, pharmaceutical manufacturers can improve product safety and compliance, reduce the risk of recalls, and ensure higher quality standards.

3.2 Potential Applications in Pharmaceutical Process Design and Optimization

African pharmaceutical industries are still in the early stages of adopting emerging digital technologies into their production processes, and as shown in Fig. 3, several parameters including challenges and impacts of these technologies are to be analyzed in some of the African countries with major pharmaceutical industries. The production of pharmaceutical products involves several complex processes that can be

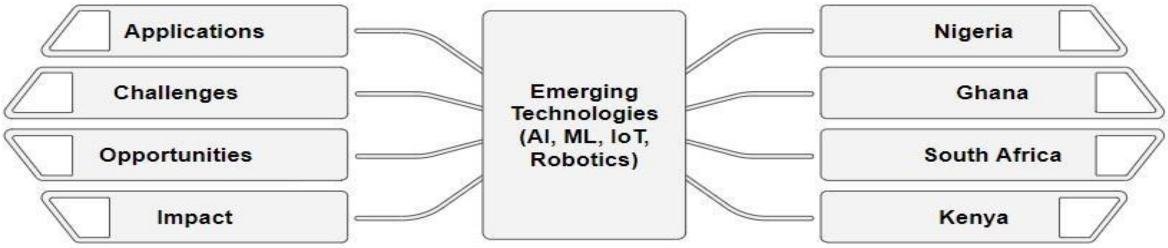

Fig. 3. A flowchart summarizing the review process

optimized using digital technologies, thereby enhancing transparency, traceability, and product quality throughout the production process [49]. Products communicate with their manufacturers through continuous feedback from sensors that monitor ambient production conditions, quality attributes, and resource usage, enabling internal and external real-time connectivity in manufacturing plants [8,50].

Artificial intelligence (AI) and machine learning (ML) can enhance workflows through ongoing analytics of process data to identify inefficiencies, thereby reducing waste and improving yield [43]. Additionally, AI-driven quality control systems can detect manufacturing defects and ensure product consistency in real-time, minimizing the risk of recalls [17,51].

The Internet of Things (IoT) systems offer real-time visibility into operations and can monitor production environments, equipment performance, and critical production parameters, ensuring optimal manufacturing conditions and reducing downtime [41,43]. Internet of Things (IoT) data can also be utilized to predict equipment breakdowns before they occur, minimizing production disruptions through predictive maintenance [43,51]. By deploying sensors on equipment, in storage areas, and on products, pharmaceutical companies can gather critical data on inventory controls, supply chain integrity, and trace efficient resource utilization [52].

Robotic technologies can automate repetitive tasks such as material handling, packaging, and assembly, boosting production speed and precision while lowering labor costs [43,53]. These machines operate with precision, reducing human error and ensuring product quality [54]. Robots operate without compromising safety or contaminating the production floor and can handle hazardous materials safely, protecting human workers from exposure to potentially harmful substances [55]. Robots equipped with advanced imaging and sensing technologies can perform rigorous quality checks, ensuring compliance with industry standards [56].

By integrating these emerging technologies, pharmaceutical manufacturing industries in Africa can significantly enhance their production capabilities by ensuring higher efficiency, reduced costs, and consistent product quality.

4. CHALLENGES, OPPORTUNITIES AND CASE STUDIES IN THE AFRICAN CONTEXT

4.1 Challenges

Africa is globally known to be a slow adopter of new digital technologies [57]. The pharmaceutical industries in Africa continue to face difficulties such as a shortage of skilled workers, budgetary limitations [7], and inadequate infrastructure including a lack of reliable power supplies, internet connectivity, and outdated equipment [58]. This hinders the effective deployment and utilization of advanced technologies. The high capital costs associated with advanced technologies also present a barrier, making it difficult for many African pharmaceutical companies to invest in and adopt new digital technology solutions. Additionally, regulatory and compliance issues hinder the adoption of these emerging technologies [57,59]. The lack of consistent regulatory frameworks across African countries can cause delays in approving and integrating new technologies. Cultural barriers and a shortage of skilled workers prevent the uptake and use of these technologies in a resource-constrained environment [60,61].

