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Review

Blockchain and Healthcare: A Critical Analysis of Progress and Challenges in the Last Five Years

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Abstract: Utilizing the fundamental characteristics of the decentralization, immutability, and transparency of blockchain technology, the healthcare industry has made notable advancements in incorporating it over the past five years. This review examines the progress and challenges encountered in this critical study by assessing 124 articles published by MDPI between 2018 and the current date. Examining blockchain's potential uses, like safe data exchange and interoperability in supply chain management and electronic health records, provides exciting new directions for the future of healthcare. Blockchain technology can greatly increase efficiency and cost-effectiveness by guaranteeing data integrity, protecting patient privacy, and reducing administrative procedures. This paper objectively evaluates blockchain's advancement in healthcare through a thorough analysis of real-world applications and research projects. By highlighting both its advantages and disadvantages, this analysis seeks to add to the continuing conversation about how blockchain will influence the way healthcare is managed and delivered in the future.

Keywords: blockchain technology; healthcare industry; advancements; data integrity; patient privacy

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1. Introduction

As our population ages, not only do we have a greater demand for healthcare, but also for increased productivity [1]. The aging population and the prevalence of chronic diseases have increased the focus on health and the quest for better medical care [2]. There is a shift in perspective away from traditional healthcare and toward patient-centered care. Recent years have seen a shift away from healthcare that focuses on the patient and the hospital, toward healthcare that is more mobile and electronic; this shift has resulted in universal healthcare [3].

The industry is at the forefront. Healthcare organizations, equipped with the necessary tools, are at the forefront of participating in the blockchain movement [4]. The health ecosystem's primary focus is on patients, and its primary objective is to increase the security, confidentiality, and portability of health information. The healthcare sector generates copious amounts of data, including patient records, data from clinical trials, billing, and research findings [5]. Securing all internet-connected medical devices is the biggest obstacle to universal electronic healthcare [6].

Blockchain, a distributed, immutable, and powerful technology, is having profound effects on the healthcare industry [7]. The elimination of third-party middlemen is another useful feature of blockchain technology. These days, blockchain is used for more than only cryptocurrency transactions [8]. Since these problems are real ones, the healthcare management system has social relevance [9]. The overarching goal is to boost happiness by solving actual health problems [3]. Healthcare information technology emerged as a result of the incorporation of computer science into healthcare, leading to significant improvements in medical care [10]. There are significant problems and gaps in the healthcare system, notwithstanding its progress [11].

Since its start with cryptocurrencies and continuing with the latest blockchain-based application for industry 5.0 [12], blockchain technology has been deployed in a wide variety of areas as part of the infrastructure of some firms that require transparency, integrity, and reliability [13]. The applications of blockchain technology in healthcare extend far beyond just patient records and include things like supply chain management and drug security, disease prediction, medicine traceability, insurance claims, and more. By automating formerly laborious processes that relied on inefficient configurations and wasted time, blockchain technology has fundamentally altered how things are implemented [14]. Blockchain's trustworthy environment and user-friendly network produce effective results that foster confidence among parties [14,15].

In light of the rapidly evolving landscape, this paper draws upon reliable research and current knowledge, primarily focusing on MDPI articles. Our collaborative effort delves into the advantages and disadvantages of blockchain integration in healthcare, with the aim of identifying potential areas for development and future research directions. It serves as a resource for decision-makers, healthcare experts, and technology enthusiasts, offering insights into the current state of blockchain in healthcare and its potential to reshape the industry in the years ahead.

2. Background

2.1. Core Features and Characteristics

The potential for blockchain technology to completely overhaul the healthcare sector has surfaced [16]. Blockchain is fundamentally a distributed, decentralized digital ledger that securely and permanently records transactions [17]. In the healthcare industry, where the confidentiality and security of patient data are crucial, this functionality is very useful [18]. Blockchain technology assures that no single party has complete control over the data by functioning on a peer-to-peer network [17,19]. This increases transparency and lowers the possibility of data modification or unauthorized access [18]. Healthcare data is protected by a crucial layer of security thanks to the immutability of blockchain records [17]. Since each transaction or item on the blockchain is cryptographically connected to the one before it, updating historical data would require changing every block after it [16]. This tamper-resistant quality protects medical data and critical information, greatly lowering the possibility of fraud, and boosting patient confidence [18].

All network users have access to a complete transaction history, allowing for the traceability of medical data, the authentication of products, and regulatory compliance [20]. Additionally, being able to audit and track data access improves accountability and fortifies security against data breaches. The long-standing issue of sharing medical data among various systems and stakeholders can be addressed with the help of blockchain's interoperability features. Blockchain-based platforms can enable secure and seamless data transmission, improving care coordination and minimizing redundant procedures, by using standardized data formats and protocols.

Blockchain's special ability, smart contracts, automates healthcare procedures. Among other things, the processing of insurance claims, consent management, and supply chain tracking can all be automated using these self-executing agreements with specified rules. Smart contracts can streamline procedures, lower costs, and improve overall efficiency in the healthcare ecosystem by removing the need for middlemen and manual interventions. Despite its enormous promise, the implementation of blockchain in healthcare confronts difficulties. Significant obstacles still need to be solved in the areas of scalability, regulatory compliance, data protection, and interaction with current healthcare infrastructure [21]. However, continuous research and development in this field continue to look at novel approaches to deal with these difficulties as the fundamental traits and properties of blockchain drive the goal of a more secure, effective, and patient-centric healthcare environment.

2.2. Employing Blockchain in Healthcare

Blockchain technology implementation in the healthcare industry has many benefits, including improved data security, interoperability, and simplified data management [22]. To do this, it is needed to first pinpoint the precise use cases where blockchain can provide value. These applications cover managing medical records, monitoring the medical supply chain, sharing data from clinical trials and research, processing healthcare payments, and integrating data from internet of things (IoT) devices. Once the use cases have been established, choosing the best blockchain platform is essential, taking into account elements like scalability, privacy needs, and consensus techniques.

