Accepted Chapter

Industry 4.0 or Pharma 4.0?Assessing Suitability, Benefits, Challenges, and Opportunities for Healthcare Supply Chains

**Muhammad Ibrahim Khan**

*Iqra University, Pakistan*

**Mirza Amin Ul Haq**

*Iqra University, Pakistan*

 **Mustafa Rehman Khan**

*UCSI University, Kuala Lumpur, Malaysia*

**Arsalan Mujahid Ghouri**

*London South Bank University, UK*

**Raheel Farooqui**

*Bahria University, Karachi, Pakistan*

 rr

319

# ABSTRACT

*This chapter examines the convergence of Industry 4.0 and Pharma 4.0 in the context of healthcare supply chains. It investigates the potential applications of these industrial revolutions to enhance the flexibility, benefits, challenges, and opportunities of healthcare supply chains. This chapter highlights the application of state-of-the-art technology to create intelligent, adaptable, and personalized supply chain systems for the healthcare and pharmaceutical sectors. The literature on “Pharma Industry 4.0” is reviewed, with a focus on the opportunities for sustainable value creation and pharmaceutical supply chain research. Healthcare supply chain has some serious issues like counterfeit drugs, non-transparent supply chain, unfear track and trace system of medicines and biomedical instruments. The authors identi- fied the potential solutions for these issues with the help of current innovative technologies and practices.*

# INTRODUCTION

The convergence of Industry 4.0 and Pharma 4.0 presents a significant opportunity for the pharmaceutical industry to undergo transformation in the context of healthcare supply chains (Sharma et al., 2023). The present book chapter undertakes a thorough analysis, assessing the suitability, benefits, challenges, and prospects that result from the integration of these state-of-the-art technologies into health care supply chains. Munirathinam (2020) says that the term “industry 4.0,” often known as the “fourth industrial revolution,” describes the blending of digital and conventional production processes. This marks the beginning of an era of intelligent, automated, and networked systems and includes big data, the Internet of Things (IoT), cyber-physical systems, and artificial intelligence (AI).

With a special focus on the pharmaceutical sector, Pharma 4.0 aims to transform medication discov- ery, production, and distribution. Digital technologies are being used in the pharmaceutical industry in a number of areas, including as production, packaging, diagnostics, and analysis. Primary manufacturers, secondary manufacturers, logistics service providers/wholesalers, and healthcare providers make up the intricate network that is the pharmaceutical supply chain (Arden et al., 2021). With the introduction of Industry 4.0 and Pharma 4.0 technologies, tailored solutions, agility, and sustainable value generation are promised. It is critical to comprehend how these developments fit into healthcare supply chains in order to maximize productivity, guarantee quality, and deal with the constantly changing needs of the healthcare ecosystem (Rad et al., 2022; Shashi 2023).

To sum up, this book chapter provides a thorough overview of the dynamic landscape produced by Industry 4.0 and Pharma 4.0 for those involved in the healthcare supply chain. It aims to clear the path for an educated and strategic adoption of these technologies by methodically evaluating their applica- bility, advantages, difficulties, and possibilities. This will eventually improve the responsiveness and resilience of health care supply chains. (Khan et al., 2017) suggest that businesses should put more of an emphasis on technology that is explicit and facilitates the adoption of new, cutting-edge technology in the workplace. Companies should encourage their team members by giving them independence, incen- tives, awards, and recognition for their creative workers.

(Ghouri et al., 2023) developed and evaluated a novel artificial intelligence (AI)-based Omni channel blood supply chain (OBSC) model utilizing feedback from semi structured interviews with health care professionals working in a blood supply chain. In critical scenarios for blood supply networks, the im- balance between supply and demand is addressed by the suggested AI-based OBSC model. Blockchain technology application areas were categorized as safety and security, tracking and tracing, drug delivery, and prevention of counterfeit drugs. Preventing counterfeit drugs was the most often mentioned category, which is in line with the main goal of the pharmaceutical sector (Zakari, et al., 2022).

The objective of this chapter to address the questions is how we see the future of Pharma 4.0 with respect to industry 4.0. By analyzing the existing literature we will be able to find the current status of pharma 4.0 and practical implications in the age of industry 4.0.

RQ 1. How does Industry 4.0, also known as Pharma 4.0, address the unique technology and operational requirements of health care supply chains?

RQ 2. What obstacles can health care supply chains encounter when putting Industry 4.0 or Pharma 4.0 into practice, and how might these obstacles be overcome?

RQ 3. What opportunities and benefits are associated with the adoption of industry 4.0, pharma 4.0 for the healthcare supply chain. And how it can be maximized?

# LITERATURE REVIEW

* 1. **Understanding Industry 4.0 vs. Pharma 4.0**

The fourth industrial revolution, known as “industry4.0,” is defined by the incorporation of innova- tive technologies and data-driven solutions into production processes. It places a strong emphasis on utilizing cloud computing, the Internet of Things (IoT), and cyber-physical systems to build intelligent, networked production systems that can boost output, productivity, and decision-making (Sharma et al., 2023). Industry 4.0 seeks to transform conventional manufacturing techniques by facilitating greater automation, improved machine-to-machine communication, and the use of real-time data for produc- tion optimization and predictive maintenance. The goal is to build an industrial ecosystem that is more responsive, efficient, and flexible so that it can change to meet shifting consumer and market demands. Contrarily, Pharma 4.0 is a particular implementation of Industry 4.0 ideas in the pharmaceutical sector. It entails the integration of data analytics and digital technologies to improve supply chain man- agement, production, quality control, research and development, and other aspects of pharmaceutical manufacturing. Pharma 4.0 is centered on utilizing innovative technologies like big data analytics, artificial intelligence, and smart sensors to enhance pharmaceutical processes, guarantee the quality and safety of products, and maximize production efficiency. In order to satisfy the population’s changing healthcare needs, it seeks to expedite the development and delivery of novel, high-quality pharmaceuticals while

streamlining pharmaceutical operations and cutting costs.

Word “phama 4.0” first coined by the International Society of Pharmaceutical Engineering (ISPE) in 2017. It refers to the adoption of Industry 4.0 technologies in the health care supply chain system. It is an operational model that helps the pharmaceutical sector achieves digital maturity, data integrity, and industry 4.0 capabilities for their sustainable supply chains. Pharmaceutical supply chains are cru- cial instruments to establish in order to support the operational and managerial goals as well as future demands of pharmaceutical goods throughout their life cycle (Lws 40 years).

# Blockchain Technology

Blockchain is revolutionary technology which is introduced by Satoshi Nakamoto in 2008. The initial use of blockchain technology was in crypto currency (Ravi et al., 2022). Key issues with data transpar- ency, traceability, immutability, audit, provenance, flexible access, privacy, and security confront today’s healthcare data management systems (AbuHalimeh & Ali, 2023).Despite block chain’s great potential to solve traditional supply chain problems, there is a dearth of research on its application in pharmaceutical supply chains (PSCs) (Ghadge et al., 2022).

Furthermore, many of the healthcare systems now in use for data management are centralized, which increases the possibility of a single point of failure in the event of a natural disaster. The way data is managed in the healthcare industry might be drastically revolutionized, reshaped, and transformed by blockchain, an up-and-coming and disruptive decentralized technology (Yaqoob et al., 2021).”Industry4.0” describes the deployment of “smart” devices along the value chain that are able to autonomously connect with one another. The Fourth Industrial Revolution, which is described as a new degree of association and control over the value chain of the product lifecycle with an emphasis on more customized customer demands, has been referred to in recent years as “industry 4.0.”

