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Adoption of Blockchain Technology in Healthcare Supply Chain Management: A Review

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Abstract

The healthcare supply chain encounters difficulties with transparency, efficiency, and security, which have an impact on patient safety and the quality of treatment concerning the items involved. The use of blockchain technology, which has intrinsic characteristics such as confidentiality, transparency, and traceability, offers a possible resolution to tackle these problems. This paper aims to comprehensively review the adoption of blockchain technology in healthcare supply chain management, particularly in response to the challenges posed by the COVID-19 pandemic. It investigates the significance of efficient and transparent healthcare supply chains, focusing on blockchain's application in vaccine distribution, Personal Protective Equipment (PPE), drugs, medical devices and blood products. The analysis critically evaluates research papers proposing innovative blockchain-powered solutions, discussing their benefits, challenges, and the need for further research. Findings highlight blockchain's potential in enhancing vaccine traceability, preventing counterfeit vaccines, and ensuring equitable access to immunization. It also outlines blockchain's role in real-time tracking of PPE shipments, secure distribution of medical devices, managing blood products, and combating counterfeit drugs. The paper also emphasizes the prevalence of consortium-based and public blockchain implementations and the importance of smart contracts while advocating for addressing scalability and technological challenges. This review offers a critical assessment of blockchain's potential in fortifying healthcare supply chains during crises, underscoring the need for ongoing research and development to overcome implementation limitations.

Keywords: Blockchain Technology; Supply Chain; Healthcare; Medical Products and Tools; Transparency; Traceability, Security.

1. Introduction

In the recent years, the healthcare industry has witnessed a paradigm shift in its approach to supply chain management, with the adoption of blockchain technology emerging as a disruptive force. Amid the unprecedented challenges posed by the COVID-19 pandemic, the importance of efficient and transparent healthcare supply chains has become more apparent than ever. This paper aims to provide a comprehensive review of the adoption of blockchain technology in healthcare supply chain management, focusing on its application to various aspects of pandemic response, including the distribution of vaccine, personal protective equipment (PPE), drugs, etc.

The rapid development and distribution of COVID-19 vaccines have highlighted the importance of vaccine supply chain integrity as the vaccine supply chain has several potential risks [1] that caused worries in the vaccine supply chain due to the reported fraud and data tampering [2]. Blockchain technology can enhance vaccine traceability and transparency, from manufacturing facilities to distribution points, helping to prevent counterfeit vaccines and ensure equitable access to

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immunization. This is because the data on the chain can only be added and modified through consensus mechanisms [3-5]. Thus, compared to the current vaccine supervision system that uses the traditional centralized information management system that easy to tampering and a key of failure, the blockchain able to solve the potential issues becomes a promising approach.

Similarly to the distribution of Personal Protective Equipment (PPE) during the COVID-19 pandemic [6], where it has underscored the critical need for secure and efficient supply chains to meet the extraordinary demand for PPE. The sudden increase in demand for PPE, such as gloves, gowns, face shields, surgical masks, and googles, has triggered overwhelming global production and corresponding price increase, making inequitable distribution of access to PPE. This has been the most significant challenge during a crisis to ensure the quantity of PPE items are adequate and available for healthcare workers to use as and when needed [7]. In order to combating the challenge, blockchain technology offers a promising solution by enabling real-time tracking and authentication of PPE shipments, ensuring their safe and timely delivery to healthcare facilities and frontline workers. Not only in this particular area, but blockchain also has proven its capabilities in simplifying clinical trial processes [8], supplies [9], tracking donations, managing patient healthcare records, ensuring the safety and integrity of blood and blood products [10] and securing drugs delivery [11].

Not to mention that the demand for COVID-19 medical devices and supplies, such as ventilators, respirators, and testing kits, has surged during the pandemic. Medical devices are subjected to strict certification processes that vary depending on each country's healthcare regulation and approvals [12]. This adds to the hurdles in terms of required urgent supply and delivery of medical devices and supplies. The extensive and lengthy testing procedures and the long distances that threaten traceability fast response, security, and trust can be achieved through blockchain technology as it can facilitate the transparent and traceable distribution of these critical supplies, enabling healthcare providers to access dependable and quality-assured products.

Due to that, the cloud-based blockchain technology [13] offers a scalable and cost-effective solution for identifying counterfeit vaccine, blood, drugs and medical products in the healthcare supply chain. By leveraging cloud infrastructure and blockchain's immutable ledger, stakeholders can collaborate in real-time to detect and mitigate counterfeit incidents, safeguarding patient safety and trust. There are also various blockchain architectures have been proposed for drug traceability, including permissioned [14], permissionless, and hybrid models. These architectures leverage blockchain's decentralized nature to create transparent and auditable records of drug transactions, enhancing supply chain visibility, and regulatory compliance.

In this review paper, we will examine the existing literature on this field, critically evaluate the opportunities and challenges associated with the adoption of blockchain technology in healthcare supply chain management during the COVID-19 pandemic as well as in the daily basis. Moreover, it seeks to identify future research directions and practical implications for healthcare stakeholders, highlighting the transformative potential of blockchain in enhancing the resilience, integrity, and efficiency of healthcare supply chains in times of crisis and beyond. By synthesizing insights from academic research, industry reports, and case studies, this paper seeks to contribute to the growing body of knowledge on the transformative role of blockchain technology in revolutionizing healthcare supply chain management.

2. Review of Existing Projects

This section examines and evaluates relevant research and industrial applications, particularly in the healthcare industry that utilize blockchain technology to achieve traceability, prevent counterfeit products, as well as ensure product quality in supply chain management (Figure 1).

2.1. Enhancing Vaccine Safety through a Novel Blockchain-Powered

Cui et al. (2023) [2] introduce a method employing blockchain technology (BC) to enhance the safety of vaccines in the domain of supply chain management. This innovative approach addresses the pressing issues of data reliability in vaccine circulation and the strain on blockchain infrastructure [15-19]. The proposed system outlines a blockchain-cloud-system designed to safeguard the integrity of vaccine circulation data while also streamlining storage and communication processes. By assigning unique digital identities to each vaccine and linking them throughout the circulation process, the scheme tackles the challenge of ensuring accurate vaccine data. This approach, overseen by a system supervisor, involves verification and transaction signing by all entities involved in the circulation process. Only upon confirmation of data accuracy does the vaccine circulation proceed, effectively addressing concerns regarding data reliability.