Strong data privacy and permission management methods are crucial due to the sensitivity of healthcare data and the requirement for compliance with tight standards. Implementations of blockchain need to follow privacy regulations and provide impenetrable consent management to guarantee that patient data is only accessible with the appropriate authorization. Smart contracts are extremely helpful in the healthcare industry for activities like processing insurance claims and managing data access rights [23] since they play a vital role in automating procedures and transactions based on specified rules [24].

Given that the majority of enterprises have legacy systems in place, integration with existing healthcare systems is essential. While challenging, a smooth integration is essential for a successful shift to blockchain technology [25]. Another crucial choice depends on the chosen blockchain platform and the healthcare use case [26], such as whether to employ proof of work (PoW) or proof of stake (PoS). Before implementing blockchain technology in a real-world healthcare setting, thorough testing and compliance checks are essential to guarantee data integrity, security, and adherence to legal standards. Finally, after implementation, it is crucial to maintain monitoring and improvement to address any problems that may emerge and enhance the functioning of the system. Figure 1 represents the step-by-step process of implementing blockchain technology in the healthcare industry.

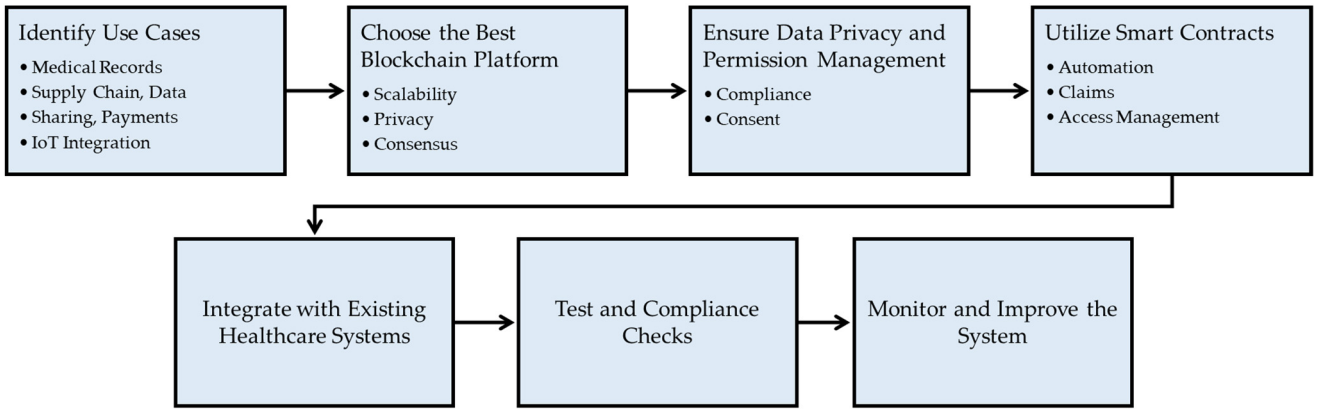

Figure 1. Implementation of blockchain in the healthcare system.

2.3. Benefits and Potential Applications in Healthcare

Blockchain technology has numerous advantages and prospective uses that could completely transform the way healthcare is delivered and managed, and how patients fare. The unmatched data security and privacy capabilities of blockchain technology are among its most important benefits for the healthcare industry. Blockchain ensures that patient data is secure and tamper-resistant by using a decentralized and immutable ledger. This lowers the possibility of data breaches and illegal access, fostering more confidence in the healthcare system.

Acheiving interoperability between various systems and stakeholders has been a major difficulty in the healthcare industry [27]. This problem is resolved by the open and standardized data exchange protocols offered by blockchain technology [28]. Healthcare organizations may safely exchange patient information in real time, allowing for seamless

care coordination and a reduction in the number of tests and procedures that need to be repeated. Because of interoperability, healthcare professionals can make better judgments and provide patients with more thorough and effective care.

The integration of blockchain technology has enormous potential benefits for electronic health records (EHRs). Blockchain technology can be used to make EHRs into a unified and impenetrable system. Authorized healthcare practitioners can quickly access medical records stored on the blockchain, assuring accurate and current patient information during medical treatment. A more accurate diagnosis, individualized treatment strategies, and ultimately better patient outcomes may result from this simplified access to patient data.

The management of supply chains, notably in the pharmaceutical sector, is another prospective use of blockchain in healthcare [29]. Transparency and traceability are improved by blockchain's capability to follow the distribution of medications and medical equipment from the maker to the final consumer. This supports patient safety and confidence in the healthcare system by ensuring the authenticity and integrity of medications while also assisting in the fight against the growth of counterfeit drugs.

Blockchain technology can also have a big impact on managing research data and clinical trials. Researchers can use the transparent and auditable ledger of a blockchain to check the accuracy of trial outcomes and guarantee protocol adherence. Medical breakthroughs are ultimately accelerated by the immutability of data stored on the blockchain, which improves the reproducibility and legitimacy of study findings [30].

Blockchain-based smart contracts have the potential to transform other industries as well, including health insurance and claims processing [31]. Smart contract automation of claim settlements lowers administrative loads and avoids errors, resulting in a more effective and economical insurance system. Additionally, blockchain can give patients more control over their personal information by enabling them to manage their medical data and consent through smart contracts.

Despite these promising uses, problems with scalability, legal compliance, and system integration continue. Blockchain technology is continuing to advance, overcoming these challenges and advancing the healthcare sector toward a more secure, effective, and patient-focused future. Blockchain technology is expected to have a revolutionary impact on healthcare as it develops, transforming how healthcare data is maintained, shared, and used to improve patient care and general public health.