Innovative technologies like artificial intelligence (AI) and the Internet of Things (IoT) are used in the pharmaceutical sector. The pharmaceutical industry is using artificial intelligence (AI) more and more these days. AI has the potential to improve formulation results while saving time and money. AI makes robots that are just as intelligent as humans. The pharmaceutical industry has reinvented the process of developing new pharmaceuticals with the application of AI in recent years. AI may primarily be used in the study and creation of essential, game-changing drugs. Radiology and radiation have been thought to benefit greatly from artificial intelligence. Almost all aspects of clinical trials, including patient hap- piness, monitoring medication adherence, exchanging medical records, analysis, and design, may be impacted by AI. Block chain has the potential make transparent the supply chain process of programmatic advertising and prevent the whole ecosystem from ad fraud (Khan M. I., 2024).

The Internet of Things (IoT) is an intelligent network that employs a human-computerization system to reduce human labor. IoT includes both software and hardware architecture. The pharmaceutical industry is one where Internet of Things is revolutionizing. For easy conduction, the pharmaceutical industry’s IoT blueprint is essential. Connecting disparate individuals and supply chain operations into a single network with enhanced capacity and reduced expenses while maintaining safety and security is made easier by IoT. In the pharmaceutical industry, IoT offers healthcare services. Advanced technology (e.g., AI and IoT) is used in the creation of pharmaceuticals for small-scale manufacturing in diagnostic-based therapeutics. The internets of things (IoT) paradigm’s quick advancements have completely changed the healthcare sector by bringing about significant advancements in prescription medication data, insurance information, and e-health/medical records (EHR/EMR) (Ray et al., 2020; Griggs et al., 2018).

The vast production and consumption of goods that eventually jeopardize human and animal life as well as the interests of future generations is the primary cause of most environmental and climatic problems. One tactical solution to these disasters appears to be sustainable supply chain management, whose application is rather difficult yet flexible. Through Block chain based supply chain we can achieve sustainability (Khan et al, .2023).

# Counterfeit Drugs Entering the Supply Chain

The integrity and sustainability of the entire ecosystem are seriously threatened by the introduction of fake medications into the pharmaceutical supply chain. In addition to the direct health risks to consumers, the widespread use of fake medications erodes patient and pharmaceutical company trust, which lowers market share and brand reputation. Addressing this issue, however, offers sustainable pharmaceuti- cal supply chains the chance to improve their traceability technologies and put in place strong quality control procedures. Pharmacies can be guaranteed to be authentic and safe by using supply chains that are transparent and secure, thanks to the use of innovative tracking and authentication technologies like blockchain and serialization. Furthermore, by promoting moral and responsible business conduct, these initiatives not only protect public health but also help the pharmaceutical industry develop a culture of trust and accountability (Haq & Esuka, 2018).

We are now in the era of Industry 4.0 as a result of the four developmental stages. The fourth indus- trial revolution, or “Industry 4.0,” will affect how goods are produced. The pharmaceutical industry will benefit from Industry 4.0 since it will make it simpler to produce sophisticated medicines. Processes are now more flexible due to Industry 4.0 and its innovative technologies like artificial intelligence (AI), robots, and the Internet of Things (IoT) (Arden et al., 2021). The goal of introducing Industry 4.0 was to eliminate the need for human labor and simplify complex operations. It is utilized in numerous aspects

of the pharmaceutical industry, including manufacture, packaging, diagnosis, and analysis. Building a connection between business and sustainability, Industry 4.0 promotes sustainable growth. By implement- ing advanced Industry 4.0 production practices, sustainability may be observed. Additionally, Industry

4.0 may improve pharmaceutical production in terms of flexibility, costs, standards, and safety. It has been noted that Industry 4.0 encourages sustainable growth by introducing innovative technologies that result in flexible production procedures (Sharma et al., 2023).

Pharmaceutical companies employ “advanced analytics” from Industry 4.0 across the complete value chain, including R&D, safety, production, and regulation. The pharmaceutical business plays a vital role in the healthcare system by producing and selling drugs, biological products, and therapeutic devices that are used to identify and treat illnesses. It also conducts research to develop new products that benefit human welfare.co Therefore, it would be essential to maintain the standard of the pharmaceutical items to prevent health concerns as many of them are lifesaving (Ugvekar et al., 2021).

Therapeutic agents are made available by the pharmaceutical industry to treat illnesses. It improved the population health. Through research and development, the pharmaceutical sector creates innovative medications that enhance patients’ quality of life around the globe. The pharmaceutical industry provides a significant benefit to global prosperity (Zozaya et al., 2019). The pharmaceutical business is always looking for new and creative ways to extend people’s lives and make them healthier. The manufactur- ing of pharmaceutical products directly increases the world’s gross domestic product and creates jobs for a large number of people. Although pharmaceuticals are utilized in the diagnosis and treatment of illnesses, they can occasionally have negative side effects. One of the primary issues facing mankind, according to reports, is the presence of toxins like medicines in drinkable water systems (Peake, Braund, Tremblay, & Tong, 2016).

In the era of fast growing technological advancements and the convergence of digital innovations, the concept of “Industry 4.0” and “Pharma 4.0” have surfaced as essential agents of change cutting across diverse sectors. Within this evolving landscape, the healthcare industry has become a focal point for in-depth scrutiny, as it navigates the adoption of these transformative paradigms. This introduction chapter serves as the foundation for a holistic investigation into the profound impact of Industry 4.0 and Pharma 4.0 on healthcare supply chains, dissecting their applicability, advantages, barriers, and prospects (Malheiro et al., 2023).

The advancement from Industry 3.0 to Industry 4.0 suggests a significant shift in the way supply chain processes are managed. In the era of Industry 3.0, the primary focusing to transform various supply chains process in digital and computerized process. Such as (ERP) Enterprise Resource Planning and (EDI) Electronic Discharge of Information systems were introduced, the main purpose of that advance- ment to streamline manufacturing process and systematizing tasks like purchase orders and documen- tation (Farziyeva & Dhanik, 2022). However, Industry 4.0 emerged as the next phase of technological transformation in the 21st century. Industry 4.0 focuses on to ensure data-driven transparency in supply chain processes while ensuring security and encryption. The main purpose to generalize supply chain processes and encourages stakeholders to work on a more digital approach, finally leading to increased sustainability.

In Industry 3.0, data was mostly used for internal processes and limited stakeholder management. These limitations create some challenges in achieving effective collaboration and sustainability through the supply chain. Using innovative technologies like Artificial Intelligence (AI), Blockchain, Cloud Computing, Internet of Things (IoT), and Cyber Physical Systems (CPS), Industry 4.0 aims to address these issues (Pelaez, et al., 2023). The process of globalization, which has increased connectivity, simul-

taneously introduces a higher level of complexity. The effectiveness and efficiency of meeting societal requirements are continually evaluated across multiple dimensions (Farziyeva & Dhanik, 2022). Thus, it becomes imperative to examine how industry 4.0 applications, a potentially significant topic across industries, can integrate and redefine the workflow within supply chains networks, fostering enhanced traceability, transparency, and collaboration among supply chain actors. This evolution addresses the collaboration gap that was evident in Industry 3.0 applications and enables trustworthy and flexible stakeholder management.

# Privacy

Individuals have the fundamental right to data privacy and protection (Ventura & Coeli, 2018). Infor- mation gathered by healthcare institutions frequently includes medical and personal information about patients. A data breach puts all of that information at danger of being compromised, which would be detrimental to the entire goal of digitizing healthcare. It is possible to identify the necessity for efficient data protection with regard to the healthcare industry by taking this factor into account. Furthermore, this demonstrates the applicability of the research and the design criteria for the study’s important fac- tors. “Electronic health records (EHRs)” are a common digital tool that gives individuals access to the medical data they require. Important patient data can also be shared by service providers via “health information exchanges (HIEs)”. But there are concerns related to data security with this method. EHR patient records include information on the patient’s medical history, social security number, course of treatment, insurance, and payment data (Cowie, et al., 2016).