The proposed strategy covers all stages of the vaccine circulation process, from production to distribution, assigning a unique digital identity to each vaccine from its inception. This meticulous tracking enables swift action in case of vaccine incidents, as the system supervisor can trace the origin of vaccines and implement preventive measures promptly [20]. However, despite the innovative strides made in the proposed system, the paper critically evaluates its methodology and identifies several areas of concern. Methodological issues such as data verification processes and system scalability are highlighted, indicating potential areas for further research and improvement. Moreover, the authors point out research gaps in areas such as real-world implementation challenges and long-term sustainability of the proposed system. After all, the paper provides a comprehensive analysis of the challenges and potential solutions for enhancing vaccine safety through blockchain technology in supply chain management. Not just that, it also underscores the importance of addressing methodological problems and research gaps to realize the full potential of such systems.

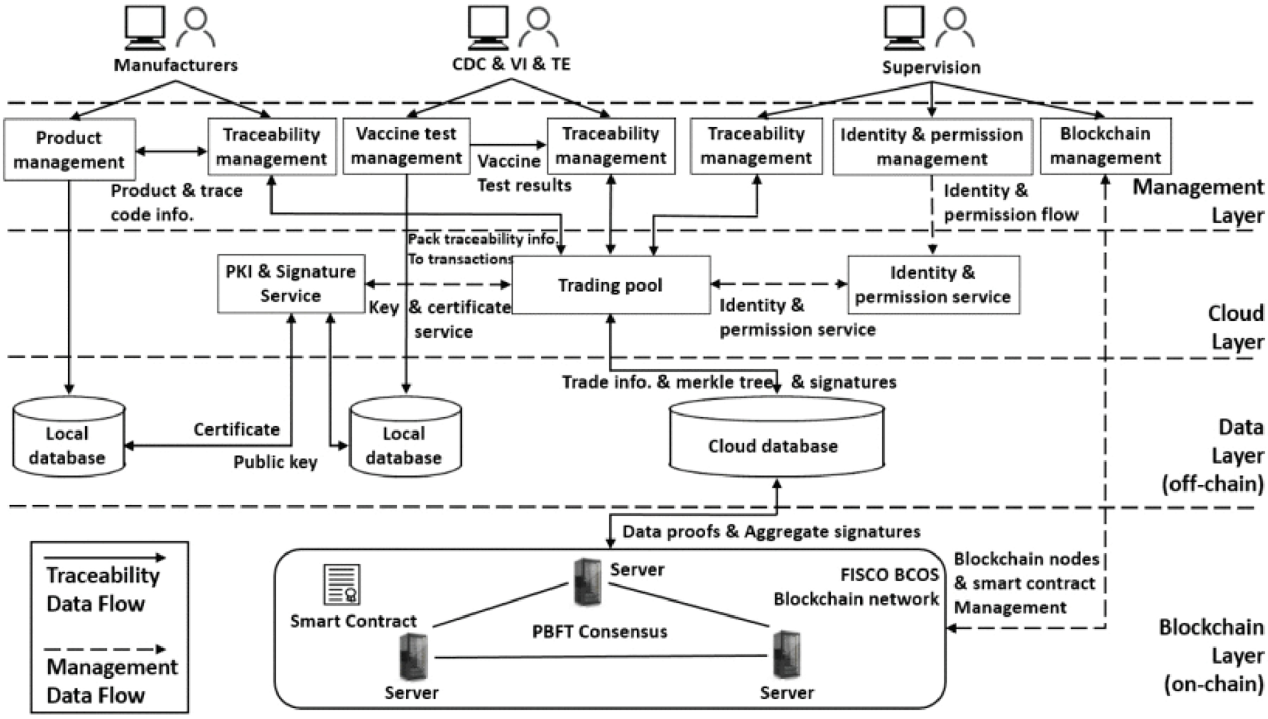

Figure 1. Proposed System Architecture for Vaccine Traceability [2]

2.2. Blockchain-Driven Anti-Counterfeiting Solutions

The study by Humayun et al. (2022) [11] introduce a robust framework aimed at optimizing the drug distribution process (DDP) through the application of the blockchain technology (Figure 2). This framework targets key challenges such as coordination failures, ensuring secure drug delivery, and maintaining pharmaceutical authenticity. The Drug Regulatory Authority (DRA) [21, 22] assumes a pivotal role in overseeing and controlling the end-to-end drug distribution process. Additionally, the framework incorporates smart contracts [23] to automate and verify transactions, ensuring transparency and authenticity [24]. The proposed framework holds the capacity to improve the security, transparency, and efficiency of drug distribution systems, ultimately ensuring the availability of authentic medicines and mitigating the risk of counterfeit drugs [25-27]. The papers also emphasizing the critical role of a centralized monitoring system in addressing coordination failures and combating counterfeit drugs within the drug market.

The authors present a thorough literature review and detail their proposed methodology, supplemented by mathematical modeling and a real-life case study to evaluate its effectiveness in bolstering transparency, traceability [24], and security [28] within the drug distribution process [29-32]. While the paper exhibits methodological strengths in these aspects, there are also notable areas for improvement. One methodological concern is the insufficient exploration of the limitations and potential challenges associated with implementing the proposed framework. Moreover, a deeper analysis of the risks and vulnerabilities inherent in blockchain-based drug distribution systems could enhance the paper's accuracy. Notably, the absence of discussion on the scalability and interoperability of the proposed framework with existing healthcare systems leaves questions unanswered. Furthermore, the ethical and privacy implications of integrating blockchain technology into the pharmaceutical industry remain unaddressed. In summary, although the paper presents a comprehensive examination of its proposed framework and evaluation, critical discussions on methodological limitations and research gaps are necessary for strengthening its overall contribution to the field.