2.4. Evaluation of Improved Efficiency and Cost-Effectiveness

Blockchain accelerates administrative procedures by utilizing its decentralized and tamper-proof ledger system, doing away with the need for middlemen and manual record reconciliation [32]. Smart contracts can automate processes like patient registration, billing, and insurance claim processing, which speeds up decision-making and improves collaboration among healthcare providers [33]. This improves patient care while simultaneously saving time.

Blockchain's interoperability features enable smooth data sharing between various healthcare organizations and systems [34,35]. Secure data exchange improves care coordination and lowers medical errors with patients, caregivers, and other authorized parties. Repetitive tests and treatments can be reduced with better patient access to their medical records, which lowers costs for both patients and healthcare providers. Moreover, efficiency and cost-effectiveness are further enhanced by blockchain's ability to revolutionize supply chain management [36,37]. Counterfeit goods can be found and supply chain integrity ensured by tracking medications and medical equipment on the blockchain [38]. This openness not only increases patient safety but also lessens financial losses brought on by recalled goods and fake goods. Table 1 provides a comprehensive analysis of the potential impact of implementing blockchain technology in the healthcare industry. It examines various aspects of healthcare operations, comparing traditional systems to blockchain-based systems.

Table 1. Blockchain in healthcare: evaluating improved efficiency, cost-effectiveness, and challenges.

Aspect	Traditional System	Blockchain System	Challenges/Limitations	Reference
Data Security/Privacy	Limited security, data breaches possible.	High security via cryptographic algorithms.	Regulatory complexity, private key management	[16]
Interoperability	Data silos, incompatible formats.	Shared, standardized, transparent data access.	Integration challenges	[39]
Data Integrity	Centralized data, tampering risks.	Immutable ledger, reduced errors.	Scalability concerns	[40]
Claims Processing	Manual verification, time-consuming.	Efficient smart contract validation.	Transition challenges	[41]
Supply Chain Management	Lack of transparency in tracing.	Traceable supply chain data.	Onboarding difficulties.	[42]
Medical Research	Limited access to diverse datasets.	Decentralized data sharing with consent.	Data privacy, compliance challenges	[43]
Counterfeit Drugs Detection	Inadequate counterfeit drug identification.	Unique identifiers, history tracking.	Adoption hurdles	[44]
Auditability/Compliance	Manual audits, compliance issues.	Transparent, auditable blockchain records.	Privacy vs. transparency balance	[45]
Cost of Intermediaries	Increased costs due to intermediaries.	Direct peer-to-peer transactions.	Stakeholder trust transition	[46]

3. Methodology

To examine the development and difficulties of blockchain adoption in the healthcare industry during the past five years, this study used a mixed-methods methodology. A review of research papers on blockchain technology in healthcare that have been published in MDPI journals was performed. "Medical" or "Health" or "Healthcare" AND "Blockchain" were the keywords. The search encompassed the past five years (2018–19 July 2023) to ensure that the study included the most recent and relevant information.

The first search produced 158 papers. After screening based on criteria, 124 articles were selected to review. A variety of adoption-related metrics for blockchain technology in healthcare were gathered and examined. These comprise the number of articles started, the number of implementations that were successful, and the growth pattern during the previous five years.

Limitations:

- The study might be constrained by the data and published studies on blockchain in healthcare that are currently available, particularly for certain locations or particular applications;
- Because blockchain technology and healthcare are both quickly growing fields, it may be difficult to keep up with the most recent advances;
- Examining studies within the context of MDPI publishers.

Providing a comprehensive overview of the progress and challenges in integrating blockchain technology into the healthcare industry, this study aimed to offer valuable insights for stakeholders. This approach leveraged the well-established benefits of conducting reviews in swiftly evolving fields, ensuring the synthesis of pertinent evidence. The purpose of this study's conclusions was to provide insightful information that will help stakeholders, decision-makers, and researchers make informed judgments about the potential applications of blockchain technology in healthcare.

4. Analysis of Current State

Blockchain technology's current situation in the healthcare industry indicates both tremendous advancements and enduring difficulties. Several initiatives and projects have

been launched during the past five years to investigate the potential of blockchain to revolutionize healthcare operations and address pressing concerns. However, some challenges need to be carefully overcome before the technology can be fully integrated.

According to the number of publications published in respected journals like MDPI during the past five years (Figure 2), there has been a consistent and significant increase in research interest. With only three articles published in 2018 and a steady increase to 21 articles in 2021, the pattern of research publications points to a healthy trajectory. In particular, the year 2022 saw a notable acceleration with 47 publications, demonstrating the expanding understanding of blockchain's potential in resolving healthcare issues. The output of research did, however, see a modest decline in 2023, which is clear given that the year has not yet ended.