In order to achieve one, we frequently have to give up the other. Visibility and privacy are generally mutually exclusive. The greatest solution for this trade-off is blockchain, which can guarantee the au- thenticity of data made publicly available while maintaining the privacy of an entity’s private informa- tion hidden and without compromising it. The items in a pharmaceutical supply chain system may be verified without revealing any details on the manufacturing process. However, many network users will be able to view the patient’s medical record without being aware of the patient’s personal information (Haq & Esuka, 2018).

Patients are reluctant to offer useful information for the Blockchain-based solution because they are worried about their privacy being compromised. Past incidents, such as privacy leakage situations like AMCA (American Medical Collection Agency) data breach in 2018, erode the patient’s faith in data protection. (Agbo et al., 2019) mentioned that Enhanced privacy and security of data Health data secu- rity is ensured by block chain’s immutability virtue. The health data cannot be removed, distorted, or changed once it is added to a blockchain system. On a blockchain system, information is time-stamped, encrypted, and kept in chronological order.

# METHODOLOGY

Rousseau et al. (2008) state that the systematic literature review (SLR) approach, also known as synthesis, “is the critical first step in the effective use of scientific evidence”. The rigorous literature review proce- dure used for this research is described in this section. The procedures described by the methods put out by Transfield et al. (2003) and Okoli (2015), which include (a) Planning, (b) Selection, (c) Extraction, and (d) Execution, served as the foundation for the search and review process.

We used to search many well-known and up-to-date research databases, such as Google Scholar, Semantic Scholar, and IEEE Xplore databases, to find relevant literature. These databases offer selective coverage, superior content, and a wider range of publications. Creating keywords and strings to extract relevant scholarly articles from the database is the first step in the selection process in a systematic literature review (SLR). Typically, the boolean operators “AND”, “OR”, “NOT”, and so forth are used for this. In this systematic literature review, the terms “industry 4.0,” “pharma 4.0,” “sustainability,” “medical 4.0,” and “health care” were employed. In order to incorporate only relevant papers and maintain a reasonable quantity of articles for the research, a screening mechanism was implemented. Additionally, any items older than ten years were removed. This facilitates post-auditing and replication of the research as well. After doing a search on the selective database, 8524 items were found. The number of articles was decreased to 2231 after these first findings were filtered and restricted to search strings in abstracts and keywords. Peer-reviewed studies from the fields of business management & accounting, health care and medical sciences, and economics that had been published during the previous 10 years were also excluded from the screening process. As a result, there were 61 articles and 15 reports are left, which have been included in this SLR for in-depth evaluation and analysis. In Figure 1, a PRISMA flow diagram is shown.

*Figure 1. PRISMA flow diagram for literature search*



# THEMATIC FINDINGS

This chapter focuses on discussing the thematic findings in the research and reporting the main find- ings relevant to answering the research questions. Relevant research questions have been framed in the introduction, and understanding and deciphering the answers to the research questions will be the ultimate motive of this thematic findings chapter. This chapter will try to focus on the frameworks that have been developed and incorporated into the supply chain systems to ensure transparency measures in sustainability and the ability to measure and report these measures correctly. This chapter also intends to analyze digitalization and the efforts by the industry and the government to ensure that the latest technologies are adopted to ensure sustainability

# Challenges of Implementing Pharma 4.0 in the Pharmaceutical Industry

Healthcare supply chains, which offer essential services for daily living, are complex, worldwide, and comprise several firms. Impurities including a lack of transparency, incorrect information, and a restricted data provenance are introduced by the complexity of the healthcare system. One of the main effects of the current supply chain is counterfeit medication, which not only negatively impacts people’s health but also causes significant financial hardship for the healthcare sector. Studies already conducted have underlined how important it is for the healthcare system to have a robust end-to-end tracking and trac- ing mechanism. The elimination of counterfeit pharmaceuticals and the assurance of product safety are the main goals of this end-to-end drug tracking system. Now a days the track and trace systems used in health care supply chain are centralized and they have some major problems like transparency, privacy and authenticity (Musamih, et al., 2016).

Prior to the advent of Industry 4.0, conventional technologies used a three-step energy conversion procedure. Traditional manufacturing does not adequately address the needs of patient populations, both military and civilian, and healthcare providers because it is not sufficiently capable of monitoring and controlling automated and complex manufacturing processes to produce personalized products expertly and beneficially (Sharma et al., 2023). The advancement of materials using conventional processes has hit a limit, even for uses in medicine. The disadvantages of classic medication delivery systems include their low therapeutic indices and poor solubility in water. New drug development is expensive and routine production processes that include batch processing are frequently inefficient. Pharma 4.0’s automation features might help the pharmaceutical industry. Significant challenges encountered by earlier innovations or revolutions include the high price of producing novel treatments, unclear procedures, and inefficient regular manufacturing that results in batch failures (Steinwandter et al.,2019).

Now a day’s one of the most challenging things in pharmaceutical industry is counterfeit drugs. What is mean by counterfeit drugs? According to WHO definition “the drugs which is made illegally, misla- beled, produced with low quality raw material, the source detail and identity of source is unknown or hidden and the define standards for production is not followed is known to be fake or counterfeit drugs”. According to a World Health Organization (WHO) assessment, every tenth medication used by patients in underdeveloped nations is either fake or of poor quality (WHO, William 2014, White 2022). This report may be not accurate and the ratio of counterfeit drugs are maybe increase or decrease in numbers but alarming situation is “ that the pharmaceutical supply chain has the room to add these counterfeit drugs in the supply chain system. Around 0.7 Million deaths are occurred due Malaria and 0.2 Million deaths are due to counterfeit drugs worldwide.

# High Cost and Time Consumption

Healthcare supply chains face many obstacles when implementing Industry 4.0 and Pharma 4.0, most of which are related to high costs and time commitment. The integration of advanced technologies results in high initial costs because it requires significant financial investments in infrastructure upgrades, train- ing, and the adoption of sophisticated equipment (Ding, 2018).The complex nature of these technologies requires thorough employee training, which can further drain time and resources. When old systems and procedures are modified to meet Industry 4.0 and Pharma 4.0 criteria, there are sometimes delays and disruptions in production during this phase of change. Furthermore, it takes more time and money to validate new systems’ efficacy and ensure regulatory compliance (Sharma et al., 2023).

These difficulties highlight the necessity of rigorous budgetary planning, efficient change manage- ment techniques, and the creation of long-term implementation plans in order to reduce expenses and time constraints throughout the integration process. In order to successfully integrate Industry 4.0 and Pharma 4.0 and enhance patient outcomes and the efficiency of the healthcare supply chain, it is impera- tive that these obstacles be addressed.

# Little Awareness and Understanding of Sustainability

Adoption of Industry 4.0 and Pharma 4.0 in healthcare supply chains is being limited by a widespread lack of understanding and familiarity with sustainable standards. In the healthcare industry, sustainable practices are often underestimated while playing a critical role in ensuring the resilience and long-term profitability of supply chains (Tortorella et al., 2023). This leads to a broad disregard for environmen- tally friendly manufacturing and distribution methods as well as an ignorance of how activities affect the environment. When there is a lack of understanding, it usually leads to inaction on waste reduction, energy efficiency, or introduction of environmentally friendly industrial methods (Ferronato & Torretta, 2019). Moreover, a deficiency of knowledge about the potential benefits of sustainability makes it more challenging to adopt environmentally friendly practices, leading to missed opportunities to save costs and improve operational efficiency. To solve this issue and encourage stakeholders to integrate eco-friendly practices into their healthcare supply chain operations, education and awareness campaigns emphasizing the benefits of sustainable practices are required (Maryville 2019).