4.2 Opportunities

Emerging technologies present significant opportunities for enhancing operational efficiency in the African pharmaceutical industry. These technologies lead to production process improvements and cost reductions [20]. A report by McKinsey highlights that AI can potentially reduce pharmaceutical manufacturing costs by up to 20% through process optimization and predictive maintenance [62]. Their adoption can stimulate economic growth, create job opportunities, and enhance data utilization [63]. The World Economic Forum reports that digital transformation in industries, including pharmaceuticals, is expected to create millions of jobs globally, particularly in emerging markets like Africa [64,65]. AI, ML, and IoT systems provide valuable insights into production trends and operational performance, enabling more informed decision-making and accelerating drug production, thus bringing new drugs to market more swiftly [66].

4.3 A Case Study of Nigeria, Ghana, South Africa, and Kenya

The integration of emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), and robotics is reshaping the landscape of pharmaceutical operations in countries like Nigeria, Ghana, South Africa, and Kenya [67]. Emerging digital technologies are being integrated into manufacturing processes to enhance efficiency, ensure product quality, and overcome persistent challenges [68,69]. This case study focuses on how these technologies are being applied within the pharmaceutical manufacturing sectors of these countries, illustrating their impact and potential for the future.

Nigeria, the most populous country in Africa, presents a complex landscape for pharmaceutical industries, as key pharmaceutical companies have exited the country [70]. Despite challenges, there are promising developments in adopting AI and ML to enhance quality control and optimize production to address historical challenges related to manual processes and infrastructure limitations. [71]. By monitoring production in real-time and predicting equipment failures, AI and ML are improving product quality and efficiency, enabling Nigerian manufacturers to meet growing demand more effectively [72]. Indigenous companies known for producing over-the-counter drugs, have embraced AI for drug development. They are also leveraging AI for supply chain optimization including their inventory management and logistics, where it analyzes market trends, and historical sales data to predict demand more accurately [71,73].

The pharmaceutical industry in Ghana is increasingly leveraging IoT technologies to address challenges related to product quality and supply chain integrity [74]. By deploying smart sensors within manufacturing facilities, companies can continuously monitor environmental conditions, such as temperature and humidity, which are critical for maintaining the efficacy of drug products [41]. These sensors provide real-time data, allowing manufacturers to respond to deviations from optimal conditions. For instance, by 2022, mPharma’s AI-powered stock control mechanism had increased access to essential pharmaceutical stocks in Ghanaian drugstores, cutting down instances of stock-outs by over 30%. Furthermore, utilizing data analysis with the supply chain brought about 20% of purchase charges and a 15% enhancement in overall performance effectiveness [74].

South Africa has a well-established pharmaceutical industry and is at the forefront of driving advancements in manufacturing automation [75,76]. Robotics are being extensively used in South African pharmaceutical plants to automate tasks previously performed manually, such as filling, packaging, and quality inspection. For example, Aspen Pharmacare, a major pharmaceutical manufacturer in South Africa, has incorporated advanced robotics into its production lines. These robots perform repetitive tasks with precision and speed, reducing human error and increasing production throughput [76,77].

Kenya's pharmaceutical industry is exploring the potential of emerging technologies, particularly AI, for process optimization and predictive maintenance [78]. AI analyzes manufacturing data to improve processes like chemical reactions and predict equipment failures, thereby improving efficiency and yield, reducing costs and wastes, and ensuring timely maintenance. [78,79]. This is particularly important in a market where resources can be scarce, and cost-efficiency is crucial for competitiveness.

As these countries continue to embrace digital transformation, their pharmaceutical manufacturing industries are poised to become more competitive, innovative, and capable of meeting both local and global demand for high-quality medicines [20].

