Trends in Health Informatics

www.thi.reapress.com

THI. Vol. 2, No. 2 (2025) 98–107.

Paper Type: Original Article

Leveraging Blockchain Technology for Secure and Interoperable Health Information Exchange: Opportunities and Challenges

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Citation:

Received: 25 August 2024 *Revised: 22 October 2024* *Accepted: 29 December 2024*	Kazemi, M. H. (2025). Leveraging blockchain technology for secure and interoperable health information exchange: Opportunities and challenges. *Trends in health informatics*, 2(2), 98-107.

Abstract

The integration of blockchain technology into health information systems presents a promising avenue for enhancing security, transparency, and interoperability in healthcare data exchange. Traditional Health Information Exchanges (HIEs) often face challenges related to data fragmentation, privacy breaches, and lack of standardized protocols, which can compromise patient safety and hinder efficient care delivery. Blockchain, with its decentralized ledger structure, cryptographic security, and immutable record-keeping, offers solutions to these challenges by enabling secure, auditable, and patient-controlled data sharing.

This article explores the potential applications of blockchain in facilitating interoperable HIE across multiple healthcare providers. It highlights opportunities such as improving data integrity, enabling real-time access to patient records, and supporting consent management through smart contracts. However, the implementation of blockchain in healthcare is accompanied by significant challenges, including scalability issues, high computational costs, regulatory uncertainty, and integration with existing Electronic Health Record (EHR) systems.

Future research and practical deployment should focus on hybrid approaches that combine blockchain with traditional HIE frameworks, standardized interoperability protocols, and privacy-preserving techniques. By addressing these challenges, blockchain can significantly enhance secure data sharing, support informed clinical decision-making, and pave the way for more connected and patient-centered digital health ecosystems.

Keywords: Blockchain, Health informatics, Interoperability, Health information exchange, Data security.

1 | Introduction

In recent decades, the digitization of healthcare systems worldwide has resulted in a dramatic increase in the volume and heterogeneity of health-related data; ranging from Electronic Health Records (EHRs), laboratory results, clinical imaging, to data generated by wearable devices and Internet-of-Medical-Things (IoMT) sensors. This expanding data landscape holds significant promise for improving patient care, supporting

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https://doi.org/10.22105/thi.vi.36

clinical research, and enabling data-driven decision-making. Nevertheless, a persistent and critical challenge remains: data fragmentation. Health data are often stored in disparate, siloed systems across different providers, care settings, and infrastructures; a condition that undermines continuity of care, complicates comprehensive access to patient histories, and hinders effective information exchange across stakeholders [1].

Conventional Health Information Exchange (HIE) frameworks typically rely on centralized or semi-centralized architectures. In such models, each institution maintains its own repository, and data sharing depends on bilateral agreements or gateways. While these methods provide a route for information exchange, they are afflicted by well-known drawbacks: susceptibility to single points of failure, risk of unauthorized access or data breaches, inconsistent data standards, and substantial administrative and maintenance overheads.

Moreover, recent global trends such as the COVID-19 pandemic have highlighted the urgent need for rapid, reliable, and secure data sharing across multiple healthcare organizations. Delays or failures in exchanging critical health information can directly affect patient outcomes, public health monitoring, and timely response to emerging health crises [2]. These developments have increased the attention of both policymakers and technologists toward novel approaches like blockchain for overcoming data silos.

In this context, blockchain technology emerges as a compelling paradigm for transforming health information systems. With its core properties (distributed ledger, immutability, cryptographic security, transparency, and consensus-based validation), blockchain offers a foundation for a secure, tamper-resistant, and auditable record of health transactions. Through decentralized architecture, blockchain can eliminate single points of failure and central authority biases, enabling stakeholders to share and validate data without a trusted central intermediary [3], [4].

Blockchain's potential extends beyond mere data storage. By combining smart contracts, cryptographic keys, and distributed consensus, it can enable automated compliance with access policies, patient-consent enforcement, and traceable data usage. Such capabilities are increasingly relevant as healthcare systems generate massive amounts of sensitive data from multiple sources, including genomic sequencing, IoMT devices, and telemedicine platforms [5].