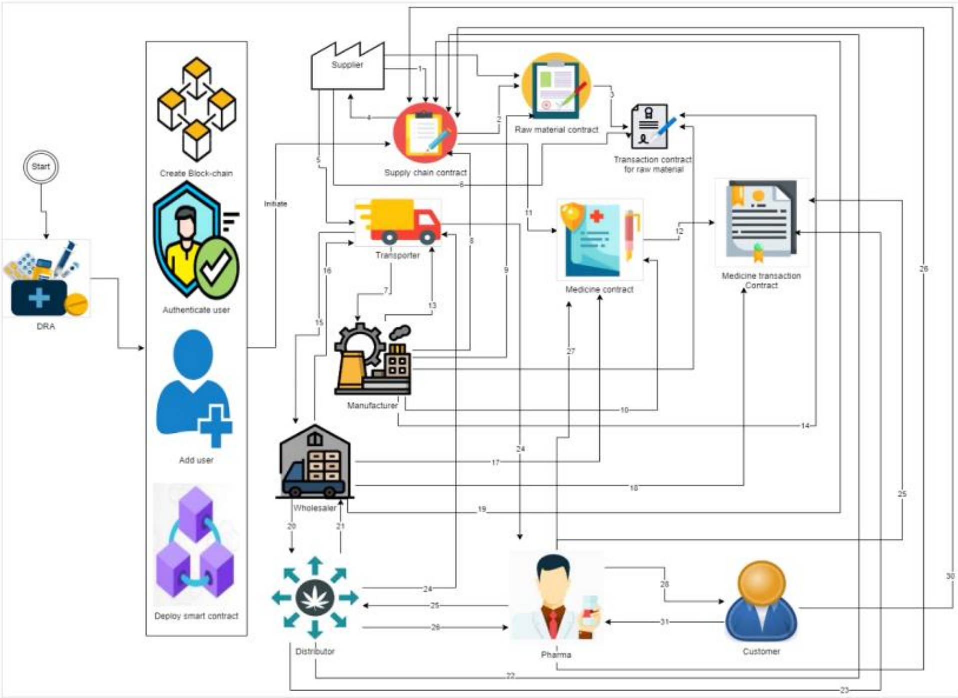

Figure 2. An integrated framework for DDP and supply chain big data analytics [11]

2.3. Enhancing Transparency and Efficiency in PPE Distribution

Omar et al. (2022) [6] explore the difficulties encountered by the healthcare industry during the COVID-19 pandemic, particularly in tracking and managing Personal Protective Equipment (PPE) [7, 33-35] within the supply chain. The authors advocate for the implementation of blockchain (BC) technology [36, 37] to enhance the capacity to track PPE items throughout the supply chain (SC). They underscore the advantages of blockchain, including decentralized control [38], enhanced security, robust traceability [39], and auditable transactions. The study presents a blockchain-driven approach utilizing Ethereum smart contracts [40] and decentralized storage systems [38] to streamline processes and facilitate information exchange among supply chain stakeholders. Detailed algorithms clarify the interaction among stakeholders, accompanied by a thorough cost and security analysis of the proposed solution. The utilization of smart contracts and decentralized storage systems emerges as a promising avenue to tackle traceability and transparency issues within the PPE supply chain. However, the analysis falls short in thoroughly addressing the potential limitations and drawbacks of implementing blockchain technology in healthcare supply chains. Furthermore, research gaps include a deeper exploration of barriers to blockchain adoption in healthcare supply chains and a more robust assessment of the economic and operational viability of the proposed solution (see Figure 3).

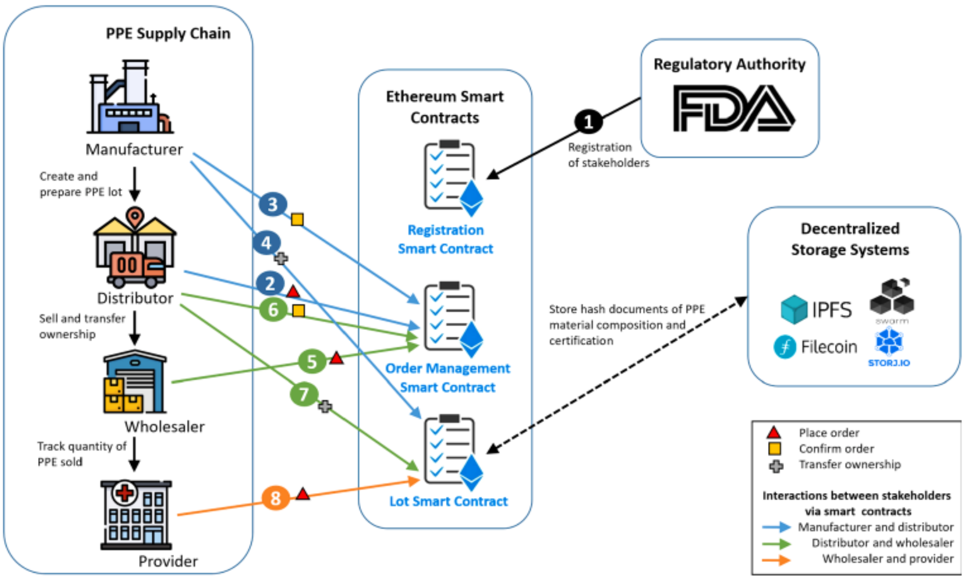

Figure 3. A Decentralized Blockchain Architecture for Secure and Transparent PPE Tracking [6]

2.4. A Paradigm Shift in Medical Device and Supply Chain Management

Alkhader et al. (2021) [12] propose an automated system for decentralized digital manufacture of medical goods in response to the COVID-19 pandemic (see Figure 4). By leveraging blockchain technology, specifically Ethereum smart contracts [41], the proposed solution aims to facilitate decentralized digital manufacturing while ensuring transparency, traceability, reliability, suitability, security, and trustworthiness [42] throughout the process. The paper delves into the system architecture, algorithms, and implementation details, including the incorporation of the Interplanetary File System (IPFS) for decentralized storage of IoT-based device records and manufacturing specifications. The proposed method seeks to address the difficulties encountered by conventional supply chain systems, such as the limited reliable traceability for pharmaceutical products [23, 43]. Additionally, it conducts an evaluation of the proposed approach, focusing on cost and security parameters, and compares it with existing solutions.

The use of blockchain technology to ensure transparency, traceability, and security in the manufacturing and supply chain of medical devices represents a novel and promising approach in addressing the challenges posed by the COVID-19 pandemic. In short, the paper presents an innovative approach to address the challenges of medical device manufacturing and supply during the COVID-19 pandemic, it could benefit from a more robust methodological discussion and a clearer identification of research gaps within the existing literature. Addressing these shortcomings would elevate the paper's contribution to the field of blockchain-based solutions for decentralized digital manufacturing and supply chains in healthcare emergencies.