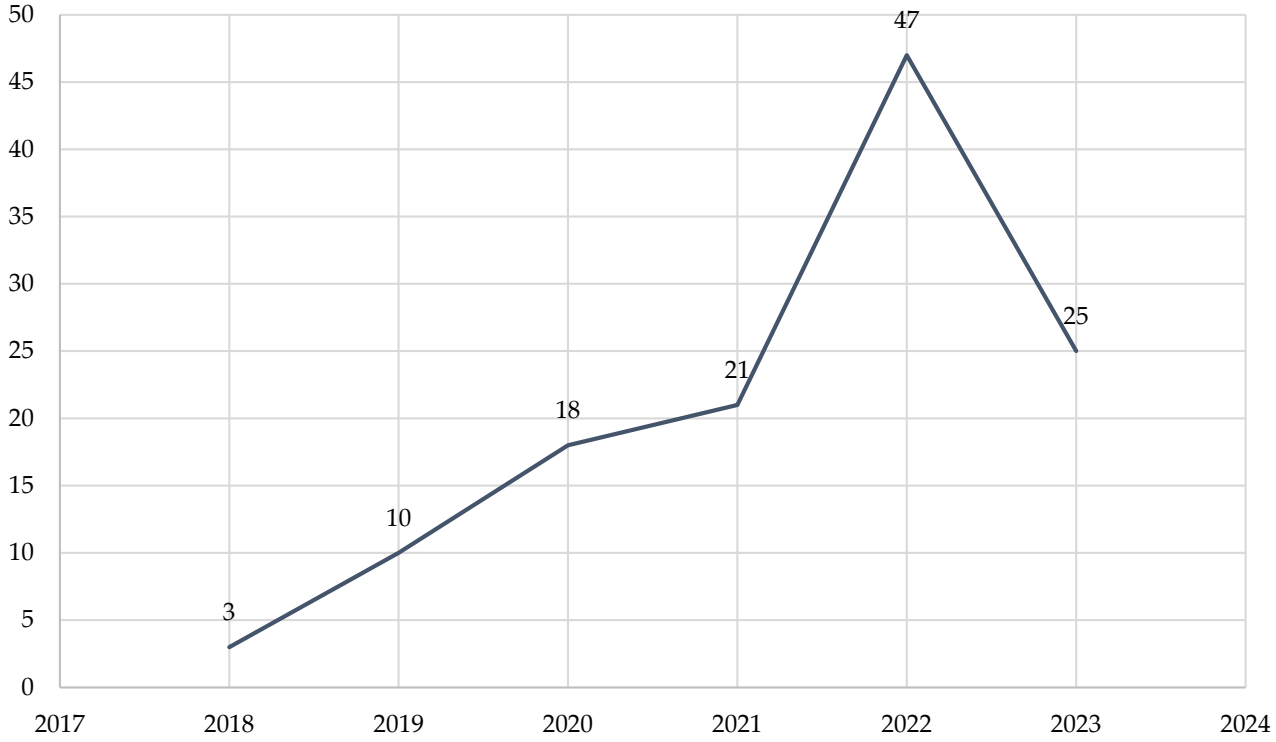

Figure 2. Number of MDPI articles.

A greater emphasis is being placed on blockchain as a workable solution for many healthcare concerns, as seen by the increase in research publications in 2022. Numerous topics are covered in these articles, including the management of electronic health records, the tracking of the supply chain, patient permission and data sharing, interoperability, and data protection.

Over the past five years, Blockchain technology has garnered considerable interest and research activity in the healthcare sector, as evidenced by the publication trends in various MDPI journals (Figure 3). With 35 published articles, "Sensors" is the most prominent journal platform, reflecting a strong emphasis on the use of sensors in blockchain-based healthcare applications, such as ubiquitous health devices and remote patient monitoring. Following closely with 24 and 17 articles, "Electronics" and "Applied Sciences" likely cover a broad range of topics, including blockchain-based electronic health record systems, secure data sharing, and medical device integration. There is a growing interest in investigating blockchain's potential to revolutionize healthcare by improving data security, interoperability, and patient-centric care, as evidenced by these publications.

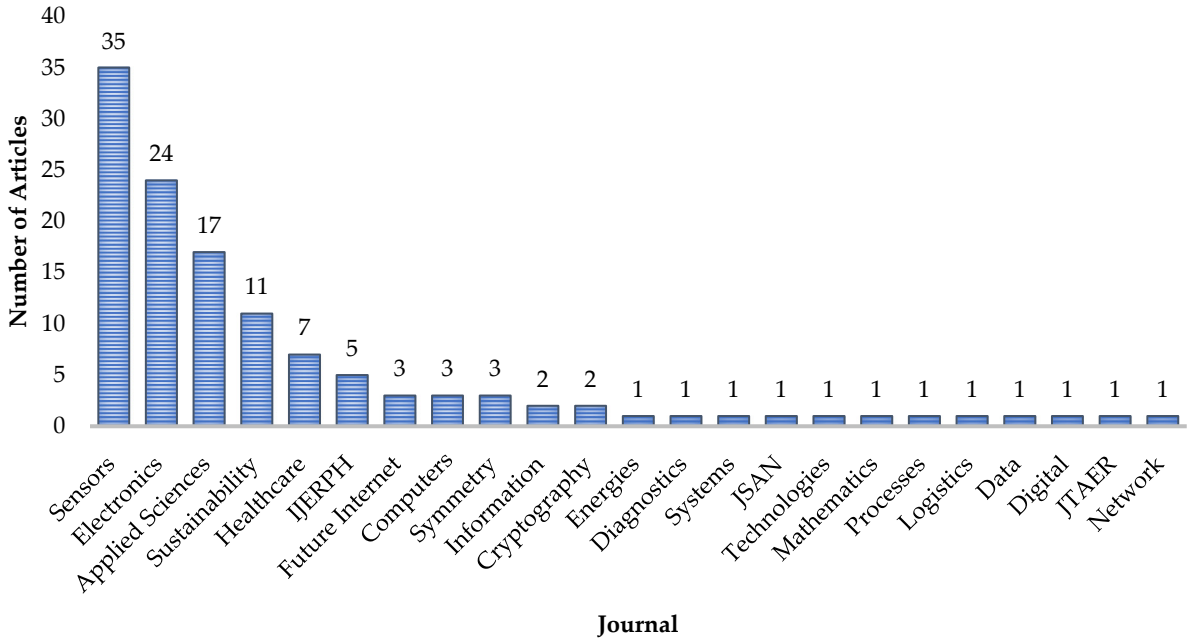

Figure 3. Distribution of MDPI journals in the case of blockchain application in the medical industry.

Eleven articles published in the journal "Sustainability" demonstrate the importance of sustainability and environmental concerns in healthcare. Researchers are eager to investigate how blockchain technology can contribute to sustainable healthcare solutions, including supply chain transparency and waste reduction. Furthermore, "Healthcare" as a specialized journal contains seven articles wholly devoted to blockchain in the healthcare domain, demonstrating the topic's niche appeal. The remaining journals, including "IJERPH", "Future Internet", "Computers", "Symmetry", "Information", and "Cryptography", among others, have also contributed to the body of knowledge in this field by publishing between one and five articles highlighting the diverse aspects and potential applications of blockchain in the healthcare industry.