5. IMPACT ASSESSMENT

The combined effect of these emerging technologies not only impacts manufacturing efficiency and capacity but also affects drug development timelines, costs, quality, and safety. Full digital maturity, including advanced data analytics and the seamless integration of digital technologies, is necessary to transform traditional production processes into more efficient operations.

5.1 Impact on Manufacturing Efficiency

Automated process controls improve manufacturing efficiency and increase productivity through streamlining operations [80,81]. Emerging technologies like Artificial Intelligence (AI) and Machine Learning (ML) can predict process outcomes before the start of any production process as well as monitor progress through the continuous tracking of production performance metrics and trends in the production line [82,83]). Internet of Things (IoT) devices can provide real-time process monitoring and control, ensuring the maintenance of optimal production conditions throughout the production cycle [84].

Performance data can be captured via process analytical technologies (PAT) connected to the cloud, analyzed, and organized to AI-based algorithms which are then converted into insights for improved process control [8]. The organized AI-based algorithms can predict product quality attributes downstream in the process pipeline. This adaptive process control facilitates real-time process design and optimization [85].

5.2 Impact on Drug Production Costs

Production processes were streamlined when African pharmaceutical industries transitioned from batch manufacturing to continuous manufacturing, thereby reducing downtime and lowering inventory costs in the use of resources [86]. Automated pharmaceutical processes will reduce the need for manual labor, decrease labor costs, and increase production efficiency by integrating robotics into the process pipeline to handle repetitive tasks, and minimize errors and waste. This can lead to significant cost reductions in production and faster time-to-market for new drugs [87].

Conversely, powerful computing tools integrated with digital systems that merge real-time process data collection and analyses with high-speed communications in the production process will impose financial burdens on small-scale pharmaceutical industries [88]. Hence, these smaller industries strive to keep pace with larger competitors, potentially leading to a widening gap in technological capabilities and market share.

5.3 Impact on Drug Quality and Safety

The pharmaceutical industry in Africa faces unique challenges that impact the efficiency, quality, and accessibility of healthcare. Traditional manufacturing methods are challenged by increasing population demands and the stringent requirements of global standards [89]. By harnessing emerging technologies, Africa can transform its pharmaceutical production process, address critical issues, and elevate its industry to compete globally. Producing drugs under controlled conditions reduces variability and the risk of human error, leading to more consistent product quality and higher safety standards [8].

Advanced data analytics and Artificial Intelligence (AI) enhance, predict, and detect potential quality defects in their early stages before they become critical [46]. These technologies analyze vast datasets to uncover hidden patterns and anomalies, ensuring consistent quality and safety in drug production. Also, the risk of contamination is reduced through real-time monitoring of production processes and environmental conditions [90].

Leveraging emerging technologies like robotics, advanced computing, artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) in pharmaceutical process design and optimization is expected to lead to safer, more affordable, and efficient drug production, ultimately improving medication accessibility, driving innovation, and accelerating the development of new therapies [3,82].

6. CONCLUSION

The emerging technologies can transform pharmaceutical process design and optimization in Africa. This review has highlighted the opportunities and challenges of adopting emerging technologies such as AI, ML, IoT, and Robotics in the African pharmaceutical industries. By leveraging these technologies, African pharmaceutical companies can improve process efficiency, enhance product quality, reduce costs, and increase accessibility to essential medicines. However, addressing the challenges of infrastructure, skills, and regulatory frameworks is crucial for successful adoption. As the African pharmaceutical industry grows, embracing emerging technologies will be vital for staying competitive, improving public health, and achieving sustainable development goals. Further research and collaboration among industry stakeholders, governments, and academia are necessary to fully harness the potential of emerging technologies and drive innovation in African pharmaceutical development.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of manuscripts.

CONSENT AND ETHICAL APPROVAL

It is not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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