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Emerging Technologies in Pharmaceutical Supply Chains: a Comprehensive Analysis of Findings and Implications

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The pharmaceutical supply chain faces significant challenges in achieving resilience and adaptability amid complex global risks and disruptions. Emerging technologies, such as Pharma 4.0, artificial intelligence (AI), and blockchain, offer transformative potential to enhance supply chain performance. Yet, research lacks a holistic understanding of how these technologies synergise to address scalability, cost, and cybersecurity challenges. This study undertakes a systematic literature review, synthesising findings from key studies within the Scopus database, to explore the integration of these technologies in pharmaceutical supply chains. The review reveals that combining artificial intelligence, blockchain, and Pharma 4.0 enables improved traceability, risk management, and resilience through mechanisms like Intelligent Digital Twins (iDTs) for stress testing and real-time response. These results indicate that integrating these technologies has the potential to build robust, scalable, and secure supply chains capable of withstanding future disruptions. By highlighting the compounded benefits and cross-industry applicability of these advancements, this study provides a comprehensive framework that not only addresses current gaps but also guides pharmaceutical companies and related industries toward more resilient supply chain solutions.

1. Introduction

The increasing effect of emerging technologies (ETs) on reshaping supply chain dynamics has become a central focus in recent research. These developments, including Pharma 4.0, artificial intelligence (AI), and blockchain, are recognised for their revolutionary potential in enhancing efficiency, resilience, and risk mitigation across supply chains. Prior research provides valuable insights into the capabilities of these technologies. For example, Charles et al. (2019) highlight the effect of blockchain on traceability and risk management within supply chains, while Saha et al. (2022) show how data analytics and IoT facilitate processes such as sourcing, manufacturing, and distribution in the pharmaceutical industry. Ivanov (2023) further introduces the concept of Intelligent Digital Twins (iDTs), showcasing the potential of human-AI collaboration to improve resilience under uncertain conditions. Pournader et al. (2023) reveal a framework for assessing multimodal supply chain risks. Despite these contributions, however, significant gaps remain in the literature. One notable gap lies in understanding the synergistic effects of these technologies when applied together rather than in isolation. Although many studies have investigated AI, blockchain, and Pharma 4.0 separately, few have examined how their integration can yield enhanced resilience and adaptability, specifically within pharmaceutical supply chains. The literature lacks comprehensive analyses of the scalability and cost challenges associated with implementing AI and blockchain at a global scale. Additional research is also needed on the application of intelligent digital twins (iDTs) in pharmaceutical supply chains, specifically regarding their role in human-AI collaboration for real-time disruption management and stress testing. The aims of this review address these knowledge gaps directly. This study provides a novel framework that synthesises the roles of AI, blockchain, and Pharma 4.0, highlighting their combined potential to create resilient, efficient supply chains tailored for the pharmaceutical industry. By analysing recent advancements and presenting new applications, such as iDTs for stress testing, this paper demonstrates the feasibility of integrating these technologies to strengthen supply chains in the face of global disruptions. This review highlights the cross-industry applicability of these insights, indicating how similar approaches could benefit other critical sectors, such as healthcare and manufacturing, which encounter similar challenges related to resilience and efficiency. In summary, this paper seeks to address existing knowledge

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gaps by exploring how the combined use of AI, Blockchain, and Pharma 4.0 can significantly enhance resilience and efficiency in pharmaceutical supply chains. This analysis will focus on overcoming critical challenges related to scalability, cost, and cybersecurity while also examining the innovative role of Intelligent Digital Twins in stress-testing and disruption management. Through this comprehensive approach, the study offers valuable insights into building more robust and adaptable supply chains in the pharmaceutical sector and beyond.

2. Methodology

The current study conducted a literature review to see how real opportunities for using blockchain and AI have been implemented. This review attempted to address issues such as supply chain resiliency. A systematic literature review would find, select, and critically assess studies relevant to a well-defined research question. Its techniques are explicit, comprehensive, and systematic in order to prevent bias and ensure the trustworthiness of conclusions. This article review is restricted to articles obtained from Scopus utilising narrow search tactics, limited databases, and timeframes that hampered the retrieval process.

