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Literature Review

Blockchain Applications in Healthcare Supply Chain: A Systematic Review on Enhancing Traceability and Security from a Data Analytics Perspective

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ABSTRACT

With the rapid advancement of digital technologies, improving traceability and security has become a primary objective for healthcare supply chains seeking to ensure product authenticity and patient safety. This study used a systematic literature review to investigate the application of blockchain technology, alongside data analytics to improve transparency, traceability, and security in healthcare supply chains using PRISMA guidelines. Peer-reviewed articles published between 2015 and 2025 are used in this investigation, and the findings are structured using the Technology-Organisation-Environment framework. The findings indicate that blockchain can offer immutable transaction records and enable real-time monitoring across the healthcare supply chain. Additionally, data analytics are useful in risk identification, selection of decisions, and effective supply chains. There are still several obstacles such as the high cost of implementation, insufficient staff training, system integration problems, and poor legal frameworks. This study proposes addressing these issues with the help of pilot projects, enhancing skills of the staff, and developing collaboration between organisations.

Keywords: Blockchain; Healthcare supply chain; Traceability; Patient safety; Data analytics; Technology-Organisation-Environment (TOE)

INTRODUCTION

The supply chains of high-risk medicines and vaccines have become increasingly complex and technologically advanced in recent years. The healthcare supply chains are in a difficult situation when it comes to traceability and safety. Inherent problems of the traditional logistics systems include information silos, impossible tracking, and limited visibility (Hölbl et al., 2018). These issues are capable of interfering with patient safety and drug quality control gravely (Fiore et al., 2023; Jadhav & Deshmukh, 2022).

As digital transformation continues, blockchain technology has become an important tool to improve transparency and trust in supply chains. In this context, blockchain can be understood as a distributed digital ledger in which records are chronologically and cryptographically stored to prevent unauthorised modification (Hasselgren et al., 2020). It enables secure and transparent data sharing within healthcare supply chains (Hasselgren et al., 2020). When combined with data analytics, its value becomes even greater. Data analytics can enable blockchain systems to provide valuable insights, support real-time decision-making, and enhance security, moving well beyond simple record keeping. Within the framework of blockchain-based healthcare supply chains, predictive analytics takes place based on the data flows (scans) recorded by Internet of Things (IoT) sensors, including temperature, humidity and location, which are stored on the blockchain directly or addressed via cryptographic hash. IoT devices may operate

alone but combining them with blockchain provides the integrity of data, provenance, and multi-party trust that is crucial in the regulatory requirements of specific laws, including the U.S. Drug Supply Chain Security Act (DSCSA). Even though blockchain is not a solution to real-time computation, it should be connected to off-chain analytics systems to facilitate close-to-real-time feedback and anomaly detection (Munasinghe & Halgamuge, 2023; Sim et al., 2022).

The organisation and safety of the blockchain systems are the concern of many contemporary studies. Few of them discuss the use of data analytics in enhancing blockchain in terms of tracking and safety. Although other studies do recognise the concept of organisational conservatism and stakeholder complexity in healthcare (Agbo et al., 2019; Fiore et al., 2023; McGhin et al., 2019; Oliveira & Martins, 2011), a lot of literature still puts emphasis on technical feasibility. Specific sector barriers, including regulatory reservations, fragmented governance, and institutional asymmetric capabilities, are relatively under-researched (Kumar et al., 2025; van Hoek, 2020). This is why the present literature review aims to address this gap. It analyses the research from three perspectives, namely Technology-Organisation-Environment (TOE). The aim of this investigation is to generate both practical insights and academic contributions that support the development of more traceable and safer healthcare supply chains.

LITERATURE REVIEW

This section summarises existing research on blockchain and data analytics in healthcare supply chains, structured around the TOE framework. The following discussion examines three key dimensions of blockchain adoptions: technological capabilities, organisational readiness, and external environmental forces. The last remaining sections further examine each dimension of TOE, providing major drivers, and barriers to the implementation of blockchain within healthcare supply chains, as well as outcomes.