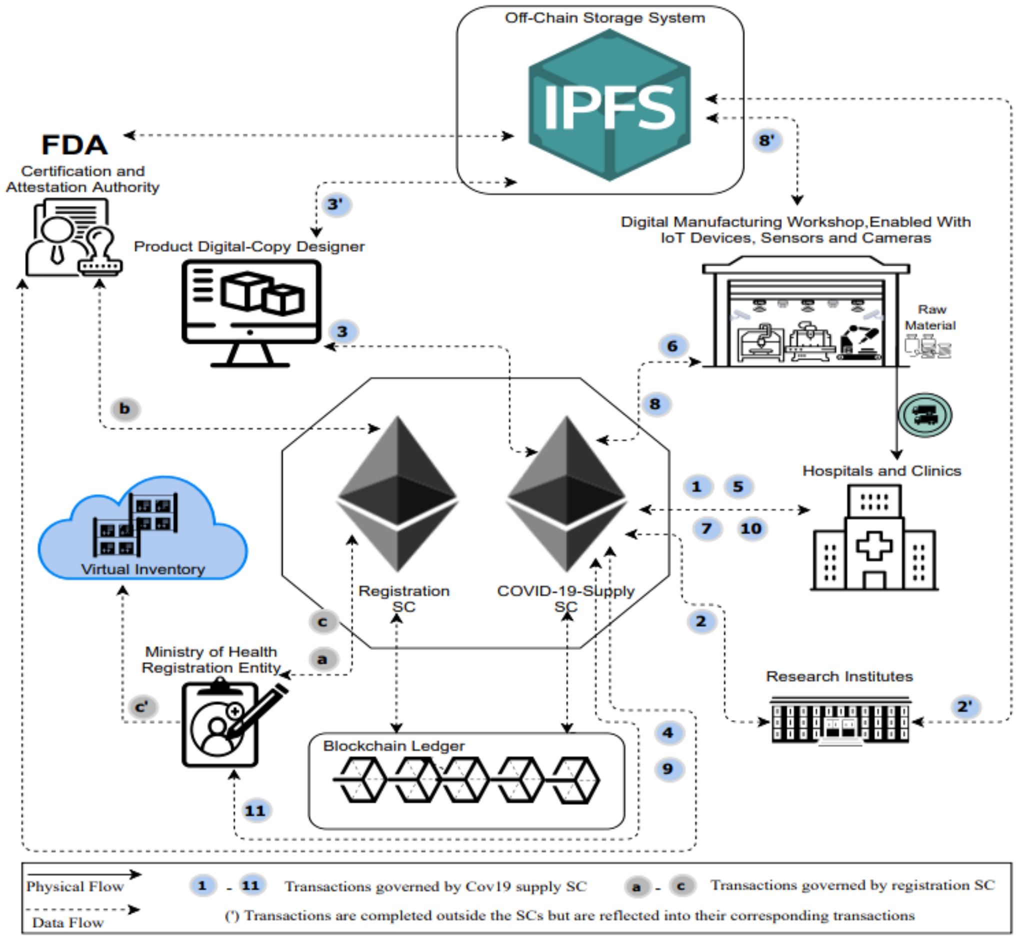

Figure 4. A Decentralized Network Architecture for Distributed Design and Manufacturing [12]

2.5. Utilizing Cloud-Based Blockchain Technology for Identification of Counterfeits

The study by Mani et al. (2022) [13] examines the efficacy of employing blockchain technology within the pharmaceutical supply chain to combat issues such as counterfeiting [44, 45], illegal imports, and operational inefficiencies [46]. They propose a framework leveraging cloud-based blockchain technology to ensure traceability [46], data storage [47-49], privacy, and quality assurance throughout the supply chain. Their approach involves the utilization of smart contracts within the Hyperledger Blockchain like Hyperledger Caliper [50] and Hyperledger Fabric [51], activity identification through tagging, and access control mechanisms to facilitate secure information sharing [52]. Implementation results indicate improved drug transactions with attribute-based visibility, enhanced privacy, and increased transparency.

However, while the framework addresses significant challenges in the pharmaceutical supply chain, it lacks a thorough discussion of its limitations and challenges in real-world applications. Moreover, there is a need for further research to assess the scalability and long-term sustainability of the proposed framework, particularly in large-scale supply chain networks. Even so, the paper contributes valuable insights into the potential of cloud based blockchain technology in combating counterfeit drugs, it requires addressing methodological limitations and research gaps for further studies to build upon (Figure 5).

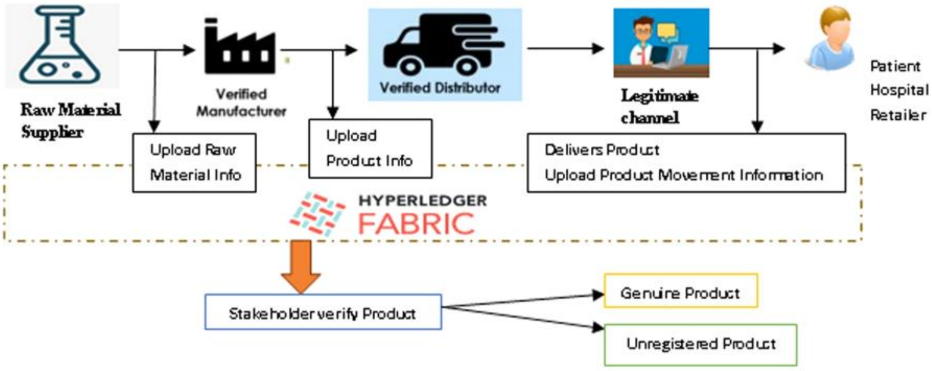

Figure 5. Proposed System Framework [13]

2.6. Blood and Product-Chain Supply Chain Management with Blockchain

Trong et al. (2022) [10] introduce a novel approach in their paper, focusing on leveraging Blockchain technology to revolutionize the management and transportation of blood and its derivatives (Figures 6 and 7). The authors present the Blood and Product-Chain model as a solution to the shortcomings of traditional centralized storage systems, advocating for a decentralized, traceable, accountable, transparent, secure, and auditable approach [53] to managing the blood supply chain [54, 55]. While the paper admirably addresses the pressing need for innovation in blood supply chain management, several methodological issues warrant consideration. Firstly, the paper lacks a comprehensive analysis of the limitations and challenges inherent in implementing the proposed Blood and Product-Chain model even though the authors has emphasized it including the tendency to focus solely on blood data while neglecting its byproducts [56].