The increasing number of scholarly articles published in various fields over the past five years demonstrates the current condition of blockchain technology in the healthcare industry (Figure 4). Engineering emerged as the discipline with the most articles, totaling 82, indicating a strong interest in investigating how blockchain can be applied to various engineering aspects in the healthcare industry. These applications may include securing medical devices, assuring data integrity in medical records, and optimizing supply chains in the healthcare industry.

Environmental and earth sciences and computer science and mathematics, with 72 and 63 articles, respectively, followed closely behind. This suggests that researchers in these fields are increasingly recognizing the potential of blockchain technology to resolve healthcare-related environmental challenges, such as tracing the provenance of medical products and facilitating the secure exchange of data between healthcare providers. Similarly, in chemistry and materials science and physical sciences, with 58 and 48 articles, there is a great deal of interest in improving the traceability of pharmaceutical products and ensuring the authenticity of medical equipment and materials.

In the context of life sciences and healthcare-specific disciplines, the quantity of articles indicates a growing interest, albeit at a lower level than in other disciplines. 22 articles were devoted to biology and life sciences, 16 to public health and healthcare, and 15 to medicine and pharmacology. This indicates that researchers in these disciplines recognize blockchain's potential to enhance healthcare data management, patient privacy, and medical research. While business and economics and social sciences, arts, and humanities had relatively fewer articles, with 14 and 12 publications, respectively, this may indicate a growing interest in investigating the economic and societal implications of blockchain

implementation in healthcare, including cost-effectiveness, patient empowerment, and ethical considerations.

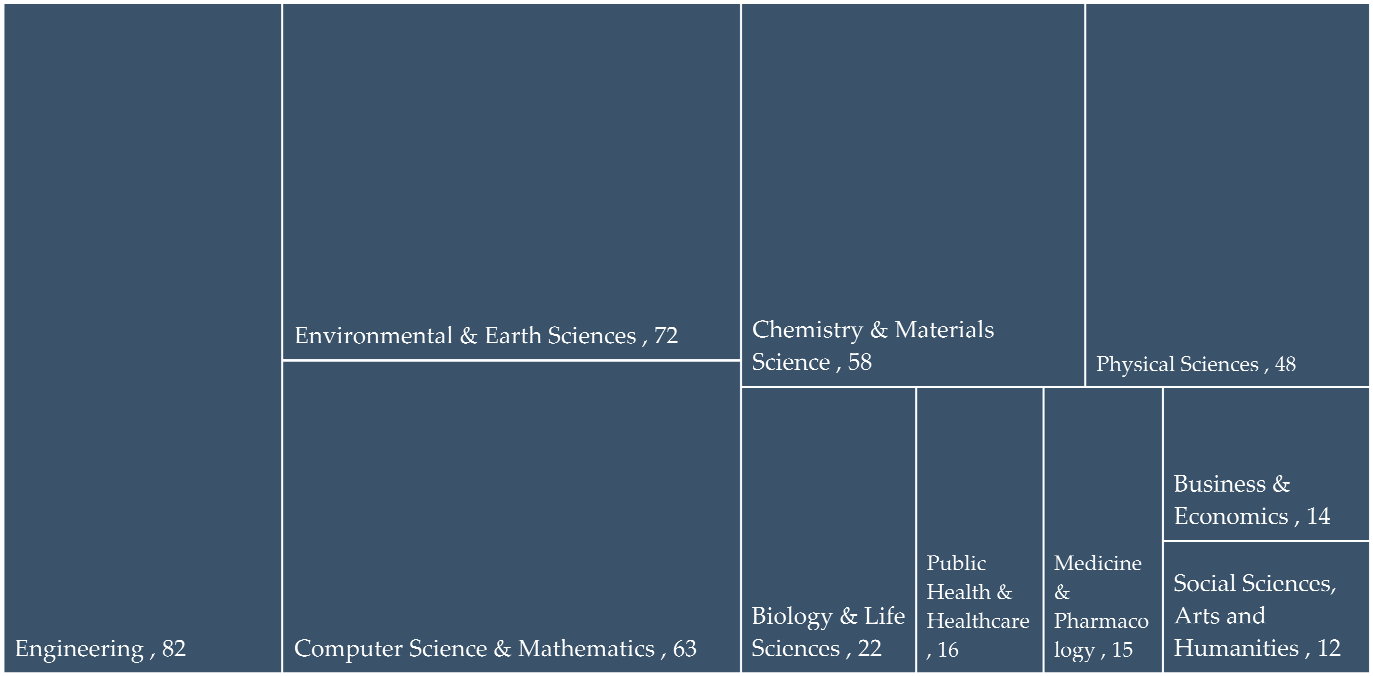

Figure 4. Topic distribution for blockchain applications in the medical industry.

The healthcare industry is being revolutionized by blockchain technology, which offers a variety of prospective applications. The expedient sharing and management of healthcare data is a primary focus. The immutable and transparent ledger system of blockchain has enabled the development of platforms that facilitate secure and seamless data sharing among healthcare providers. Whether it's enhancing the transmission of DNA sequencing data, expediting the administration of electronic health records, or ensuring the integrity of drug supply chains within smart hospitals, blockchain solutions are improving the security and accessibility of medical information.

Privacy and security are of the utmost importance in healthcare, and blockchain is up to the task. This theme examines innovative approaches to protecting sensitive patient information. From privacy-preserving techniques and encryption techniques to comprehensive access control frameworks, blockchain provides a solid foundation for the development of secure healthcare systems. These developments foster a more reliable and secure environment for medical data management by nurturing trust and ensuring compliance with stringent regulations.