Technology dimension

The technological aspect underscores the importance of blockchain infrastructure, smart contracts, IoT sensors and analytics platforms toward the delivery of transparent and responsive healthcare logistics. Blockchain-based smart tracking and tracing systems create decentralised, tamper-proof records that monitor drugs from production to the point of care, that is, the stage where medicines reach hospitals, pharmacies, or patients (Fiore et al., 2023). In fact, in real-life scenarios, blockchain has mitigated these old problems in several operational ways. For example, the threat of counterfeits is minimised since every batch of medicine is assigned a unique digital identifier that is referred to in the ledger and authenticity can be confirmed at any point during the hand-off. Inventory imprecision is minimised by real-time updates of the IoT sensors and automatic reconciliation using smart contracts. All these characteristics allow establishing end-to-end visibility and reliable data exchange between manufacturers, distributors, and healthcare providers, minimising the manual paperwork, compliance time, and expenses (Jadhav & Deshmukh, 2022).

Although the majority of the reviewed studies claim blockchain can provide tamper-proof records, these studies are mostly based on theoretical models or small-scale pilots, lacking verification data from large-scale actual deployment. This highlights the need to focus on the actual effects in complex healthcare environments.

The IoT sensors are useful in tracking the product status when it is in transit, including temperature, humidity and position. Such sensors send real-time information to blockchain nodes, which subsequently record irreversible timestamped and condition logs (Singh et al., 2020). New study indicates that the combination of IoT and blockchain can enhance efficiency of information technology activities in pharmaceutical supply chain (Chen et al., 2023), as well as solve the related complicated issues to increase the visibility, flexibility, and disruptions of such activities, especially when it comes to breaking the risk of disruption inherent to the COVID-19 pandemic (Sim et al., 2022). The existing

healthcare professionals have already been overwhelmed since COVID-19. The implementation of new blockchain systems can lead to the complexity of their operation, which is highly understated in the current studies (Jadhav & Deshmukh, 2022; Sim et al., 2022).

Regarding implementation platforms, the current body of knowledge reveals a number of blockchain frameworks, which can be applied in healthcare environments. Using Ethereum-based systems has the benefit of smart contract functionality, so the compliance process is automated, and anomalies are detected (Marino & Diaz Paz, 2025). A permissioned blockchain Hyperledger Fabric is also quite popular because of the sensitivity and privacy of health-related data as this aspect offers improved security and privacy levels that can be applied to healthcare supply chain management (Sim et al., 2022).

Based on these operational capabilities, data analytics is another way to expand the value of blockchain in healthcare supply chains by converting documented information into actionable insights. In this context, responsiveness means the capability to identify and react to risks before product quality or availability is impaired. Analytics platforms enable real-time monitoring and response to potential disruptions. They generate early warnings using blockchain-verified, time-stamped records. To illustrate, cold-chain failure can be detected based on the analysis of temperature variations or shipping anomalies (Munasinghe & Halgamuge, 2023; Sim et al., 2022). Blockchain-based dashboards contribute to enhanced transparency and coordination of manufacturers, distributors and healthcare providers, whereas predictive analytics assists regulating agents to predict recalls and enhance compliance preparedness (Jadhav & Deshmukh, 2022).

Organisation dimension

The organisational dimension highlights the internal challenges that healthcare institutions encounter when attempting to adopt blockchain-based traceability systems. Across the literature, organisational preparedness is consistently identified as a crucial determinant of whether digital transformation efforts succeed. Most studies emphasise three core organisational factors that shape blockchain adoption: the strength of data-governance capabilities, the digital literacy of employees, and the organisation's overall openness to innovation (Fiore et al., 2023; Jadhav & Deshmukh, 2022). However, while these works point to the need for technical training and workflow redesign, they pay considerably less attention to the broader coordination challenges that arise when multiple healthcare organisations must collaborate. In reality, many healthcare providers still rely heavily on fragmented legacy information systems, creating a wide gap between the optimistic technological narratives in academic discussions and the practical constraints faced in everyday operations (Agbo et al., 2019; McGhin et al., 2019). These disparities suggest that future research should move beyond conceptual arguments and examine how institutions can build genuine readiness—through improved governance mechanisms, clearer incentive structures, and more effective cross-organisational cooperation—to support real-world blockchain deployment.