Additionally, the research gaps identified in the paper underscore the need for further investigation. A more thorough comparison of the proposed Blood and Product-Chain model with existing blood supply chain management solutions would provide valuable insights into its comparative advantages and shortcomings. Furthermore, the paper falls short in discussing the scalability and interoperability of the proposed system with other healthcare and supply chain management frameworks, limiting its potential applicability and integration into broader systems. To conclude it, the paper presents an innovative approach to addressing the challenges of blood supply chain management through Blockchain technology, it is not without its limitations. The lack of critical analysis regarding methodological issues and research gaps diminishes the overall impact of the study. Future research endeavors should aim to rectify these shortcomings, offering a more nuanced understanding of the proposed Blood and Product-Chain model and its implications for the healthcare industry.

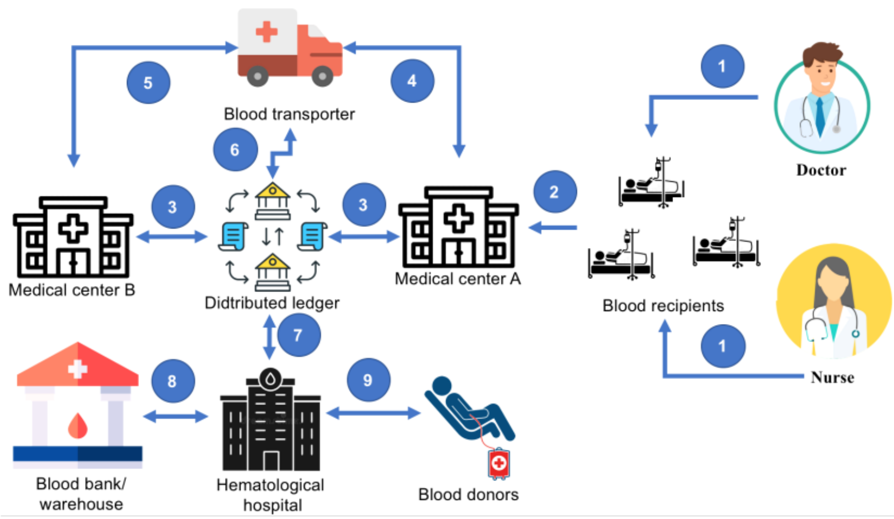

Figure 6. The Comprehensive Structure of the Blood and Product Chain [10]

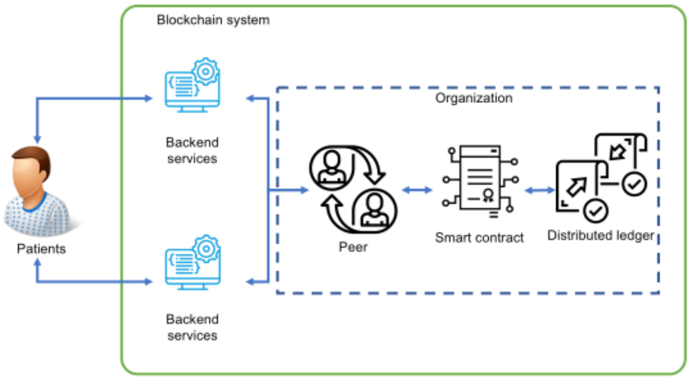

Figure 7. Component in Hyperledger Fabric [10]

2.7. Blockchain Drug Traceability Architectures and Open Challenges

Uddin et al. (2021) [14] offered an insightful examination of drug traceability within the pharmaceutical supply chain and delved into the potential of blockchain technology to mitigate issues surrounding the provenance [57-62], tracking, and tracing of pharmaceutical products [59]. The authors advocate for the adoption of two blockchain-based decentralized architectures, namely Hyperledger Fabric [63] and Besu [64], which purportedly fulfill crucial prerequisites for drug traceability, including privacy, trust, transparency, security, authorization, authentication, and scalability [65, 66]. Additionally, the review identifies and deliberates on various open research challenges associated with employing blockchain technology for drug traceability [52, 67]. These challenges encompass various aspects, including the need for consensus among stakeholders, the ability for different systems to interoperate seamlessly, the financial implications of implementation, the potential for cyberattacks and vulnerabilities [68], and the lack of universally accepted regulations (Figures 8 and 9).

Furthermore, the paper is lacking in empirical evidence or case studies demonstrating the efficacy of these architectures within real-world pharmaceutical supply chain settings, as it has a more profound analysis of the potential ramifications of blockchain technology on stakeholders within the pharmaceutical supply chain, encompassing regulatory authorities, pharmacies, hospitals, and patients, which could enhance the review's comprehensiveness. Moreover, a comprehensive discussion of the limitations and open challenges pertaining to the integration of blockchain technology into the drug supply chain is warranted. Research gaps may encompass the necessity for further exploration of stakeholder consensus, energy consumption considerations, susceptibility to attacks and vulnerabilities, and the potential impact of blockchain technology on combating counterfeit medications. Furthermore, a more extensive discourse on the implications of blockchain technology for regulatory oversight and product safety in the pharmaceutical supply chain would enrich the paper's depth. Overall, while the paper offers valuable insights for health informatics researchers, a more exhaustive and critical analysis of the proposed blockchain architectures, methodological intricacies, and research gaps within the realm of drug traceability in the pharmaceutical supply chain would bolster its scholarly contribution.