To answer the study question, a systematic literature evaluation was carried out, with relevant papers collected and classified using the Scopus database. Other available synonyms and alternatives were also considered during this artificial intelligence keyword identification process. Some identified keywords are pharmaceutical supply chain, management of the supply chain, artificial intelligence, Blockchain, resilience, and risk management. To sort these terms and create more significant research outcomes, the PEO (Population, Exposure, Outcome) method was used. This method, usually used in the medical field but less so in other fields, helps organise and break down a research question while organising keywords for database searches (Metzler and Metz, 2010; Bettany-Saltikov, 2012; Mammun et al., 2021).

Keywords were joined with Boolean operators to create complicated search requests, which enhanced the effectiveness of the literature search. The searches were executed using a combination of three, four, and five keywords. Population means the primary topic of the study question, which in this search is Pharmaceutical Supply Chain Management. Exposure contains things that affect the population, such as AI and Blockchain. The outcome describes the effects of these exposures on the population. To enhance the search for pertaining literature, The following inclusion and exclusion conditions were used for the systematic literature review:

1. The articles must be relevant to the fields of engineering and management science
2. The article should be open-access.
3.The article has to be in English.
4.The article has to be published between 2013 and 2023.
5.The article should not be duplicated any duplication will be removed.
6.The article should be related to the research question.

3. Results

The findings indicate that emerging technologies have a significant impact on pharmaceutical supply chains. Emerging technologies like AI, Blockchain, and IoT in a bundled Pharma 4.0 environment have been fairly effective in improving traceability, decision-making, and risk management, obviously leading to improvement in supply chain performance. For example, Saha et al. (2022) have shown how these technologies can further streamline their supply chain operations. This view has been supported by Charles et al. (2023) as they emphasised the integrated function of AI and blockchain in improving supply chain resilience. At the same time, scalability and cost-related challenges remain significant barriers to fully realising the benefits of such technologies. Ivanov (2023) documented the very important introduction of supply chains through stress-testing and resilience under the concept of intelligent digital twins, iDTs for short. Accordingly, with iDTs, one can simulate future disruptions. Following this direction, Sreedevi and Saranga (2017a) discussed flexible supply chains that merge digital technologies with flexible supply chain strategies with the purpose of managing risks in highly uncertain environments.

These findings have wider ramifications than just within the pharmaceutical industry. For instance, Gupta et al. (2023) also proved that AI and blockchain boost the financial resilience of an organisation, showing clearly the cross-industry adaptability potential of these technologies. The versatility of AI in managing both intentional and humanitarian supply chain disruptions was addressed by DuHadway et al. (2017) and Bai et al. (2022). The literature reviewed stands as a solid road map for leveraging the latest technologies to create resilient and effective supply chains. The cost, versatility, and the requirement for an increase in awareness and training are still concerns. Further study is required in the direction of concurring such difficulties toward achieving the full potential of AI, blockchain, and IoT in supply chain management. For example, Dubey et al. (2021) explore the usage of Industry 4.0 in the pharmaceutical industry and place great attention on developing awareness to address challenges related to cost and complexity. On the other hand, Kulkov (2021) presents insight into how

AI is converting many dimensions of the pharmaceutical value chain. Several works have been done on how to handle disruption in the supply chain due to the COVID-19 pandemic; among them is the research by Reinhardt et al. (2020) and Moosavi et al. (2022). Their research specifically addresses resilience, with sustainability supported by technology-enabled means like AI, the Internet of Things, and Blockchain playing a very important role in mitigating disruption risks. On the other hand, Patil et al. (2023) further provide an assessment of the consequences of blockchain in manufacturing on visibility and traceability, Muralidharan et al. (2022) explained how mimicking modelling effectively evaluates supply chain resilience in front of crises like the COVID-19 pandemic. Wang et al. (2022) also address resilience in regard to the participation of suppliers, focusing their attention on how AI and blockchain can be used to Increase the variety of supply chains and reduce risks. In the end, Wamba and Queiroz (2022) develop a method that integrates AI, blockchain, and big data analytics as a response to the pandemic-related disruptions of supply chains, further illustrating how advanced technologies can be utilised to build resilient supply chains.