In healthcare supply chains, data governance is key. Different levels of digital maturity among stakeholders often lead to data silos and inconsistent workflows (Fiore et al., 2023; McGhin et al., 2019). Deploying centralised data architectures such as master data management systems is considered helpful in eliminating data redundancy and improving real-time visibility and accuracy of prescription and inventory information (Kumar et al., 2025; van Hoek, 2020).

Employee capabilities and digital resistance are also major organisational barriers. Research by Sim et al. (2022) and Agbo et al. (2019) emphasises that structured, role-specific digital-literacy programmes and performance-support systems, such as embedded help, simplified interfaces, and technical help desks are required. Although

technical structures are becoming more mature, little research has critically addressed the sustainability of blockchain implementation in the high-energy-consumption environment, an issue that is particularly critical to healthcare operations with cost constraints (Fiore et al., 2023; Kasyapa & Vanmathi, 2024). Moreover, the costs of implementing blockchain estimated in some studies might be too optimistic and do not cover the financial feasibility factor of implementation in small and intermediate healthcare entities (Jadhav & Deshmukh, 2022; Munasinghe & Halgamuge, 2023).

Environment dimension

The environment dimension identifies how the external factors are important in determining blockchain adoption in the healthcare supply chain. National strategies of digital health, regulatory frameworks, and competitive market forces are considered the key driving or inhibiting forces to successful implementation. Such external pressures are stimuli and limitations at the same time, and they ensure challenging operational conditions that healthcare organisations have to manage successfully (Agbo et al., 2019; Katuwal et al., 2018). Current research mainly focuses on the adaptability of policy standards and technical interoperability, but discussion of potential tension between patient privacy protection and supply chain transparency is relatively limited. This issue is particularly critical in the healthcare field. Although blockchain systems can enhance transparency and traceability, excessive data visibility may raise ethical risks of patient privacy leakage. Additionally, regarding responsibility mechanisms when blockchain systems fail or data errors occur, current literature lacks systematic discussion. As blockchain is widely deployed in healthcare scenarios, such ”accountability mechanism gaps” may become key bottlenecks in practical applications (Beck et al., 2017; Xu et al., 2019).

The environmental dimension in the TOE framework includes external influences on the adoption of technology, such as regulatory, policy, and market conditions (Oliveira & Martins, 2011). In healthcare supply chains, regulatory uncertainty is one of the most common environmental challenges that have been identified as reasons to implement blockchain. The ongoing development of digital-health policies, such as requirements for drug traceability, electronic prescription, and health-information-exchange regulations, has generated persistent interoperability challenges between national health platforms and commercial healthcare providers (Radanović & Likić, 2018; Zhang et al., 2018). The cross-institutional deployment of blockchain systems is highly complicated by the differences in data sovereignty and healthcare liability across the national judicial systems.

Limitations

There are a few limitations of this systematic review that should be seen. To begin with, it is restricted to English-language peer-reviewed articles that are published within the period of 2015-2025. Although this period represents the recent advancements of the blockchain technology in the healthcare sector, it might not include more recent and applicable research in other languages or grey literature, which might include industry reports and white papers containing more practical information. Second, existing literature has limited the findings based on its quality. As it has been mentioned above, the majority of present-day research is dependent on theoretical perspectives or pilot projects instead of the large-scale real-life application. It makes it hard to come up with solid conclusions regarding the effectiveness of blockchain in a complicated healthcare setting. Third, blockchain technology is evolving at a high pace and, therefore, some of the most current developments and practices in the industry might not appear in peer-reviewed articles yet. It is not unusual to find that there is a period after an event occurs in industry and it is published in academic journals. Lastly, despite the fact that the TOE framework can offer a valuable approach

to the analysis of factors influencing the adoption of blockchain, it might not represent all the unique issues that various healthcare organisations or health systems in various regions may encounter. In spite of these shortcomings, this review nevertheless gives a valuable overview of what is known to date and what areas are omitted that further research should focus on, especially in terms of applying blockchain to healthcare supply chains.