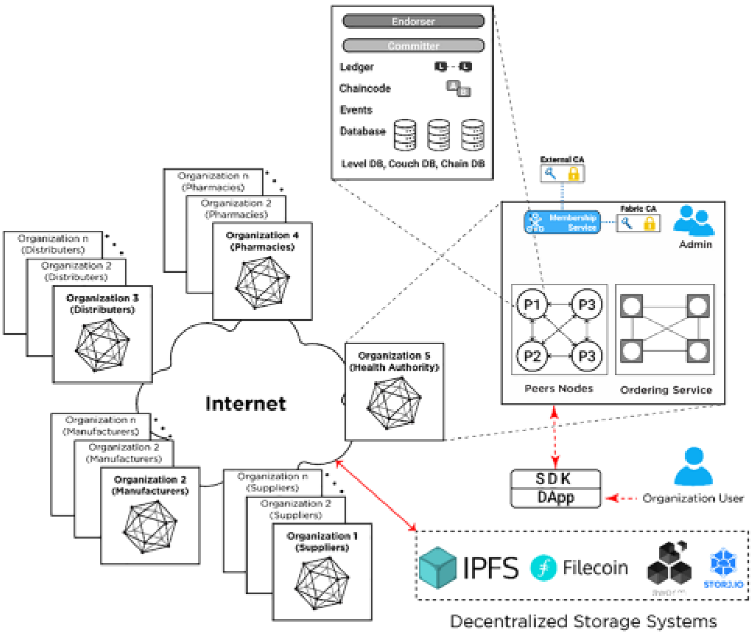

Figure 8. System Architecture of Hyperledger Fabric [14]

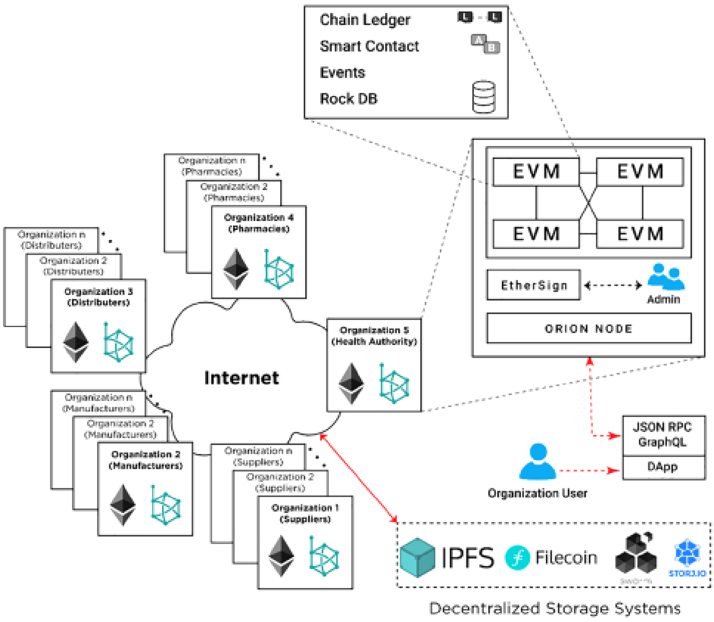

Figure 9. System Architecture of Hyperledger Besu [14]

3. Methods

3.1. Search Strategy and Selection Criteria

A comprehensive analysis of scholarly works from various prominent online databases such as PubMed, IEEE Xplore, and ResearchGate was conducted to locate pertinent papers on the advancement of blockchain technology to bolster medical supply chain management (MSCM). The search criteria used include "Healthcare," "Supply Chain," and "Blockchain Technology" to get pertinent scholarly articles. A meticulous cross-referencing of the identified review articles and the final included studies was undertaken to uncover potentially relevant publications. The inclusion criteria encompassed observational or experimental studies peer-reviewed publications, and primary research articles written in English, with a publication year range from 2021 to 2023. The review excludes non-primary studies such as reviews, meta-analyses, opinion pieces, systematic reviews, as well as surveys and publications in languages other than English.

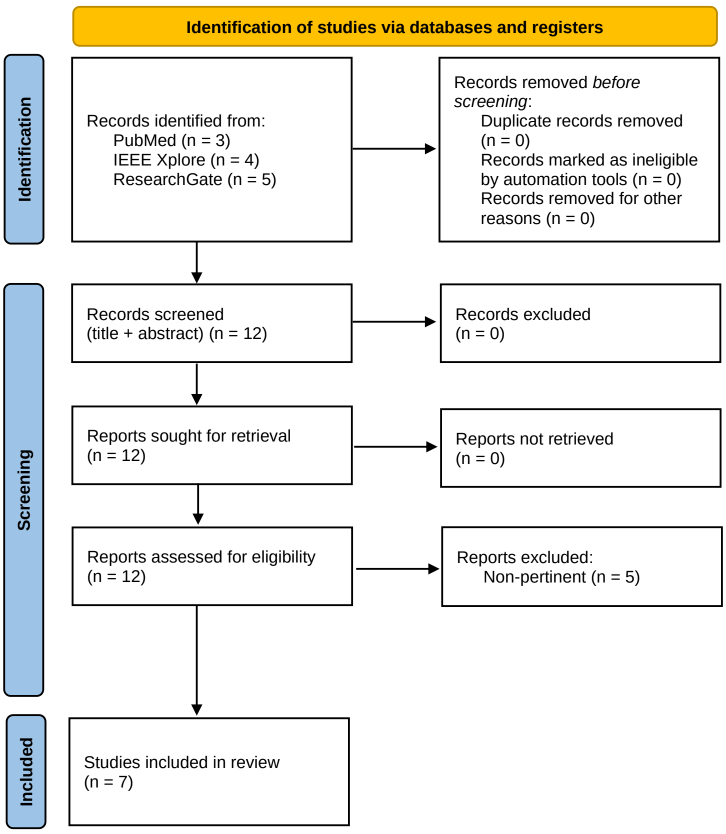

Figure 10. PRISMA Flowchart [69]

3.2. Data Analysis

A three-stage screening method was implemented to ensure the selection of relevant content. At first, the papers were evaluated by two reviewers who separately rated them based on their titles and abstracts. This was followed by a comprehensive examination of the entire text. Any inconsistencies in the reviewers' judgments were managed via deliberations within each pair. If a unanimous agreement could not be achieved, a third impartial author (DG) functioned as an arbitrator to resolve the deadlock. Data extraction for the same set of articles was performed by the two reviewers using a uniform extraction table in order to maintain consistency. Disputes over the retrieved data were settled via deliberations with an impartial arbitrator (DG). The PRISMA reporting requirements have been followed Page et al. (2021) [70].

3.3. Included Studies

We conducted an initial search and found a total of 12 publications from various databases, including PubMed, IEEE Xplore, and ResearchGate. Following the preliminary screening, we selected all 12 for a comprehensive assessment of the whole text. A total of 7 papers that satisfied our inclusion criteria were identified in Figure 10. All of the research included in the analysis were published exclusively within the timeframe of 2021 to 2023.

provides a comprehensive summary of these investigations.