# Insufficient Investment for Technological Advancement

The lack of proper funding for technical development is still one of the main barriers to the implemen- tation of Industry 4.0 and Pharma 4.0 in the supply chains that handle health care. The high expenses associated with adopting new technologies like digital supply chain systems and the Internet of Things make it difficult to integrate them into existing infrastructures. In addition, financial constraints and a lack of financing prevent healthcare institutions from fully using the potential benefits of these advances (Ding, 2018). Without enough financing, it becomes more difficult to deploy innovative technological tools that might enhance supply chain management and increase operational efficiency. Because of this, the industry finds it difficult to keep up with the rapid evolution of technology, which eventually keeps Industry 4.0 and Pharma 4.0 in the health care supply chain from realizing their full potential (Huang et al., 2023).

# Digitalized Product Monitoring and Traceability

Digitalized product monitoring and traceability are the most significant of the issues that come with implementing Industry 4.0 and Pharma 4.0 in health care supply chains. The use of digital technology enables the real-time monitoring of many characteristics, such as temperature, humidity, and location, which ensures the uniformity and safety of pharmaceutical products throughout the supply chain. By combining IoT sensors with advanced tracking systems, stakeholders may have more insight and control over the whole product path, from manufacture to distribution and delivery (Ma et al., 2022: Arden et al., 2021).

This greater transparency helps to swiftly identify and address any quality concerns, which reduces the likelihood of product recalls and enhances patient safety generally. Additionally, supply chain managers may use digital traceability to cut costs and boost operational performance by identifying bottlenecks, managing inventory more skillfully, and streamlining shipping procedures (Gottipolu, 2020). Despite these benefits, there are still problems that need to be overcome, such the challenge of connecting dif- ferent digital systems, safeguarding data security and privacy, and the necessity of industry standard- ization. Overcoming these challenges will need strong stakeholder engagement, investments in secure digital infrastructure, and the development of common protocols and standards to ensure seamless data interchange and interoperability throughout the supply chain.

# Compliance and Coordination of Stakeholders

The adoption of Industry 4.0 and Pharma 4.0 in healthcare supply chains have some challenges with stakeholder coordination and compliance, such as:

1. Regulatory Compliance: Upholding industry-specific rules and regulations in relation to the adop- tion of innovative technologies is essential to preserving standards for both quality and safety.
2. Interoperability: Ensuring smooth communication and data sharing among diverse systems and platforms is essential for coordinating multiple stakeholders, such as manufacturers, suppliers, and distributors.
3. Data Security and Privacy: To avoid unwanted access and breaches, managing private and sensitive patient data calls for strong cyber security procedures and controls.
4. Collaborative Culture: Industry 4.0 and Pharma 4.0 cannot be successfully adopted and integrated unless a collaborative culture is fostered among stakeholders, including healthcare providers, technology providers, and regulatory bodies.
5. Training and Skill Development: Successful implementation and operation of Industry 4.0 and Pharma 4.0 solutions depend on stakeholders having the skills and knowledge to take advantage of innovative technologies.

# IMPORTANCE OF ASSESSING THEIR SUITABILITY, BENEFITS, CHALLENGES, AND OPPORTUNITIES FOR HEALTHCARE SUPPLY CHAINS

Evaluating the suitability, advantages, difficulties, and prospects of healthcare supply chains is essential to guaranteeing the efficient and successful provision of medical services. Healthcare organizations can make sure that their supply chains are suited to the unique requirements of the healthcare industry, such as timely and precise delivery of essential medical supplies, by assessing their suitability (Kilpatrick, et al., 2020). Gaining an understanding of the advantages makes it possible to pinpoint possible areas for development, which enables healthcare companies to improve patient care, cut expenses, and streamline operations. Simultaneously, acknowledging the obstacles present in healthcare supply chains, such as possible disturbances or limited resources, enables the creation of preemptive tactics to minimize hazards and guarantee uninterrupted services. Furthermore, identifying opportunities within healthcare supply chains can lead to the implementation of innovative technologies, optimized logistics, and strategic partner- ships, thereby fostering advancements in healthcare delivery and patient outcome (Zamiela et al., 2022).

# 5.1 Increased Efficiency and Productivity

Pharma 4.0 and Industry 4.0 provide a number of advantages to healthcare supply chains that boost production and efficiency. Among these benefits are the following: Enhanced Connectivity: Industry

4.0 encourages linked systems that allow for smooth data exchange and communication across different healthcare supply chain participants. This promotes more effective coordination and decision-making processes (Haleem et al., 2022). Automation and Streamlining: The automation of activities, the stream- lining of workflows and the reduction of mistake potential are all encouraged by Industry 4.0 and Pharma

4.0. These actions improve the overall operational efficiency of healthcare supply chains. Data-Driven Insights: These innovative technologies make it possible to gather and analyze enormous volumes of data, which produces insightful information that can be used to improve the procurement, production, and inventory management procedures in healthcare supply chains (Javaid et al., 2022). Enhanced Qual- ity Control Industry 4.0 and Pharma 4.0 provide real-time monitoring and quality control procedures, guaranteeing compliance with legal requirements and the provision of premium medical supplies.

# Customized Medications

From a Pharma 4.0 standpoint, customized drugs are a major breakthrough in the pharmaceutical sector that allow for more precise customization of drug formulations to meet the needs of individual patients. Pharma 4.0 makes it easier to produce personalized medications by utilizing technologies like 3D print- ing and the Internet of Things. This enables the creation of drug release profiles and dosages that are unique to each patient. This strategy is in line with the main objective of personalized medicine, which stresses giving the appropriate medication to the appropriate patient at the appropriate time (Andreadis et al., 2022). Pharma 4.0 aims to improve patient outcomes and treatment efficacy by incorporating these technological innovations and guaranteeing that medications are precisely tailored to meet individual patient characteristics and medical needs. A new era of individualized and successful pharmaceutical interventions may be brought about by this personalized approach, which has the potential to completely transform patient care and treatment plans.

# Additive Manufacturing

From the points of view of Industry 4.0 and Pharma 4.0, additive manufacturing has revolutionized the pharmaceutical and manufacturing sectors by introducing innovative methods of production and enhanced customizability. Customized drug formulations and medical devices can now be produced by the phar- maceutical industry thanks to additive manufacturing, commonly referred to as 3D printing. This has allowed for the precise customization of drug regimens to meet the needs and preferences of individual patients (Sharma et al., 2023). By simplifying the administration of treatments catered to the specific requirements of each patient and improving overall therapeutic outcomes, this approach has significantly advanced personalized medicine. In the larger framework of Industry 4.0, additive manufacturing has completely transformed conventional manufacturing processes by enabling the rapid and economical production of complex parts and components. Increased production efficiency, decreased waste, and improved product design flexibility have resulted from the incorporation of additive manufacturing into Industry 4.0 initiatives, which has raised operational agility and competitiveness in the manufacturing sector (Mobarak, et al., 2023).

# Improved Patient Data Analysis

Enhancing the analysis of patient data is essential to Industry 4.0 and Pharma 4.0. The use of technology and digital innovations makes it possible to analyze patient data more thoroughly and effectively in the era of Industry 4.0 and Pharma 4.0. Pharmaceutical companies can now collect and analyze data using machines thanks to these advancements, which creates flexible and efficient processes. Industry 4.0 offers the framework for real-time patient data collection and analysis by merging physical and digital systems (Mukhlas et al., 2022). More individualized and accurate treatment plans are made possible by this data-driven approach, which also makes it possible to spot trends and patterns that can guide clinical trials and medication development. Additionally, Pharma 4.0’s focus on interconnectivity and Big Data utilization improves the analysis of patient data even more. The amalgamation of artificial intelligence and machine learning algorithms facilitates the more extensive and precise analysis of patient data. This degree of analysis can help identify possible health risks proactively, lead to earlier and more accurate diagnoses, and improve treatment outcomes (Haleem et al., 2022). All things considered, Pharma 4.0 and Industry 4.0 offer the framework and instruments for enhanced patient data analysis, leading to more efficient and customized healthcare outcomes through the integration of technology and data analysis capabilities.