The combination of artificial intelligence and blockchain represents a new frontier in the innovation of healthcare. This category explores the relationship between artificial intelligence algorithms and blockchain technology, with applications spanning from medical diagnosis and digital twinning to IoT device authentication. By combining the analytical power of artificial intelligence with the data integrity and transparency of blockchain, healthcare systems are becoming more intelligent and capable, facilitating informed decision-making and enhancing patient care.

5. Discussion

The implementation of blockchain technology in healthcare is examined from a variety of angles in this collection of research publications. Included in the discussion are privacy and security in healthcare systems, integration with the IoT, implications for the COVID-19 pandemic, and the application of blockchain in the management of the health supply chain. Additionally, data security, privacy-preserving healthcare applications, management of

health information, artificial intelligence (AI), and blockchain are covered. By ensuring data integrity, enhancing patient privacy, enabling secure and decentralized health records management, and facilitating creative responses to healthcare concerns, these articles demonstrate how blockchain technology has the potential to change healthcare.

5.1. Blockchain Applications in Medical Informatics and Healthcare

A promising answer in several areas of medical informatics and healthcare has emerged: blockchain technology. Studies by Lee et al. [47] and Hölbl et al. [48] shed light on the potential uses and difficulties of putting blockchain into use in the healthcare sector. While the latter provides a thorough overview of current blockchain use cases in healthcare, highlighting the influence on data management and patient privacy, the former examines how blockchain may rapidly and securely transport DNA sequencing data.

Additionally, studies by Shen et al. [49] and Yang et al. [50] offer creative approaches to safe and cooperative data exchange among healthcare professionals. MedChain makes use of the decentralized nature of blockchain to speed up data access, while proof-of-familiarity introduces a privacy-preserving system to aid in reliable medical judgment. Studies by Khatoon [23] and Capece and Lorenzi [51] also look into the use of smart contracts and blockchain-based EHR platforms to enhance patient data accessibility and healthcare management.

Additional studies, such as the study by Ejaz et al. [52] and Park et al. [53] concentrate on improving healthcare service delivery and data security. The former uses proxy re-encryption for secure data sharing among numerous healthcare providers, while the latter connects blockchain with edge computing to create low-latency healthcare apps. Ali et al. [54] and Lee et al. [55] also address data privacy and regulatory compliance by integrating secure access frameworks and chaotic maps in blockchain transactions.

5.2. Blockchain and IoT in Healthcare

The integration of blockchain and IoT in healthcare is the subject of several research studies, demonstrating the disruptive potential of this pairing. For instance, Jo et al. [56] suggest a hybrid blockchain and IoT network to track the condition of underground structures in healthcare facilities while assuring data security and real-time structural health monitoring. Dwivedi et al. [57] focus on developing a decentralized and privacy-preserving healthcare blockchain that is especially suited for IoT applications, enabling secure communication and data sharing while maintaining patient confidentiality. A study by Fernández-Caramés et al. [58] also looks into the fusion of blockchain, IoT, and fog computing to create a continuous glucose monitoring system for diabetes patients that enables real-time data insights and patient engagement.

Access control approaches and techniques are suggested in several research articles for protecting healthcare data within the IoT environment. For instance, the paper by Figueroa et al. [59] proposes an attribute-based access control model for healthcare environments using blockchain and IoT technology, ensuring data security and controlled access based on predefined attributes. For secure communication in medical cyber-physical systems, Shu et al. [60] suggest an effective certificateless aggregate signature scheme for blockchain-based medical cyber-physical systems. Additionally, Satamraju and B [61] present a proof-of-concept demonstrating the efficient integration of IoT devices with blockchain technology in healthcare, focusing on scalability and data integrity.

The possibility of blockchain-enabled healthcare workflows within federated hospital IoT clouds is explored in several research studies. As an illustration, Celesti et al. [62] suggest a blockchain-based healthcare workflow to enable effective and secure data sharing among medical laboratories in federated hospital IoT clouds, benefiting telemedicine and patient care. Furthermore, Bai et al. [63] present a healthcare identity system based on Fabric blockchain and zero-knowledge proofs, ensuring secure and private interactions within the IoT-based healthcare ecosystem. Additionally, Rana et al. [64] focus on developing a decentralized access control model using blockchain and AI to guarantee secure

interoperability of healthcare systems within the IoT infrastructure, facilitating seamless data exchange while enforcing stringent access control policies.

Several studies propose blockchain-based trust mechanisms to overcome security issues in IoT-based healthcare systems. For instance, Ali et al. [65] describe a blockchain-based trust mechanism that uses fuzzy logic to identify Sybil attacks and improve the reliability of IoT devices and data. The article by Kerrison et al. [66] also examines the application of blockchain and IoT in rural healthcare settings, utilizing hybrid-channel communication with digital twinning to enhance healthcare services and data exchange in remote areas. Additionally, Albakri and Alqahtani [67] present a smart healthcare system combining IoT, blockchain, metaheuristics, and deep learning models to improve patient monitoring, diagnosis, and treatment while also optimizing resource allocation.

The possibilities of blockchain-enabled federated learning in healthcare and its effect on at-home health monitoring are also shown in study studies. To ensure privacy-preserving data analysis and training models, Farooq et al. [68] studied federated learning in the context of in-home health monitoring. This empowers patients to take an active role in their treatment. In addition, Ali et al. [69] explore how these three technologies are combined in healthcare to promote immersive experiences, open AI-driven decision-making, and secure patient data management. These research articles demonstrate how combining blockchain with IoT has the potential to transform healthcare delivery by guaranteeing data security, interoperability, and scalability and improving patient outcomes.

5.3. Privacy and Security in Healthcare Blockchain Systems

The use of blockchain technology in healthcare in recent years has highlighted the importance of privacy and security while handling sensitive patient data. Many books on the topic provide insight into various methods and frameworks for guaranteeing data security, privacy, and exchange. The idea of healthcare blockchain systems with privacy protection is one approach being looked at. Studies by Ali et al. [69] and Hu et al. [70] highlight how important it is to protect patient privacy through effective and secure data-sharing mechanisms. These simplified methods that rely on encryption try to balance data security and accessibility.