3.4. Quality Assessment

To evaluate the caliber of the selected papers, a quality checklist devised by Kitchenham & Brereton (2013) [71], Kitchenham & Charters (2007) [72] was utilized. This checklist was derived from the guidelines established by the Centre for Reviews and Dissemination (CRD) [73, 74]. The assessment focused on four key aspects:

(a) Study design (Are the research aims clearly stated?)

(b) Conduct (Does the study include sufficient facts about the evaluation of blockchain?

(c) Analysis (How can the comprehensiveness of research findings documentation be assessed via analysis?)

(d) Conclusions (Does the paper adequately address the research questions?).

Using this set of questions, each selected paper was carefully evaluated. The scoring method allocated 1 point for each "Yes" response and 0 points for each "No" response. Consequently, the highest possible score for the primary study was four. As a result, the mean score was 2.00 (±0.71) on a four-point system, where four represents the highest level of quality.

4. Results and Discussion

4.1. Study Type, Domain, and Technology

Blockchain's dominance in managing healthcare drug supply chains was evident, with a majority of respondents (n=3, 43%) recognizing its significance among other applications. Two studies, accounting for 29% of the total, examined the capacity use of BC technology in the supply chains of medical devices. Specifically, one study focused on vaccines while the other focused on blood management, each accounting for 14% of the total studies.

Consortium blockchains were the most common form among the various blockchain types, accounting for 43% (n = 3). There were two instances (29%) of public blockchain implementations, one instance (14%) of private blockchain implementation, and one instance (14%) of hybrid blockchain implementation. Ethereum and Hyperledger Fabric were the preferred platforms, with each being utilized in three investigations, accounting for 43% and 29% of the total, respectively. Two of the remaining investigations (29%) specifically focused on FISCO BCOS and Hyperledger Besu.

Smart contracts experienced significant popularity, being included in three papers, accounting for 43% of the total. Nevertheless, scalability was given limited consideration, as just three investigations delved into its complexity. All three studies emphasized the scalability of their approach, but one of them (n = 2, 29%) did not comment on this aspect. The remaining two studies expressly acknowledged the limited capabilities of their system to manage increasing demands and expand in size.

4.2. Blockchain Principles

Every item in the review addressed a minimum of one (1) of the five (5) fundamental concepts of blockchain: accountability, security/integrity, transparency/traceability, privacy/confidentiality, and reliability as shown in Table 1. Seven (7) researchers claimed that their methods promoted data traceability and transparency. Five research emphasized enhanced data integrity and security, whereas four studies focused on data confidentiality, privacy, reliability, and responsibility.

Table 1. Comparison of the Reviewed Article

Reference	Sector	Blockchain Type	Accountability	Security/ Integrity	Traceability/ Transparency	Confidentiality /Privacy	Reliability	Smart Contract	Scalability
Cui et al. (2023) [2]	Vaccine	Consortium	1	1	1	0	1	Yes	Not explored
Humayun et al. (2022) [11]	Drugs	Publics	0	0	1	0	1	Yes	✗
Omar et al. (2022) [6]	Tools	Publics	1	1	1	1	1	Yes	✗
Alkhader et al. (2021) [12]	Tools	Hybrids	1	1	1	1	1	Yes	Not explored
Mani et al. (2022) [13]	Drug	Consortium	1	1	1	1	0	Yes	✓
Trong et al. (2022) [10]	Blood	Consortium	0	0	1	0	0	Yes	✓
Uddin et al. (2021) [14]	Drugs	Privates	0	1	1	1	0	Yes	✓

Notes:

Yes	Used in the Implementation
No	Not used in the Implementation
✗	Explored but Not Providing the Criteria
✓	Explored and the Criteria are Provided

4.3. Technical Overview

Our analysis revealed a prevalence of consortium-based and public blockchain implementations, while hybrid and private versions were less commonly adopted. Our analysis reveals that the problem of scalability is not exclusive to public blockchains. This is apparent as studies investigating consortium or hybrid blockchains have not specifically tackled the problem of scalability. The result of this analysis implies that BC technology is not scalable enough and further investigations have to be conducted before its actual employment [75]. Other articles have emphasized ETH being the best platform for this purpose as mentioned by Humayun et al. (2022) [11], Omar et al. (2022) [6], Alkhader et al. (2021) [12]. The reason why ETH was chosen was due to its open-source nature as well as its ability to cross from one industry to another which eases the decentralization process [76]. Moreover, the concept of smart contracts has been tried and evaluated in practice through transparent and automated contract and data exchanges that save costs incurred while using intermediaries [77]. Nevertheless, the actual efficacy of these solutions remains uncertain due to the limited technological preparedness of the suggested approaches.

4.4. Vaccines and Drugs

The period between 2021 and 2022 saw a surge in publications focused on vaccine strategies, with notable contributions from Fiore et al. (2023) [75]. Among these, Das et al. (2021) [67] proposed a framework aimed at ensuring the secure distribution and tracking of vaccines, particularly pertinent amidst the COVID-19 pandemic. This framework, utilizing a cloud -assisted blockchain solution within the Internet of Medical Things (IoMT) environment [13], prioritizes the secure storage of vaccine distribution and administration data. By aligning with the goal of ensuring traceability and verifiability in vaccine circulation processes, as highlighted by other studies [1], thus the approach by Das et al. (2021) [67] underscores the significance of blockchain technology in enhancing vaccine management strategies. Similarly to the Cui et al. [2] where they identified the identified the COVID-19 pandemic as a stressor for healthcare monitoring systems (SCHMs), advocating for blockchain-powered solutions to bolster digital supply chains (SCs) within healthcare monitoring systems. Their proposal addresses potential vulnerabilities in vaccine distribution, such as unqualified production and counterfeit vaccines, by leveraging blockchain's decentralized nature [78]. Conventional SCHMs, reliant on centralized systems, often face challenges in ensuring secure and unalterable transactions among authorized parties, thus compromising the reliability of the supply chain [75]. While real-world case studies evaluating this strategy are scarce, the researchers endorse blockchain implementation as a means to enhance data integrity and security within healthcare supply chains. These studies collectively emphasize the pivotal role of blockchain technology in addressing challenges associated with vaccine distribution and management. By providing secure, transparent, and decentralized solutions, blockchain offers promising avenues for improving the reliability and efficiency of healthcare supply chains, particularly in the context of pandemic response efforts.