# Resource Optimization

The pharmaceutical industry’s “Pharma 4.0” digital operating model combines the ideas of Industry 4.0 to maximize resources and boost productivity (Sharma et al., 2023). Pharma 4.0 integrates digital tools and technologies to enable proactive resource management, process automation, and real-time data analy- sis. Organizations can improve their resource utilization by employing data-driven decision-making and identifying waste or inefficiencies in their supply chain, marketing, research, and production processes. Digital twins, or digital copies of real assets and operations, are used more easily thanks to Pharma 4.0. Increased connectivity and transparency made possible by these digital twins help organizations track and manage resources in real-time, spot inefficiencies or bottlenecks, and make the necessary correc- tions to optimize resource allocation (Hariry et al., 2021). There are obstacles unique to implementing Pharma 4.0 and attaining better resource optimization. The need for significant investment in digital infrastructure and technologies, as well as the integration of legacy systems with new digital solutions, are a few of these difficulties.

Ensuring data integrity and compliance with current GMP standards and regulatory guidelines may also present difficulties. However, these difficulties are outweighed by the advantages of Pharma 4.0 and enhanced resource optimization. The COVID-19 pandemic has significantly improved digital technolo- gies’ adaptability in the pharmaceutical and healthcare sectors. With its emphasis on automation and digitization, Pharma 4.0 is now even more pertinent in this setting (Khan & Manzoor, 2021). Pharma

4.0 streamlines and boosts productivity throughout the value chain to give pharmaceutical companies a competitive edge. This entails integrating self-organizing and autonomous manufacturing facilities, facilitating quick decision-making, and streamlining drug manufacturing through real-time optimization and control systems.

# OPPORTUNITIES FOR SUSTAINABLE PHARMACEUTICAL SUPPLY CHAIN

The researchers explore both the positive aspects and potential challenges associated with the integration of Industry 4.0 and Pharma 4.0 in healthcare supply chains:

1. **Better Product Protection and Supply Chain Security**: Industry 4.0 in the pharmaceutical industry provides better tools for supply chain security and product protection, which helps to maintain the general integrity of healthcare supply chains (Sharma et al., 2023).
2. **Empirical Research for Performance Improvement**: Research indicates that the interaction of new technologies with pharmaceutical supply chains often referred to as “Pharma 4.0” improves supply chain performance. This involves applying managerial techniques to boost productivity.
3. **Beneficial Effect on Hospital Performance**: As part of Pharma 4.0, integrating Industry 4.0 into medical treatments is said to have a short-term beneficial effect on hospitals’ performance, dem- onstrating prospective advantages for healthcare delivery (Tortorella 2023).
4. **Implications for Supply Chain Performance:** Both favorable and unfavorable effects on supply chain performance are highlighted by a thorough analysis of Industry 4.0 technology. To optimize the integration process, it is important to comprehend these ramifications (Rad, et al., 2022).
5. **Using Cyber-Physical Technology to Increase System Smartness:** Industry 4.0, the latest in- dustrial revolution, uses cyber-physical technology to increase system smartness, which includes autonomous devices. The progression from Industry 4.0 to Pharma 4.0 reflects this shift (Hariry et al., 2021).
6. **Integration for Sustainable Supply Chains:** Industry 4.0’s contribution to supply chains includes sustainability promotion. Supply chain sustainability and Industry 4.0 integration is a novel strategy that highlights the necessity for a fair assessment of the integration’s environmental effects (Naseem & Yang, 2021).

# Sustainable Manufacturing and Distribution

In the pharmaceutical industry, supply chains that are socially and environmentally responsible can be established through sustainable manufacturing and distribution. Using sustainable practices encourages resource efficiency and long-term cost savings in addition to guaranteeing a decrease in waste production and carbon footprints. Utilizing renewable energy sources, like solar or wind power, is a key compo- nent of sustainable manufacturing initiatives as it helps minimize dependency on fossil fuels and lower greenhouse gas emissions overall (Raman et al., 2023). Furthermore, a more sustainable approach to drug development can be fostered by incorporating green chemistry principles and using bio-based ma- terials in pharmaceutical production to significantly reduce the environmental impact of manufacturing processes. The distribution stage is essential to improving the sustainability of pharmaceutical supply chains, working hand in hand with sustainable manufacturing. Reducing energy consumption and the environmental impact of product delivery can be achieved by putting effective logistics strategies into practice, such as optimizing transportation routes and using eco-friendly packaging materials. Addi- tionally, the integration of innovative tracking technologies and real-time monitoring systems improves visibility across the distribution network, making it easier to spot possible inefficiencies early and take swift corrective action. All of these factors contribute to the overall resilience and sustainability of the supply chain (Puhlmann et al., 2024).

Regulatory agencies, suppliers, pharmaceutical companies, and other stakeholders must work together to promote a sustainable culture throughout the whole pharmaceutical supply chain. In addition to en- couraging increased accountability, participating in open dialogue, knowledge exchange, and cooperative efforts for sustainable development guarantees that sustainability goals and objectives are in line with each other across the ecosystem of the supply chain (Chauhan et al., 2022). Through leveraging sustainable manufacturing and distribution practices, the pharmaceutical industry can maintain its environmental stewardship, participate in international efforts to mitigate climate change, and ultimately promote the welfare of both humanity and the environment.

# Decentralized Supply Chain Closer to the Patient

A game-changing possibility for sustainable pharmaceutical supply chains is a decentralized supply chain model that puts the patient’s proximity first (Sahoo et al., 2022). This strategy promotes improved health outcomes and patient satisfaction by guaranteeing the timely and effective delivery of medications, thereby facilitating enhanced patient-centricity. Pharmaceutical companies can minimize the environmental impact of long-distance drug delivery and significantly reduce transportation-related carbon emissions by implementing agile logistics strategies and setting up localized distribution centers. Decentralized supply chains also empower local economies and encourage community involvement, which advances social sustainability and strengthens the bond between pharmaceutical companies and the communities they service (Amjad et al., 2023). Adopting this decentralized, patient-focused supply chain paradigm enhances pharmaceutical supply chains’ overall responsiveness and resilience and is consistent with the larger sustainability objectives of lessening their negative effects on the environment and enhancing community well-being.

# 6.3. Exploring the Impact of Industry 4.0 on Healthcare Supply Chains

Pharma 4.0 is the result of the four manufacturing transformational phases. Pharma 4.0 refers to the mod- ernization of the pharmaceutical sector via the integration of innovative technology and digital tactics. The pharmaceutical industry may be able to overcome obstacles if Industry 4.0 concepts are adopted. In the pharmaceutical industry, Industry 4.0’s mission is to quickly, cheaply, and effectively create and produce innovative, personalized goods that meet the diverse tastes and needs of customers. The Pharma

4.0 operating model is the result of adding Industry 4.0 and the International Council of Harmonization (ICH). The pharmaceutical industry’s use of Industry 4.0 has given the pharmacy sectors a competitive edge (Ding, 2018; Lakner et al., 2019).

Because Industry 4.0 boosts productivity and brings new possibilities for the circular economy, transparency, and product customization, it may benefit sustainability along the whole value chain. The adoption of Industry 4.0 is one of the primary drivers behind the modernization of the pharmaceutical and biopharmaceutical sectors. Industry 4.0 uses freely available footprint information and verifiable research to minimize the ecological effect of a process or product (Filho et al., 2022).

Demands from the market became much more intense and labor-intensive as Industry 4.0 emerged. Digitalization, a key part of pharma 4.0, will connect everything and create new levels of precision and adaptability for a digitalized plant floor. It was suggested that Industry 4.0 would enhance production in order to achieve maximum mass customization at a reasonable cost and short product life cycles. The goals of Industry 4.0 for digitizing labs and applying automation to various procedures used in hospitals

and general healthcare are included in Health 4.0. In the pharmaceutical industry, Industry 4.0 offers improved tools for supply chain security and product protection (Sharma, 2023)

Pharma 4.0 is a shift in the pharmaceutical sector that uses “machines” to gather and analyze data so that processes can become more flexible and efficient. Massive data processing, networking, artificial intelligence, cooperative robotics, and distributed cloud service-based architectures are the engines driv- ing Pharma 4.0. In the pharmaceutical industry, Industry 4.0 facilitates increased operational efficiency, such as reduced resource consumption. By speeding up the analysis of patient data and empowering them to maximize resources for better patient outcomes, Health 4.0 is intended to enhance the capacity of medical professionals (Arden et al., 2021).