A growing body of empirical and review literature underscores the potential benefits of blockchain in healthcare. A systematic review of blockchain applications in health information systems found that most implementations concentrate on EHRs, with identified advantages including enhanced data integrity, privacy, and interoperability [3]. Another scoping review highlighted that blockchain can enable patient-centric data governance, personalized healthcare, secure health data tracking, and improved organizational-level functions such as HIE, pharmaceutical supply chain integrity, and insurance management [5]. Moreover, qualitative studies gathering physicians' perspectives reveal optimistic expectations: improved encryption and access control, stronger data consistency, and enhanced interoperability that supports collaboration across providers [6].

However, as with any emerging technology, significant barriers remain before blockchain-based HIE can become mainstream. Key challenges include technical limitations such as scalability, transaction throughput and latency, as well as performance issues when integrating blockchain with existing legacy EHR systems [7], [8]. Interoperability, not only between blockchain-based and legacy health IT systems, but also among different blockchain implementations, remains a major concern, primarily due to the absence of widely accepted standards and heterogeneous data formats [7]. Additionally, regulatory, privacy, and data governance issues complicate adoption, especially in jurisdictions with stringent data protection laws [9], [10]. Finally, questions around the readiness level of blockchain solutions, their cost-effectiveness, and long-term maintainability remain largely open [11].

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enforcement, and traceable data usage. Such capabilities are increasingly relevant as healthcare systems generate massive amounts of sensitive data from multiple sources, including genomic sequencing, IoMT devices, and telemedicine platforms [5].

Given the critical importance of secure and interoperable health data exchange for enhancing care quality, patient safety, and system efficiency (particularly in an era of increasingly distributed care models and global digital health transformation), a comprehensive examination of blockchain's real potential is both timely and necessary. In this article, we aim to review the current state of blockchain-based HIE, articulate the opportunities it presents, and critically analyze the challenges and obstacles hindering its widespread adoption.

The primary objective of this study is to explore the potential of blockchain technology for secure and interoperable HIE. Specifically, the article aims to: 1) review current implementations of blockchain in healthcare systems, 2) identify the opportunities and benefits that blockchain offers for enhancing data security, privacy, and interoperability, and 3) analyze the challenges, limitations, and barriers that hinder its widespread adoption [3], [4]. By systematically addressing these aspects, the study seeks to provide insights for both researchers and healthcare practitioners on the practical and theoretical implications of adopting blockchain for HIE [5].

In addition, this article integrates recent findings and emerging trends in blockchain-based HIE, aiming to provide a forward-looking perspective on its feasibility, scalability, and potential for broader adoption across diverse healthcare contexts.

The remainder of this article is organized as follows. Section 2 provides the technical background and fundamental concepts of blockchain relevant to health information systems. Section 3 examines the applications and potential benefits of blockchain-based HIE. Section 4 discusses the key challenges, limitations, and barriers associated with blockchain adoption. Finally, Section 5 presents a discussion of the implications, future research directions, and concluding remarks [6], [9].

2 | Blockchain in Healthcare: Technology and Opportunities

Blockchain technology has emerged as a transformative tool in the healthcare domain, offering solutions to longstanding challenges in security, data integrity, and interoperability. To fully understand its potential, it is essential to examine both the underlying technical mechanisms and the practical applications that can be realized in HIE. The following subsections provide a structured exploration: first, the technical overview of blockchain in healthcare details the core components, architectures, and operational principles of blockchain systems relevant to medical data. Second, the applications and opportunities of blockchain in HIE discusses real-world use cases, benefits for stakeholders, and the opportunities this technology brings to patient-centered, secure, and interoperable healthcare systems.

Recent advances in digital health, including the proliferation of IoMT devices, telemedicine platforms, and cross-institutional EHR systems, have amplified the need for secure and interoperable data sharing. Blockchain offers a promising framework to address these challenges while supporting patient-centered care, data provenance, and regulatory compliance.

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2.1 | Technical Overview of Blockchain in Healthcare

Blockchain is a distributed ledger technology that enables secure, transparent, and tamper-resistant recording of transactions without relying on a central authority [12]. In essence, a blockchain consists of a chain of blocks, each containing a list of transactions, a timestamp, and a cryptographic hash of the previous block.

This structure ensures immutability: once data are recorded in a block, altering them retroactively would require modifying all subsequent blocks, which is computationally infeasible in large decentralized networks [4].