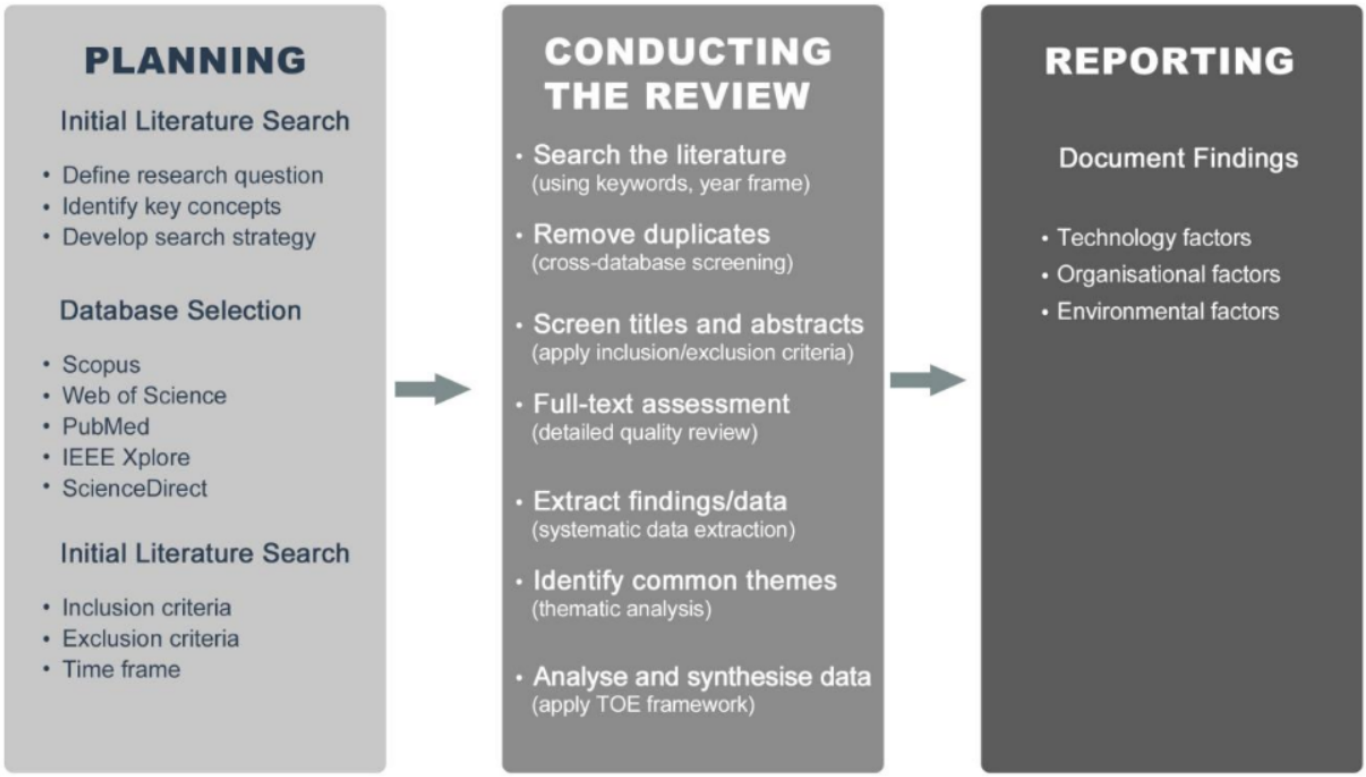
RESEARCH METHODS

This research applies the systematic literature review approach. This is to gather and examine available literature on the application of blockchain and the use of data analytics in enhancing the aspect of traceability in healthcare supply chains and ensuring safety.

The Boolean search string has been used, and the keywords were as follows: blockchain AND healthcare supply chain AND traceability OR safety AND data analytics OR predictive OR dashboard. The criteria for inclusion were peer-reviewed articles published between 2015 and 2025 and written in the English language, as well as articles that showed a clear connection to the domain of data analytics or blockchain in healthcare supply chains. This research also had to take account of the direct relationship to traceability or safety effects. Articles that were commentaries, non-reviewed publications, theoretical studies that lack practical evidence, studies that were not part of the logistics in the healthcare industry were not included.