Industry 4.0 optimizes the entire value chain, or the life cycle of a product, from its conception to its development, manufacturing, use, upkeep, and recycling. It also improves production flows. Industry 4.0 is a smart production networking system that links products and instruments without requiring human intervention. Furthermore, increased data density reduces productivity and encourages the pharmaceuti- cal industry to develop more specialized and tailored pharmaceutical products that are appropriate for tailored medication treatment rather than the current “one-size-fits-all” strategy (Barenji et al., 2019). Biopharmaceuticals can benefit greatly from the application of Industry 4.0 technologies and goals, which could lead to significant advancements in biomedicine production, availability, and advancement. The goal of the Industry 4.0 plan is to link production equipment to goods through hyper-connected technologies and unify the whole manufacturing process (Shi et al., 2020).

“Industry 4.0,” or the fourth industrial revolution, is gaining traction, especially in the aftermath of the epidemic and the present unsteady political environment globally. It is seen as a way to channel all stakeholders under the design of a digital supply chain and encourage a more open network. Academics and industry are currently working to address the dynamic demand for organizations to adopt higher flexibilities as a result of business requirements, customer-oriented supply chain solutions, and rapid changes in the market. Numerous research articles discuss various methods to accomplish this, such as blockchain solutions, virtual and augmented reality that imitates negotiations, cloud-based solutions, and cyber-physical systems (Berg, et al., 2021).

Adoption of various technologies can face specific challenges, such as those related to finances, the development of digital infrastructure, resistance to innovation, and so forth. Nonetheless, further inves- tigation into various Industry 4.0 applications may be necessary in order to select the appropriate one. Due to its capacity for secure traceability and decentralization, blockchain technology is an intriguing solution that is currently being applied throughout supply chains. This suggests that it may be a viable option to investigate within the context of Industry 4.0 and digitalization as a solution. Recent research has focused on automating financial systems under blockchain governance, which may pave the way for multi-channel or multi-stakeholder communication channels (Xia et al., 2023).

Expected benefits include a transparent transaction and a decentralized power mechanism that en- courage user cooperation and mutual trust amongst all parties. Such a technology may be able to draw more validation transactions in the process of locating the best manufacturers or suppliers when innova- tors or idea owners are also taken into account. An open channel built on blockchain technology may also impede the growth of investor and financier confidence, which is bolstered by a digital financial regulatory framework (Javaid et al., 2021). Major stakeholders that communicate with manufacturers and suppliers would also facilitate greater data sharing while defending competitive interests that could result in the achievement of sustainable, economic goals and a reduction in costs related to stakeholder interactions and negotiations, as previously mentioned in the literature (Khan et al., 2016).

# PRACTICAL CASE STUDIES

1. FarmaTrust offers a blockchain-based end-to-end pharmaceutical product provenance system that is suitable for corporate use. With this approach, counterfeit or substandard medications are pre- vented from entering the pharmaceutical supply chain; protecting customers who may use their free Consumer Confidence App to verify the legitimacy of pharmaceuticals. FarmaTrust has strategi- cally made sure to leverage modern technologies, such as mobile phone technology and different exclusive software that FarmaTrust has developed, to create solutions that can function anywhere in the world, whether it is Mongolia or Germany (FarmaTrust).
2. Merck is implementing Pharma 4.0 in their production process to enhance quality control and traceability. Through the creation of digital twins for primary packaging, the proof of concept (PoC) seeks to revolutionize the pharmaceutical supply chain. They assert that members will get complete transparency and digital trust through a single, linked network, which will save costs, enhance quality, and even open up new business opportunities because of process automation. The innovative solution, which is applied to Gerresheimer items, anchors physical things securely in the digital realm using a blockchain-based platform and multi-patented authentication technology created by Merck (Packaging Europe, 2022).
3. According to LogiPharma (2021) to support the shift in the pharmaceutical supply chain from production to end-user, Novartis is experimenting with different strategies to leverage digital technology, and notably artificial intelligence, to help in the planning, monitoring, and delivery of medicine to patients. Artificial intelligence is one aspect of Industry 4.0 that Novartis is keen to make a pillar of its digital transformation in cell therapy. The Novartis representative continued on, “[Novartis] is still investigating where best to apply AI in the manufacturing process.” “Novartis is investigating how artificial intelligence (AI) can assist us in identifying opportunities within our data to make more economical purchases of materials used in the manufacturing process.”
4. The Bosch Pharma has a long journey with industry 4.0 revolution and progress. An artificial intel- ligence (AI) system that can identify and address irregularities and failures in the manufacturing process early on has been created by the Bosch Center for Artificial Intelligence (BCAI). This ap- plication of AI guarantees better goods and more environmentally friendly, productive production. Approximately 50 facilities and 800 manufacturing lines are already supported by the AI solution, which will ultimately be implemented in all 240 Bosch factories.

In order to improve quality control and perform predictive maintenance, Bosch implemented Industry 4.0 in its factories. The World Economic Forum has recognized a Bosch facility as an Industry 4.0 lighthouse project for the second time. Bosch provides an example of how digitalized production and logistics can improve both efficiency and quality in equal measure in Suzhou, China. In 2018, Bosch included their facility in Wuxi, China, on the list of outstanding examples. The World Economic Forum emphasized there that linked solutions’ capacity for predictive maintenance and troubleshooting sets an example for factories of the future (Bosch, 2021).

1. According to (Tracxn, 2023) report, Blockchain is being widely used in healthcare start-ups in India, including Plenum Data, Shivom, NHCT, Vitraya, UHID, MedBlocks, and Rolyte. These companies offer blockchain- and IoT-based solutions for data security, data integration, and man- agement. A blockchain-based system for managing health insurance claims is offered by Vitraya

Technologies. It provides options for hospitals, healthcare providers, and insurers to process and pay claims together. For claim settlement, rewards, and fraud detection, it makes use of blockchain- based technologies and smart contacts.

Patients may schedule telehealth appointments with GraphMyHealth, an AI-powered tool. Patients may schedule appointments, have online video consultations with medical professionals, schedule pre- ventative health check-ups, tests, prescription drugs, and other medical and home care services using the mobile app. Blockchain technology and AI technologies are integrated into the platform.

# CONCLUSION

In conclusion, a dynamic view of opportunities and problems is revealed by investigating Industry 4.0 and Pharma 4.0 in the context of health care supply chains. The pharmaceutical industry has enormous potential to improve efficiency, sustainability, and customized solutions as a result of the confluence of digital technology and pharmaceutical processes. The positive effects of Industry 4.0 and Pharma 4.0, which range from improved flexibility and cost-effectiveness to sustained value generation, have been made clear by our assessment. However, there are challenges associated with using these technologies. Because the pharmaceutical industry is highly regulated, considerations like patient safety, product quality, and data integrity are necessary. To mitigate these risks, a thorough understanding of the unique requirements of the pharmaceutical supply chain and strategic planning are essential.

# REFERENCES

AbuHalimeh, A., & Ali, O. (2023). Comprehensive review for healthcare data quality challenges in blockchain technology. *Frontiers in Big Data*, 1-12.