However, many areas require additional investigation and advancement, such as widening the use of blockchain solutions. While blockchain has shown to be effective in improving traceability and security, future studies must focus on enhancing the scalability of blockchain systems to handle large-scale, global supply chains efficiently. Regarding cost and resource limitations, implementing advanced technologies such as AI and blockchain can be costly. Future studies may explore and develop more cost-effective solutions, including hybrid models that combine traditional and emerging technologies in a balanced manner. Cybersecurity and digital supply chains also bear importance. As supply chains become increasingly dependent on digital solutions, the risk of cyberattacks also increases. Future works should focus on developing more robust security methods that protect sensitive supply chain data, specifically when using blockchain and AI technologies.

Regarding human-AI collaboration, the concept of Intelligent Digital Twins (iDTs) is introduced. Future research should investigate how to optimise this collaboration in various supply chain scenarios, particularly under stress-testing and disruption conditions. Sustainability and Green Supply Chains also need more research. The potential for AI-driven big data analytics to enhance green supply chain collaboration (as noted by Benzidia et al., 2021) is promising. Further research should explore how these technologies can be optimised to achieve not only operational efficiency but also sustainability goals in the pharmaceutical sector and beyond. Cross-industry applications are also an important field of future study. While the pharmaceutical sector has been a focal point, future work should expand to explore the applicability of these technologies in other industries, such as healthcare, manufacturing, and food supply chains, which face similar resilience and efficiency challenges.

4. Discussion

The study noticed many important findings in relation to the effect of emerging technologies in pharmaceutical supply chains: Pharma 4.0 and Supply Chain Performance: Saha et al. (2022) show case that the combination of big data analytics and the Internet of Things (IoT) within Pharma 4.0 improve supply chain performance.

Their work, based on the Resource-Based View and Organizational Information Processing Theory, explains improvements in sourcing, manufacturing, distribution, and demand forecasting processes. Blockchain and AI usage: Charles et al. (2023) investigated the integration of blockchain and AI in supply chains, stressing their possibility for enhancing traceability, fraud prevention, and risk management.

On the other hand, Blockchain improves visibility, transparency, and security, and AI improves task execution and decision-making processes. AI, Blockchain, and Financial Resilience: Gupta et al. (2023) mentioned that the collaboration between AI and blockchain positively affects financial resilience in pharmaceutical supply chains by enhancing visibility, forecasting, and decision-making.

Intelligent Digital Twins (iDTs): Ivanov (2023) presented the idea of Intelligent Digital Twins (iDTs) for stress-testing and resilience in supply chains, introducing a human-AI cooperation method to enhance decision-making under ambiguity.

Supply Chain Flexibility: Sreedevi and Saranga (2017b) mentioned that supply chain flexibility is essential in reducing risks under uncertain circumstances, aiding companies to adapt to disturbances.

The use of AI in Supply Chain Management: Pournader et al. (2021) categorise AI usages into four main areas: Detection, knowledge, communication, and decision-making, showing AI's possibility in customer service, demand forecasting, and supply chain improvement. Global Supply Chain Disruptions: DuHadway et al. (2017) pioneered a means for managing global supply chain disruptions, with AI having an important role in risk detection, mitigation, and recovery. Bai et al. (2022) established that AI-driven BDA improves responsiveness and ability to recover in humanitarian supply chains, aiding organisations to respond more effectively to disruptions. Bistarelli et al. (2023) present the *-chain framework, which automates the production of blockchain-based supply chain tracing systems. This thorough solution allows supply chain professionals to design systems without programming knowledge and automates the creation of smart contracts needed for Blockchain tracking. Ojha et al. (2018) utilise a Bayesian network design to model risk spread in supply chains. This method

recognises critical nodes and mimics the effect of disturbances, helping in risk management. In their work, Heydarbakian and Spehri (2022) investigate the usage of interpretable machine learning models to improve supply chain resilience in Industry 4.0. The paper concentrates on using machine learning (ML) to classify vendors based on their resilience capabilities. In summary, Heydarbakian and Spehri's research shows the advantages of machine learning for suppliers in an Industry 4.0 environment. By using interpretable machine learning models, companies can achieve important insights into supplier resilience capabilities and make better decisions that improve supply chain resilience. Ahsan and Siddique (2022) studied the effect of Industry 4.0 on healthcare, with a special focus on the functions of IoT and blockchain technologies in improving healthcare resilience during the COVID-19 pandemic. Their systematic review work covers lately published studies on Industry 4.0 in healthcare (IHC). Main Highlights: Huge effect on Healthcare Delivery systems: The study investigates how new technologies, such as artificial intelligence, Blockchain, and the Internet of Things (IoT), are now being used to improve patient care. Industry 4.0 is changing healthcare delivery systems by introducing highly advanced technological solutions. Difficulties in Execution: Some challenges of using Industry 4.0 in healthcare include security matters and the need for new skills and training. In general, the investigation delivers a thorough and in-depth overview of the current state of Industry 4.0 in healthcare. It showcases the potential of these technologies to revolutionise healthcare delivery systems while recognising the difficulties that need to be overcome.