In total, around 40 articles were found during the initial search. After applying the selection criteria, 25 peer-reviewed articles were included in the final review. The screening process followed the PRISMA guidelines (Moher et al., 2009). Then, the selected articles were analysed using the TOE framework. This helped to identify the key factors related to the adoption of blockchain and data analytics from technical, organisational, and environmental

Figure 1: Systematic Literature Review Procedure Based on TOE Framework.



perspectives. The whole search and selection process is shown in Figure 1.

Theoretical Framework

This study uses the TOE framework as the main theoretical perspective. The TOE framework was introduced by Tornatzky and Fleischer (1990). It includes three important aspects that influence the adoption of new technologies: technology, organisation, and environment. This framework helps researchers understand how both internal and external factors affect digital transformation in complex industries like healthcare.

Compared to models such as the Technology Acceptance Model (TAM) or the Diffusion of Innovations (DoI), which focus primarily on individual-level behavior, the TOE framework provides a broader view at the system level. It is especially useful in healthcare, where strict regulations and complicated organisational structures are common (Oliveira & Martins, 2011). TOE brings together many factors from different levels and helps to explain how technologies like blockchain are adopted in healthcare supply chains.

In this study, the TOE framework is also used to show a special challenge in the healthcare field; the issue of responsibility. If a system fails, it could directly affect patient safety. Because of this high-risk nature, many healthcare institutions are very careful about adopting new technologies. This is an important reason why the TOE model fits well in this research.

DISCUSSION

This article provides valuable theoretical and practical contributions by synthesising evidence on the technological, organisational, and environmental factors influencing blockchain adoption in healthcare supply chains. The review highlights that blockchain, supported by data analytics, can enhance system transparency and safety.

Key themes

A synthesis of the 25 peer-reviewed articles reveals three dominant thematic patterns centred around technological capabilities, organisational preparedness, and environmental constraints, aligning closely with the TOE framework. From a technological standpoint, most studies emphasise blockchains immutability, decentralised verification mechanisms, and its integration with IoT devices to enhance traceability and prevent counterfeiting within pharmaceutical supply chains (Casino et al., 2019; Fiore et al., 2023; Singh et al., 2020). A related theme is the increasing incorporation of data analytics to support anomaly detection, predictive risk assessment, and improved visibility in cold-chain environments (Munasinghe & Halgamuge, 2023; Sim et al., 2022). On an organisational level, research points at the ongoing issues of digital maturity, legacy systems, employee skills, and governance coordination by multi-stakeholder networks Agbo et al., 2019; McGhin et al., 2019. The necessity of structured training, data governance frameworks and cross-institutional collaboration are the subject of many papers, and the three elements are often mentioned as these requirements must be met before adoption of blockchain can become successful. Lastly, regulatory fragmentation, data-privacy requirements, and the development of national policies that relate to digital-health are brought up as key themes (Hasselgren et al., 2020; Radanović & Likić, 2018). Throughout the literature, it is agreed that blockchain will be unable to realise its potential benefits without manoeuvre through these complicated external constraints, especially in high-risk healthcare environments.

Areas of concurrence and discord in the literature

Throughout the literature reviewed, it is apparent that blockchain has a high degree of consensus in improving

transparency, data integrity, and traceability in healthcare supply chains. Numerous authors emphasise blockchain's tamper-proof ledger as an effective mechanism for mitigating counterfeit pharmaceuticals (Fiore et al., 2023; Vazirani et al., 2020). Likewise, there is broad consensus that integrating IoT with blockchain enhances monitoring accuracy and enables real-time quality assurance throughout cold-chain logistics (Chen et al., 2023; Singh et al., 2020). However, the literature diverges on several important issues. First, researchers disagree about the scalability and operational feasibility of blockchain in real-world healthcare environments. According to some research, it has been argued that permissioned blockchains like Hyperledger Fabric provide viable performance benefits (Sim et al., 2022), and others have noticed that energy consumption, latency, and transaction throughput are problematic (Kasyapa & Vanmathi, 2024). Second, there are varying costs interpretations of blockchain by the authors: some claim that it is cost-efficient in the long-term by decreasing fraud and paperwork (Jadhav & Deshmukh, 2022), whereas others state that it is prohibitive upfront due to its implementation by small and medium healthcare providers (van Hoek, 2020). Lastly, regulatory frameworks have been called into question on whether they are mature or not - some claim to have advanced towards establishing standards (Hasselgren et al., 2020), others point to the lack of legal settlements between data immutability and privacy rights, including the right to erasure in General Data Protection Regulation (GDPR) (Sabiri et al., 2025). These discrepancies highlight the necessity of sector-based application strategies that are contextualised.