Agbo, C., Mahmoud, Q., & Eklund, J. (2019). Blockchain Technology in Healthcare: A Systematic Review. *Health Care*. PMID:30987333

Amjad, A., Kordel, P., & Fernandes, G. (2023). A Review on Innovation in Healthcare Sector (Telehealth) through Artificial Intelligence. *Sustainability (Basel)*, *15*(8), 6655. doi:10.3390/su15086655

Andreadis, I., Gioumouxouzis, C., Eleftheriadis, G., & Fatouros, D. (2022). The Advent of a New Era in Digital Healthcare: A Role for 3D Printing Technologies in Drug Manufacturing? *Pharmaceutics*.

Arden, N., Fisher, A., Tyner, K., Yu, L., Lee, S., & Kopcha, M. (2021). Industry 4.0 for pharmaceutical manufacturing: Preparing for the smart factories of the future. *International Journal of Pharmaceutics*, *602*, 120554. doi:10.1016/j.ijpharm.2021.120554 PMID:33794326

Barenji, R. V., Akdag, Y., Yet, B., & Oner, L. (2019). Cyber-physical-based PAT (CPbPAT) framework for Pharma 4.0. *International Journal of Pharmaceutics*, *567*, 118445. doi:10.1016/j.ijpharm.2019.06.036 PMID:31226474

Berg, H., Bendix, P., Jansen, M., Blevennec, K., Bottermann, P., & Melgar, M. M. (2021). *Unlocking the potential of Industry 4.0 to reduce the environmental impact of production.* Eionet Report.

Bosch. (2021). *Ten years of Industry 4.0.* Bosch.

Chauhan, C., Kaur, P., Arrawatia, R., Ractham, P., & Dhir, A. (2022). Supply chain collaboration and sustainable development goals (SDGs). Teamwork makes achieving SDGs dream work. *Journal of Busi- ness Research*, *147*, 290–307. doi:10.1016/j.jbusres.2022.03.044

Cowie, M., Blomster, J., Curtis, L., Duclaux, S., Ford, I., & Fritz, F. (2016). Electronic health records to facilitate clinical research. *Clinical Research in Cardiology; Official Journal of the German Cardiac Society*. PMID:27557678

*Digital twin solution from Merck offers increased traceability*2022Packaging Europe.

Ding, B. (2018). Pharma Industry 4.0: Literature review and research opportunities in sustainable phar- maceutical supply chains. *Process Safety and Environmental Protection*, *119*, 115–130. doi:10.1016/j. psep.2018.06.031

FarmaTrust. (n.d.). *Pharmaceutical Tracking & Data Services*. FarmaTrust.

Farziyeva, G., & Dhanik, N. (2022). *Digital Transition of Supply Chain with Industry 4.0 Applications*. Academic Press.

Ferronato, N., & Torretta, V. (2019). Waste Mismanagement in Developing Countries:A Review of Global Issues. *International Journal of Environmental Research and Public Health*, 1–28. PMID:30909625

Filho, M. G., Monteiro, L., Mota, R. d., Gonella, J. d., & Campos, L. M. (2022). The Relationship between Circular Economy, Industry 4.0 and Supply Chain Performance: A Combined ISM/Fuzzy MICMAC Approach. *Sustainability*.

Ghadge, A., Bourlakis, M., Kamble, S., & Seuring, S. (2022). Blockchain implementation in phar- maceutical supply chains: A review and conceptual framework. *International Journal of Production Research*, 6633–6651.

Ghouri, A. M., Khan, H., Venkatesh, M., Haq, M. A., & Jabbour, A. L. (2023). *An Artificial-Intelligence- Based Omnichannel Blood Supply Chain: A Pathway for Sustainable Development*. Academic Press.

Gottipolu, R. (2020). *Securing the Pharmaceutical Supply Chain with Full Traceability.* PharmaTech.com. Griggs, K. N., Ossipova, O., Kohlios, C. P., Baccarini, A. N., Howson, E. A., & Hayajneh, T. (2018).

*Healthcare Blockchain System Using Smart Contracts for Secure Automated Remote Patient Monitoring*. Med Syst. doi:10.1007/s10916-018-0982-x

Haleem, A., Javaid, M., Singh, R. P., & Suman, R. (2022). Medical 4.0 technologies for healthcare: Features, capabilities, and applications. *Internet of Things and Cyber-Physical Systems*, 12-30.

Haq, I., & Esuka, O. M. (2018). Blockchain Technology in Pharmaceutical Industry to Prevent Counterfeit Drugs. *International Journal of Computer Applications*, *180*(25), 8–12. doi:10.5120/ijca2018916579

Hariry, R. E., Barenji, R. V., & Paradkar, A. (2021). *From Industry 4.0 to Pharma 4.0*. Academic Press.

Huang, K., Wang, K., Lee, P., & Yeung, A. C. (2023). The Impact of Industry 4.0 on Supply Chain Capability and Supply Chain Resilience: A Dynamic Resource-Based View. *International Journal of Production Economics*, *262*, 108913. doi:10.1016/j.ijpe.2023.108913

Javaid, M., Haleem, A., Singh, R. P., Khan, S., & Suman, R. (2021). Blockchain technology applications for Industry 4.0: A literature-based review. *Blockchain: Research and Applications*.

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustainable Operations and Computers*, 203-217.

Khan, M., Hussain, M., & Saber, H. M. (2016). Information sharing in a sustainable supply chain. *In- ternational Journal of Production Economics*, *181*, 208–214. doi:10.1016/j.ijpe.2016.04.010

Khan, M. I. (2024). Impact of Blockchain Technology on Transparency and Trust in Programmatic Advertising Supply Chain. In M. R. Khan, N. R. Khan, & A. M. Ghouri (Eds.), Achieving Secure and Transparent Supply Chains With Blockchain Technology (pp. 57-69). IGI Global. doi:10.4018/979-8- 3693-0482-2.ch004

Khan, M. R., Ali, A., & Rind, A. A. (2024). Blockchain Technology and Supply Chain Sustainability: A View From UNSDG Perspective. In Achieving Secure and Transparent Supply Chains With Blockchain Technology (pp. 1-17). IGI Global. doi:10.4018/979-8-3693-0482-2.ch001

Khan, M. R., Khan, M. R., & Nallaluthan, K. (2023). Blockchain Supply Chain Management and Supply Chain Sustainability. In *Blockchain Driven Supply Chain Management: A Multi- dimensional Perspective* (pp. 155–180). Springer Nature Singapore. doi:10.1007/978-981-99-0699-4\_10

Khan, M. R., Khan, N. R., Tufail, M., & Ali, L. (2023). A Path Towards A Greener Future Fostering Green Supply Chain, Green Marketing, And Environmental Sustainability. *LogForum, 19* (1).

Khan, M. R., & Manzoor, A. (2021). Application and Impact of New Technologies in the Supply Chain Management During COVID-19 Pandemic: A Systematic Literature Review. *International Journal of Economics and Business Administration*.

Khan, N., Haq, M. A., Ghouri, A. M., Raziq, A., & Moiz, S. M. (2017). Adaptation of RFID Technology in Business Supply Chain Success: Empirical Findings from a Developing Country Logistic Industry. *Quality Management*.

Khan, N. R., Khan, M. R., & Ghouri, A. M. (2024). Industry 4.0 on the Way to Companies Performance. In Quality Management, Value Creation, and the Digital Economy (pp. 99- 120). Routledge.

Kilpatrick, J., Barter, L., Alexander, C., Brown, J., Calderon, R., & Carruthers, R. (2020). *Managing supply chain risk and disruption.* Deloitte.