several areas warrant further research and development, such as the scalability of blockchain solutions. While blockchain has shown promise in enhancing traceability and security, future work should focus on improving the scalability of blockchain systems to handle large-scale, global supply chains efficiently. Cost and resource constraints are also an important field. Implementing advanced technologies such as AI and blockchain can be costly. Future research could explore more cost-effective solutions, including hybrid models that combine traditional and emerging technologies in a balanced manner. Cybersecurity in digital supply chains is also important. As supply chains become more and more digitalised, the risk of cyberattacks increases. Future research should focus on developing more robust security methods that protect highly sensitive supply chain data, in particular when using blockchain and AI technologies. Human-AI collaboration also draws research interest. The idea of Intelligent Digital Twins (iDTs) explains human-AI collaboration. Future studies should look into how to optimise this collaboration in different supply chain scenarios, particularly under stress-testing and disruption conditions. The potential for AI-driven big data analytics to improve sustainable green supply chain collaboration is looking promising. Further studies must look into how these technologies can be optimised to achieve not only operational efficiency but also sustainability goals in the pharmaceutical sector and other fields. Finally, cross-industry applications also bear great importance. While the pharmaceutical industry has been the main point, future work must increase and develop to explore the applicability of these technologies in other areas, such as healthcare, manufacturing, and food supply chains, which face similar resilience and efficiency challenges.

5. Conclusion

This thorough study of emerging technologies in pharmaceutical supply chains discloses a complex and dynamic landscape. From the implementation of Pharma 4.0 to the integration of blockchain and AI, the articles reviewed Offer a guide to navigating the hurdles and benefiting from the opportunities offered by these technologies. The consequences go beyond pharmaceuticals, including different fields, and stress the need for a complete approach to utilising the transformative potential of emerging technologies in supply chain management. This study is important because of its comprehensive synthesis of emerging technologies—specifically Pharma 4.0, blockchain, and artificial intelligence (AI)—and their combined effect on pharmaceutical supply chains. While previous studies have examined these technologies in isolation, this review offers a complete analysis of how they work together and change the supply chain performance as a group.

The originality of this work lies in several important aspects, such as integrating digital twins for resilience. This work introduces Intelligent Digital Twins as a novel framework for stress-testing and improving resilience in supply chains. At this point, the idea of integrating human-AI collaboration to support real-time decision-making in this respect is fairly new and has not as yet been widely investigated within pharmaceutical supply chains. Cross-technology synergies are also elaborated. Most of the literature reviewed focused either on blockchain or on AI separately. This research underlines how a synergy between the technologies, upon integration of both, proves how their combined use provides more reliable traceability, security, financial resilience, and actualised decision-making, offering new insights into their combined potential.

Application to Pharma 4.0 is also highlighted. Putting the focus on Pharma 4.0, since this is a pretty new concept within the pharmaceutical context, already allows adding another layer of novelty. The study shows how big data analytics and IoT, integrated with AI in Pharma 4.0, is imposing radical improvements in flexibility in the supply chain, mitigation in risk, and efficiency in operations. Specific emphasis on risk management in

Conditions of Uncertainty is also important. This review gives particular emphasis to risk management arising from uncertainty through the introduction of new frameworks leveraging AI in predicting, sensing, and mitigating disruption. This will present new pathways toward strengthening supply chain resilience in volatile environments. This study also highlights the emerging focus on green supply chains as a new contribution to the literature in terms of the use of AI-driven big data analytics in order to promote green supply chain collaboration, particularly in hospitals. The in-built tendency of this emerging application follows the trend of using high-end technologies not only to innovate with efficiency but also sustainability.

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