The papers emphasize the importance of creating secure blockchain-based healthcare systems, which are of similar importance. The papers Butt et al. [71] and Ali et al. [54] highlight the use of blockchain technology to create a secure platform that cannot be tampered with or compromised for the exchange of medical records. The need for thorough security measures in managing healthcare data and protecting against cyber threats is also highlighted by articles by Farahat et al. [72] and Islam et al. [73].

The COVID-19 epidemic has highlighted the value of blockchain in healthcare even more. Blockchain technology can address healthcare issues during a worldwide crisis, as evidenced by articles like by Fusco et al. [74] and Egala et al. [75]. Although these papers might not specifically mention security or privacy, the use of blockchain in pandemic management suggests a greater emphasis on data security and reliability. Another field of research involves the application of blockchain to cutting-edge technologies like deep learning and the internet of medical things (IoMT). In smart healthcare applications incorporating IoMT, studies by Albakri and Alqahtani [67] imply the usage of blockchain to improve security. These headings highlight how healthcare systems are always changing as cutting-edge technology combines to produce more reliable and secure solutions. Table 2 summarizes key findings and contributions from each paper related to the implementation of blockchain solutions in healthcare.

Table 2. Analysis of papers on efficiency in healthcare blockchain systems.

Platform	Efficiency for Health Management	Key Findings/Contributions	Study
Permissioned	Enhanced data integrity	Proposed an integrity model for secure eHealth data.	[76]
	Protected data sharing	Implemented lightweight message sharing for privacy.	[77]
Decentralized	Controlled access to records	Developed an access control scheme for secure sharing.	[78]
	Improved record sharing	Proposed a mechanism for the secure sharing of records.	[71]
	Strengthened data security	Introduced a secure blockchain model for healthcare.	[72]
	Enhanced emergency data access	Created a framework for secret data sharing in emergencies.	[79]
	Secured data transmission	Ensured secure transmission of electronic health records.	[80]
	Trustworthy healthcare system	Developed a trustworthy system for healthcare management.	[73]
	Improved access to EHRs	Introduced a secure framework for accessing EHRs.	[54]
Symmetric	Privacy-preserving data sharing	Implemented a privacy-preserving data-sharing system.	[70]
Hybrid-Channel	Enhanced rural healthcare	Enabled hybrid-channel communication for rural healthcare.	[66]
Metaheuristics	Efficient healthcare systems	Utilized metaheuristics for efficient healthcare systems.	[67]
Patient-Centric	Patient-centric healthcare	Proposed key requirements for patient-centric healthcare.	[81]
	Enhanced healthcare assistance	Developed a secure smart healthcare assisting system.	[75]
	Efficient contact tracing	Implemented blockchain-based health passports and contact tracing.	[82]
	Streamlined asthma healthcare	Designed a consortium framework for asthma healthcare.	[83]

5.4. Blockchain and the Management of Medical Data

The creation of a cutting-edge EMR integrity management system based on a specific blockchain platform within hospitals is one such possibility. This strategy improves confidence and data dependability by ensuring the security and authenticity of Electronic Medical Records (EMRs) [84]. For collaborative healthcare, effective data sharing is essential, and MedChain provides a solution by utilizing blockchain to make data exchange simple and secure [49]. Furthermore, as illustrated by a cutting-edge medical blockchain model, blockchain is essential in addressing drug supply chain integrity within smart hospitals. To improve patient safety and regulatory compliance, this concept establishes transparency and traceability in drug-related information [85]. Smart contracts are established using a blockchain-based system that automates predefined rules and agreements among multiple stakeholders to optimize healthcare management [23].

A secure end-to-end data security approach for exchanging personal health records is made possible by the combination of completely homomorphic encryption with blockchain, protecting sensitive data while encouraging data collaboration [86]. To improve data security and secrecy, proxy re-encryption is also investigated in a safe outsourced blockchain-based medical data exchange system [53]. A blockchain-based method for preserving healthcare data that complies with HIPAA laws uses extended chaotic maps to meet privacy and security standards [55].

Dual-channel blockchain architecture based on Hyperledger Fabric is suggested for electronic health record (EHR) administration to scale up medical data management while guaranteeing effectiveness and security [87]. Access control and privacy are elevated even higher in blockchain-based systems with biometric authentication [87]. These security measures are essential for maintaining the accuracy and privacy of medical data across the whole blockchain-based healthcare ecosystem.

Finally, blockchain technology is combined with Cyber Safeguard safeguards to create a decentralized, reliable healthcare administration system. In the era of Industry 4.0, this integration strengthens the system against future cyber threats [73]. To promote interoperability, share EHRs among healthcare providers, and improve patient care, HealthBlock offers a collaborative platform [88]. A lightweight blockchain system leveraging practical Byzantine fault tolerance (PBFT) consensus is developed in the pursuit of a safe and effective healthcare application [89].

5.5. Blockchain and AI in Healthcare

Blockchain and AI are two game-changing technologies that have the potential to completely disrupt the healthcare sector. The incorporation of these technologies to address diverse difficulties in healthcare systems is explored in several research articles. The first group of articles focuses on the integration of blockchain with artificial neural networks (ANN) to improve the management and analysis of individual health records [90]. This research seeks to protect the integrity and privacy of private medical data by fusing the pattern recognition abilities of AI with the data security and transparency offered by blockchain.

The idea of metaverse technology, which builds immersive virtual environments and integrates AI and blockchain for medical diagnosis and treatment, is covered in a different set of articles [69,91]. This strategy can enhance patient care, give healthcare workers reliable and precise insights, and guarantee data security thanks to blockchain's immutable ledger. Additionally, researchers investigate the use of blockchain and federated learning to offer in-home health monitoring [68]. The analysis of dispersed healthcare data sources is made possible by this combination, which guarantees that AI models may develop and evolve without compromising data privacy.