Lakner, Z., Kiss, A., Popp, J., Zeman, Z., Mate, D., & Olah, J. (2019). From Basic Research to Competi- tiveness: An Econometric Analysis of the Global Pharmaceutical Sector. *Sustainability (Basel)*, *11*(11), 3125. doi:10.3390/su11113125

Ma, J. Y., Shi, L., & Kang, T. W. (2022). The Effect of Digital Transformation on the Pharmaceutical Sustainable Supply Chain Performance: The Mediating Role of Information Sharing and Traceability Using Structural Equation Modeling. *Sustainability (Basel)*, *15*(1), 649. doi:10.3390/su15010649

Malheiro, V., Duarte, J., Veiga, F., & Melo, F. M. (2023). Exploiting Pharma 4.0 Technologies in the Non-BiologicalComplex Drugs Manufacturing: Innovations and Implications. *Pharmaceutics*, *15*(11), 2545. doi:10.3390/pharmaceutics15112545 PMID:38004525

Mobarak, M. H., Islam, M. A., Hossain, N., Al Mahmud, M. Z., Rayhan, M. T., & Nishi, N. J. (2023). *Recent advances of additive manufacturing in implant fabrication A review*. Applied Surface Science Advances. doi:10.1016/j.apsadv.2023.100462

Mukhlas, A., Talip, B., Mustapha, J. C., & Ismail, S. (2022). Industry 4.0 (IR 4.0) for Pharmaceutical Industry: An Exploratory Review. *International Visualization, Informatics and Technology Conference (IVIT.*

Munirathinam, S. (2020). Industry 4.0: Industrial Internet of Things (IIOT). In The Digital Twin Para- digm for Smarter Systems and Environments: The Industry Use Cases (pp. 129-164). Academic Press.

Musamih, A., Salah, K., Jayaraman, R., Arshad, J., Debe, M., & Al Hammad, Y. (2016). A Blockchain- based Approach for Drug Traceability in Healthcare Supply Chain. *IEEE Access : Practical Innovations, Open Solutions*.

Naseem, M. H., & Yang, J. (2021). Role of Industry 4.0 in Supply Chains Sustainability:A Systematic Literature Review. *Sustainability (Basel)*, *13*(17), 9544. doi:10.3390/su13179544

News, I. (2021). *Novartis’ Industry 4.0 Tech Transforms Cell Therapy Manufacturing*. LogiPharma.

Okoli, C. (2015). A Guide to Conducting a Standalone Systematic Literature Review. *Communications of the Association for Information Systems*, *37*. Advance online publication. doi:10.17705/1CAIS.03743

Peake, B., Braund, R., Tremblay, L., & Tong, A. (2016). Impact of pharmaceuticals on the environment.

*The Life-Cycle of Pharmaceuticals in the Environment.*

Pelaez, R. M., Brust, A. O., Rivera, S., Felix, V., Ostos, R., & Brito, H. (2023). Role of Digital Transfor- mation for Achieving Sustainability: Mediated Role of Stakeholders, Key Capabilities, and Technology. *Sustainability*, 1–27.

Puhlmann, N., Vidaurre, R., & Kummerer, K. (2024). Designing greener active pharmaceutical ingre- dients: Insights from pharmaceutical industry into drug discovery and development. *European Journal of Pharmaceutical Sciences*, *192*, 106614. doi:10.1016/j.ejps.2023.106614 PMID:37858896

Rad, F. F., Oghazi, P., Palmie, M., Chirumalla, K., Pashkevich, N., Patel, P. C., & Sattari, S. (2022). Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies. *Industrial Marketing Management*, *105*, 268–293. doi:10.1016/j.indmarman.2022.06.009

Raman, R., Sreenivasan, A., Ma, S., Patwardhan, A., & Nedungadi, P. (2023). Green Supply Chain Man- agement Research Trends and Linkages to UN Sustainable Development Goals. *Sustainability (Basel)*, *15*(22), 15848. doi:10.3390/su152215848

Ravi, D., Ramachandran, S., Vignesh, R., Falmari, V. R., & Brindha, M. (2022). *Privacy preserving transparent supply chain management through Hyperledger Fabric*. Academic Press.

Ray, P. P., Dash, D., De, D., Salah, K., & Kumar, N. (2020). Blockchain for IoT-Based Healthcare: Background, Consensus, Platforms, and Use Cases. *IEEE Systems Journal*.

Rousseau, D., Manning, J., & Denyer, D. (2008). Evidence in Management and Organizational Sci- ence Assembling the Field’s Full Weight of Scientific Knowledge Through Syntheses. *The Academy of Management Annals*, *2*(1), 475–515. doi:10.5465/19416520802211651

Sahoo, S., Kumar, S., Sivarajah, U., Lim, W. M., Westland, J., & Kumar, A. (2022). Blockchain for sus- tainable supply chain management:trends and ways forward. *Electronic Commerce Research*. Advance online publication. doi:10.1007/s10660-022-09569-1

Sharma, D., Pate, P., & Shah, M. (2023). A comprehensive study on Industry 4.0 in the pharmaceutical industry for sustainable development. *Environmental Science and Pollution Research International*, *30*(39), 90088–90098. doi:10.1007/s11356-023-26856-y PMID:37129827

Shi, Z., Xie, Y., Xue, W., Chen, Y., Fu, L., & Xu, X. (2020). Smart factory in Industry 4.0. *Systems Research and Behavioral Science*, *37*(4), 607–617. doi:10.1002/sres.2704

Steinwandter, V., Borchert, D., & Herwing, C. (2019). Data science tools and applications on the way to Pharma 4.0. *Drug Discovery Today*, *24*(9), 1795–1805. doi:10.1016/j.drudis.2019.06.005 PMID:31207205

*The History Of Pharmaceutical Manufacturing: Industry 1.0 To Pharma 4.0*2017LWS 40 Years.

*The Importance of Environmental Awareness When Running a Business*2019Maryville University. Tortorella, G. L., Prashar, A., Antony, J., Fogliatto, F. S., Gonzalez, V., & Filho, M. G. (2023). Industry

4.0 adoption for healthcare supply chain performance during COVID-19 pandemic in Brazil and India: the mediating role of resilience abilities development. *Operations Management Research*.

Tracxn. (2023). *Blockchain in Healthcare Startups in India.* Author.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence- Informed Management Knowledge by Means of Systematic Review. *British Journal of Management*, *14*(3), 207–222. doi:10.1111/1467-8551.00375

Ugvekar, N., Kamath K, K., Subramanyam, E., & Shabaraya, A. (2021). A Review on Change Manage- ment System in Pharmaceutical Industry. *International Journal of Drug Regulatory Affairs*.

Ventura, M., & Coeli, C. M. (2018). *Beyond privacy: the right to health information, personal data protection, and governance*. Sci ELO Brazil.

White, C. M. (2022). *Dangerous Counterfeit Drugs are Putting Millions at Risk, a New Study Says.*

UConn Today.

Williams, L. (2014). *The Real Impact of Counterfeit Medications*. US Phamacist.

Xia, J., Li, H., & He, Z. (2023). The Effect of Blockchain Technology on Supply Chain Collaboration: A Case Study of Lenovo. *Systems*, *11*(6), 1–25. doi:10.3390/systems11060299

Yaqoob, I., Salah, K., Jayaraman, R., & Al-Hammad, Y. (2021). Blockchain for healthcare data man- agement: Opportunities,challenges, and future recommendations. *Neural Computing & Applications*.

Zakari, N., Al-Razgan, M., Alsaadi, A., Alshareef, H., Al saigh, H., Alashaikh, L., Alharbi, M., Alomar, R., & Alotaibi, S. (2022). Blockchain technology in the pharmaceutical industry: A systematic review. *PeerJ. Computer Science*, *8*, 1–26. doi:10.7717/peerj-cs.840 PMID:35634106

Zamiela, C., Ibne Hossain, N., & Jaradat, R. (2022). Enablers of resilience in the healthcare supply chain: A case study of U.S healthcare industry during COVID-19 pandemic. *Research in Transportation Economics*, *93*, 101174. doi:10.1016/j.retrec.2021.101174

Zozaya, N., Alcala, B., & Galindo, J. (2019). *The offset effect of pharmaceutical innovation: A review study*. Global & Regional Health Technology Assesment.

341

[View publication stats](https://www.researchgate.net/publication/379203346)