Technological dimension: security enhancement and anti-counterfeiting mechanisms

From the technological dimension of the TOE framework, blockchain provides essential mechanisms to enhance security and prevent counterfeiting. The results of multiple studies (Casino et al., 2019; Fiore et al., 2023; Vazirani et al., 2020) are consistent: blockchain enhances the traceability of drugs by providing immutable and minimise the risk of counterfeit, as well as enhancing accountability. Each drug is assigned a digital signature that is captured onto the blockchain during production and therefore can be authenticated at every point. That forms what scientists refer to as a digital fingerprint of all pharmaceutical products flowing through the pharmaceutical supply chain (Casino et al., 2019).

Data analytics also augments the counterfeit detection potential by tracing the supply chain patterns on the identification of suspect activity or unusual transactions. The algorithms of machine learning would allow identifying atypical routes of shipping, abnormal storage conditions, or unusual transaction patterns that can reflect the arrival of fake products into the supply chain (Hasselgren et al., 2020; Hölbl et al., 2018). To give an example, any deviation from temperature parameters in batches of vaccines can automatically raise alerts and get investigation processes started (Hastig & Sodhi, 2020). These studies collectively highlight blockchain's ability to ensure the integrity of data by distributed ledger architecture, and avoid unilateral manipulation of data (Zhang et al., 2018). However, according to Mettler (2016), the technology cannot eliminate the issue of garbage-in, garbage-out, as it is important to ensure data input and validation rules are in place.

Collectively, these articles provide an opportunity to draw the conclusion that the security and the transparency of traceability is based on the technological characteristics of blockchain, especially, immutability, decentralisation, and data-verification processes.

Organisational dimension: real-world implementation cases and lessons learned

Pilot projects might also provide valuable insights into the way blockchain can be implemented in real healthcare networks, on the organisational level. One example is a popular project, the MediLedger, a blockchain consortium

designed by the pharmaceutical industry that shows how decentralised systems can be used in practice to facilitate reliable drug-verification processes (Fiore et al., 2023). Nevertheless, it should be understood that such a case possibly includes survivor bias (Jadhav & Deshmukh, 2022). Participating companies are mostly resource-rich industry giants with outstanding technical capabilities. Therefore, the adopted architecture and processes may not be universally applicable. Especially for small and medium-sized enterprises that constitute the majority of global healthcare supply chains, it may be difficult to replicate this model's technical deployment and governance mechanisms (van Hoek, 2020).

Another notable case is the collaboration between Walmart and IBM in food safety, which has lessons for pharmaceutical applications (Agbo et al., 2019). This responsive rate would be a revolution to the recalls of drugs, which may save lives that might be lost in the process of isolating and recalling harmful products in the market. All these organisational experiences demonstrate that the success of the implementation of blockchains will require resource capacity, collaborative governance, and long-term investment in digital infrastructure.

Environmental dimension: regulatory and compliance considerations

From the environmental dimension, the existing regulatory conditions are likely to offer advantages as well as difficulties in executing blockchain in the healthcare supply chain. On the one hand, the drug Supply Chain Security Act (DSCSA) by FDA mandates the pharmaceutical industry to install electronic track and trace by 2023, which gives a definite regulatory push towards blockchain (Fiore et al., 2023; Sim et al., 2022). Conversely, the rapidly changing and sometimes more complex details of the healthcare rules make the implementers of blockchain uncertain of them. The various countries identify different data privacy needs, drug traceability needs, and cross border data sharing needs (Hasselgren et al., 2020; Katuwal et al., 2018).