These papers also provide insight into how decentralized data management and access control enabled by blockchain might improve outdated healthcare systems [92]. Transparency and security offered by blockchains improve interoperability between healthcare stakeholders, empowering patients and enabling effective care delivery. Large amounts of dispersed healthcare data can be examined with the help of AI integration, producing insightful findings and individualized care.

Despite the tremendous potential of combining blockchain and AI in healthcare, difficulties still exist. It is important to address scalability, legal compliance, and seamless system interaction [93]. Nevertheless, current studies and innovations in this area show an increased interest in using these technologies to improve patient care, diagnosis, and management of healthcare data.

5.6. Blockchain and Health Supply Chain Management

Healthcare supply chain management has been transformed by blockchain technology, which addresses a variety of issues faced by the sector. One noteworthy contribution is a revolutionary medical blockchain model designed exclusively for managing the integrity of the drug supply chain in a smart hospital setting [85]. By assuring the secure recording and tracking of pharmaceutical items throughout their lifecycle, this method increases traceability and authenticity, lowers the risk of counterfeit pharmaceuticals, and improves patient safety.

Another study evaluates the value of blockchain technology in supply chains for luxury goods, food, and healthcare from a broader viewpoint [94]. This analysis demonstrates how blockchain technology has the potential to improve authenticity, traceability, and

transparency in healthcare supply chains, giving stakeholders the information they need to decide whether to implement it and what kind of return on investment to expect. Additionally, a distributed information hiding system built on a blockchain solves the crucial issue of data privacy in medical supply chains [95]. Sensitive medical data is protected by using smart contracts and advanced cryptography techniques, which enable authorized parties to access some information while preventing unauthorized access.

Healthcare-Chain is a comprehensive solution that combines blockchain technology with Industry 4.0 technologies like IoT devices, AI, and cybersecurity measures to build a decentralized and reliable system for managing the healthcare supply chain [73]. The efficiency of the supply chain is increased because of the smooth data gathering and analysis made possible by this integrated method, which also guarantees data validity, integrity, and safe data exchange across stakeholders. These research papers collectively contribute to improving the reliability, security, and effectiveness of healthcare supply chains by incorporating blockchain's transparency, data immutability, and privacy features. In turn, this benefits patients, healthcare providers, and other stakeholders involved in the management of medical products and data.

5.7. Challenges

The potential of blockchain technology to improve data management, privacy, and security has attracted considerable attention in the healthcare sector. However, there are several obstacles to its acceptance. The diversity of healthcare data is one of the main obstacles [48,62]. Electronic health records and medical photographs are just two examples of the sources of structured and unstructured healthcare data, which calls for a standardized approach for effective integration and storage on the blockchain. Another significant challenge is the protection of patient privacy and data security, as highlighted in studies by Yang et al. [50] and Fu et al. [77]. While immutability and openness are guaranteed by blockchain, it needs to also ensure that private, sensitive health information is only accessible to those who are allowed to view it. Additionally, it is important to ensure interoperability between various healthcare systems and devices, as discussed in studies by Figueroa et al. [59] and Kerrison et al. [66]. Robust interoperability solutions are needed for seamless data sharing and communication between the various healthcare providers and systems.

Another key problem is scalability, as demonstrated by Ngabo et al. [96] and Islam et al. [73]. The blockchain network needs to be able to accommodate increasing transaction rates without affecting performance as the number of healthcare data grows. The highly regulated healthcare sector further emphasizes the importance of regulatory compliance in studies by Jamil [85] and Fusco et al. [74]. For blockchain deployments to be compliant with stringent data protection laws like HIPAA and GDPR, careful design and compliance mechanisms are needed.

According to the studies by Sonkamble et al. [80] and Ismail and Materwala [97] integrating blockchain technology with the current healthcare infrastructure is a difficult task. Since many healthcare facilities currently have legacy systems in place, meticulous preparation is necessary to ensure seamless transfer and backward compatibility. Additionally, as discussed in studies by Jo et al. [56] and Ahmed et al. [98] addressing the energy consumption concerns of blockchain technology, particularly proof-of-work consensus, is crucial. Healthcare firms need to consider green and energy-efficient blockchain solutions.

6. Conclusions and Future Directions

The key characteristics, potential advantages, and applications of blockchain technology in the healthcare sector have been highlighted during the past five years through a critical review of its development and difficulties. Blockchain holds promise for changing healthcare by enabling safe data management, interoperability, and patient-centric treatment thanks to its decentralized, unchangeable, and transparent nature. The system has a wide range of possible uses, including improving supply chain management, avoiding

fraud, and managing clinical trials and medical data. The assessment of increased efficacy and efficiency has demonstrated appreciable advancement, showing improved data protection, streamlined procedures, and possible cost savings in healthcare operations. To fully realize the potential of blockchain, however, issues including interoperability, regulatory issues, scalability, and standards must be resolved. Collaboration between healthcare professionals, policymakers, technologists, and patients is necessary for successful integration. Blockchain technology has the potential to lead to a revolutionary change in healthcare, ushering in a period of enhanced data security, interoperability, and ultimately better patient care.

While the review has provided valuable insights into blockchain's current and prospective impact on healthcare, broader research directions are required to completely comprehend the technology's adaptability. Exploration of how blockchain can intersect with emergent disciplines such as AI and machine learning to enable secure data exchange and transparent AI algorithm validation is needed in the future. In addition, investigating causal inference in healthcare data, blockchain's applications in unique environments such as underwater IoT, and its potential in the aerospace, airspace, and finance industries can yield insightful information. Future research can demonstrate the multifaceted nature of blockchain technology by incorporating these diverse domains, thereby fostering collaboration among stakeholders and resulting in transformative changes not only in the healthcare sector but also in other industries.

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