Several studies have highlighted the tragic consequences of counterfeit drugs, particularly in developing countries, where children often succumb to illnesses exacerbated by fake medications. The Guardian Organization (2017) [79] and the World Health Organization (2017) [80] underscore the link between counterfeit drugs and excess pneumonia deaths [75-81]. In a study by Gomasta et al. (2023) [35], the focus shifted towards addressing the multifaceted challenges associated with drug counterfeiting within the pharmaceutical supply chain. Their research emphasized the critical need for drug and vaccine traceability in healthcare, given the severe health risks posed by counterfeit products [78]. To tackle this issue, Gomasta et al. (2023) [35] developed PharmaChain, a blockchain-based drug supply chain provenance verification system built on Hyperledger Fabric [51, 63]. By leveraging the confidentiality, accountability, and interoperability features of Hyperledger Fabric, PharmaChain integrates cryptographic fundamentals to create tamper-proof logs and smart contracts to ensure data integrity and reliability. This approach aligns with similar studies [13, 14], which have proposed Hyperledger-based architectures and systems for enabling stakeholders to communicate and store information in a shared, trusted, permissioned, and decentralized manner. The implementation of cryptographic principles to establish tamper-proof logs and the utilization of smart contracts represent significant advancements in addressing the complexities of pharmaceutical supply chain management [11]. Moreover, by prioritizing coordination and quality control aspects, these studies contribute to the ongoing efforts to safeguard public health and combat the proliferation of counterfeit drugs.

4.5. Personal Protective Equipment (PPE) and Medical Tools

In addition to the focus on vaccination strategies, recent studies have explored the diverse applications of blockchain technology in combating the COVID-19 pandemic. Ahmad et al. (2023) [82] conducted a study aimed at identifying the potential role of blockchain in securing supply chain operations and Personal Equipment (PPE) certificates. While not proposing a specific solution for PPE management and tracking, their findings highlighted several key areas where blockchain could make significant contributions. These included preventing compliance violations, identifying counterfeit PPEs through data provenance, and enabling verifiable payment settlements using smart contracts. The study also emphasized the importance of public blockchain platforms for ensuring transparency in the PPE supply chain, demonstrating blockchain's potential to address critical shortages and enhance healthcare supply chain effectiveness during the pandemic, similarly to the Omar et al. [6] that aimed to address the challenges faced in the healthcare sector, particularly the critical shortages of PPE during the pandemic. These studies collectively underscore the growing recognition of blockchain technology as a promising tool for enhancing transparency, security, and efficiency in healthcare supply chains, particularly during crisis situations like the COVID-19 pandemic.

Expanding beyond the realm of vaccination and Personal Protective Equipment (PPE), Nanda et al. (2023) [83] offer a novel approach known as Novel Approach for Integrated IoT (Internet of Things) With Blockchain in Health Supply Chain (NAIBHSC), which targets the secure and efficient distribution of medical products. Their study focuses on the integration of blockchain and IoT technologies into the medical supply chain to address issues related to the distribution of medical products. This is achieved through the development of smart contracts, RFID tags for product tracking, and the use of a bi-objective mathematical model to minimize costs and reduce the number of undamaged items during transportation. The study also emphasizes the importance of security, transparency, and trust in the healthcare supply chain, and highlights the potential benefits of integrating blockchain and IoT technologies. In contrast to prior research by Alkhader et al. [12], which proposed a decentralized blockchain-based digital manufacturing and supply chain solution specifically tailored to address the challenges of providing medical devices and supplies during the COVID-19 pandemic without incorporating IoT, the approach by Nanda et al. (2023) [83] encompasses both blockchain and IoT technologies. This broader integration underscores the potential for enhanced supply chain management in healthcare settings. Both the NAIBHSC approach and the decentralized blockchain-based digital manufacturing and supply chain solution offer generic frameworks that can be adapted to various emergency use case scenarios. This adaptability highlights their versatility and potential applicability beyond the current pandemic context.

4.6. Blood Products

The blood transfusion supply chain presents a unique opportunity for blockchain adoption because of the inherent risk of adverse occurrences and potentially fatal complications [84]. Blockchain's secure visibility, transparency, and data reliability [85, 86] hold promise to revolutionize blood management. Real-time tracking of donated blood, forgery prevention, and minimized supply times could be transformative. In the study conducted by Ahamed N & Vignesh (2022) [87], they focus on developing a framework to address issues like supply time and data management by utilizing blockchain, smart contracts, and secure transactions contrast to the prior researchers [10] where they provide detailed models and evaluates performance in various related scenarios. However, existing proposals for blockchain-based blood transfusion SC management require further investigation and robust verification [88] but these studies offer complementary insights, showcasing the potential of blockchain in enhancing efficiency and security throughout the blood supply chain cycle.

5. Conclusion

Even though blockchain technology has the ability to significantly transform Healthcare Supply Chain Management (HSCM), its widespread implementation is hindered by its mainly theoretical nature and the few practical use cases. This review paper underscores the transformative potential of blockchain technology in revolutionizing healhcare supply chain management, particularly in response to the exigencies of the COVID-19 pandemic. Through a comprehensive review and critical evaluation of innovative blockchain-powered solutions, it has elucidated the benefits and challenges associated with its adoption in various aspects of healthcare supply chains. The findings highlight blockchain's efficacy in enhancing transparency, efficiency, and integrity across vaccine distribution, blood product management, PPE procurement, pharmaceuticals, and medical devices. However, the document also acknowledges the need for further research to address methodological limitations, scalability issues, and long-term sustainability concerns. Despite the progress made, scalability and technological preparedness remain crucial areas for future exploration and development. Overall, this review not only identifies key areas for improvement but also serves as a valuable resource for healthcare stakeholders, guiding them towards informed decision-making and strategic implementation of blockchain technology to fortify healthcare supply chains in times of crisis and beyond.

6. Declarations

6.1. Author Contributions

Conceptualization, M.S.S. and N.N.; methodology, M.S.S. and N.N.; validation, N.N.; formal analysis, N.N.; investigation, M.S.S.; writing—original draft preparation, N.N. and M.S.S.; writing—review and editing, M.S.S.; visualization, N.N.; supervision, M.S.S.; funding acquisition, M.S.S. All authors have read and agreed to the published version of the manuscript.

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Data sharing is not applicable to this article.

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Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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