There is an extra twist with privacy regulations like Health Insurance Portability and Accountability Act (HIPAA) in the United States and General Data Protection Regulation (GDPR) in Europe. Although there are a number of benefits such as blockchain in improving security, it constitutes permanent records, which contrast with the patient's right to delete or change data. While these regulations aim to protect patient data, they also expose governance gaps that must be addressed through adaptive legal frameworks and standardised compliance models. In general, the regulatory fragmentation and the limitation of privacy are one of the significant obstacles to blockchain adoption across borders.

Evidence gaps

Despite the growing body of literature, several important gaps remain across the selected 25 studies. First, most empirical work is based on conceptual models, simulations, or isolated pilot projects, with very limited evidence from large-scale, fully operational healthcare supply chains (Jadhav & Deshmukh, 2022; McGhin et al., 2019). This gap directly affects our understanding of blockchain's performance under real regulatory, organisational, and market pressures. Second, although many studies emphasise the technical strengths of blockchain, far fewer investigate how data analytics can be systematically embedded into blockchain-enabled systems to support proactive risk management, anomaly detection, and decision-making a core focus of this review. Only a minority explicitly link blockchain ledger data with predictive analytics or machine-learning models (Munasinghe & Halgamuge, 2023; Sim et al., 2022). Third, organisational challenges such as multi-party governance, incentive misalignment, and digital-literacy disparities are acknowledged but rarely analysed through empirical investigation, leaving a significant gap in understanding adoption feasibility across diverse stakeholder groups. Finally, the environmental dimension remains underdeveloped, such as

regulatory contradictions, cross-border data policies, and accountability mechanisms are often mentioned but not deeply examined. These gaps justify this review's objective: to synthesise evidence through the TOE framework and emphasise how blockchain, supported by data analytics, can enhance traceability and safety while addressing the under-researched organisational and environmental constraints in real-world healthcare contexts.

Future development directions and considerations

The further development of blockchain-based healthcare supply chains will rely on the balanced improvement of all three TOE dimensions. First, addressing talent gaps by developing cross-disciplinary expertise in clinical practice, data science, and IT systems is crucial for effective implementation (Fiore et al., 2023; Hasselgren et al., 2020; Hölbl et al., 2018). Second, by standardising blockchain across the borders, it is possible to create global traceability networks that would improve drug authenticity and coordination in case of current pandemics or emergencies (Fiore et al., 2023; Munasinghe & Halgamuge, 2023). Finally, the combination of blockchain and smart contracts in insurance and payment systems presents the opportunity of automating reimbursement procedures and decreasing the number of administrative loads, as well as to provide timely access to life-saving drugs (Jadhav & Deshmukh, 2022; Sim et al., 2022). All these improvements are aimed at the creation of a more robust, transparent, and data-driven healthcare supply chain ecosystem.

CONCLUSIONS

In this review, it has been highlighted that blockchain and data analytics integration holds promise to transform healthcare supply chains through enhancing real-time traceability, drug safety, and regulatory compliance. Although multiple barriers still exist at technical, organisational, and regulatory levels, the long-term strategic value indicates that related investment and implementation efforts are worthwhile in the foreseeable future. Research findings highlight the important role of phased deployment strategies, cross-sector collaboration mechanisms, and interdisciplinary capacity building in addressing technology adoption challenges.

However, considering the high sensitivity and system complexity of the healthcare industry, large-scale adoption of blockchain technology may require a longer cycle than existing literature expects. Regulatory approval processes, standard system construction, and coordination mechanisms among multiple stakeholders will constitute more challenging advancement conditions than the technology itself. Future research can further explore integration paths between blockchain technology and global universal standards, payment systems, and patient feedback mechanisms, thereby promoting interoperability and patient-centered transformation of healthcare logistics systems. Ultimately, building a digital, transparent, and highly interconnected healthcare supply chain ecosystem will become a key goal for achieving dual improvement in operational efficiency and clinical value.

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