In healthcare, blockchain offers several features that address long-standing challenges in HIE. First, decentralization eliminates single points of failure, enhancing system resilience. Second, cryptographic security protects sensitive health data from unauthorized access, while maintaining a verifiable audit trail. Third, consensus mechanisms (such as Proof-of-Work (PoW), Proof-of-Stake (PoS), or Practical Byzantine Fault Tolerance (PBFT)) ensure that all participants in the network agree on the validity of transactions [3], [8].

Blockchain implementations in healthcare typically use either public, private, or consortium models. Public blockchains are fully open and allow any participant to validate transactions; private blockchains restrict access to approved entities, offering greater privacy and control; consortium blockchains are partially decentralized and controlled by a group of trusted organizations [13]. In health information systems, permissioned (private or consortium) blockchains are most commonly adopted due to the sensitive nature of medical data and the need to comply with privacy regulations [6].

Furthermore, hybrid blockchain models are emerging, combining the strengths of public and private networks to optimize transparency, scalability, and access control. These hybrid solutions can allow selective data sharing between trusted healthcare entities while preserving patient privacy and enabling auditability across the network.

Another key aspect is smart contracts, self-executing programs stored on the blockchain that automatically enforce predefined rules and agreements. In healthcare, smart contracts can be used for consent management, ensuring that patient data are shared only with authorized parties under agreed conditions. They can also automate insurance claim processing, track medication supply chains, and monitor remote patient data from IoMT devices [3], [4].

In addition, blockchain can support advanced functionalities such as clinical trial data management, provenance tracking for medical devices, and integration with AI-powered analytics, enabling more reliable predictive models and evidence-based decision-making.

Despite its advantages, blockchain adoption in healthcare faces technical and operational limitations. Scalability remains a major concern, as transaction throughput in most blockchain networks is limited compared to traditional databases. Integration with legacy EHR systems is challenging due to data heterogeneity, interoperability standards, and governance issues [7]. Furthermore, energy consumption, transaction costs, and regulatory uncertainties complicate large-scale deployment [8], [9].

Organizational factors, such as clinician training, workflow adaptation, and stakeholder buy-in, are equally critical. Without adequate change management and end-user engagement, even technically robust blockchain solutions may fail to achieve meaningful adoption and operational impact.

In summary, blockchain provides a robust technological foundation for secure, transparent, and interoperable HIE, yet its practical application requires careful consideration of architecture, governance, scalability, and compliance. The following section discusses the specific applications and opportunities of blockchain in healthcare.

2.2 | Applications and Opportunities of Blockchain in Health Information Exchange

Blockchain technology offers a wide range of applications in HIE, promising enhanced security, transparency, and patient-centered data governance. One of the primary applications is in EHRs. By storing patient records on a blockchain, healthcare providers can ensure data immutability and integrity, preventing unauthorized alterations while maintaining a verifiable audit trail [3]. Blockchain also allows for real-time access and sharing of health data across institutions, which is critical for coordinated care and emergency response scenarios [4].

Blockchain also allows for real-time access and sharing of health data across institutions, which is critical for coordinated care and emergency response scenarios [4]. Additionally, it supports secure cross-institutional data interoperability, addressing the challenges posed by disparate EHR systems and inconsistent data formats. This capability ensures that healthcare professionals can access reliable and up-to-date patient information regardless of their organization [7].

Another significant opportunity lies in patient-centered data control. Smart contracts enable patients to dynamically manage access permissions to their medical records, determining which providers or organizations can view or modify specific data. This fosters trust, enhances privacy, and aligns with regulatory requirements such as HIPAA and GDPR [5], [6]. Patients can also benefit from personalized healthcare services, as blockchain facilitates secure sharing of wearable device data, remote monitoring results, and genomic information, allowing providers to tailor interventions based on comprehensive and trustworthy datasets [3].

Patients can also benefit from personalized healthcare services, as blockchain facilitates secure sharing of wearable device data, remote monitoring results, and genomic information, allowing providers to tailor interventions based on comprehensive and trustworthy datasets [3]. This integration of diverse data sources not only supports precision medicine but also enables predictive analytics, allowing healthcare providers to anticipate potential health risks and implement preventive measures proactively.

Blockchain also supports interoperability across heterogeneous healthcare systems. Traditional HIE frameworks struggle with inconsistent data standards and incompatible infrastructures. By serving as a decentralized and standardized platform, blockchain can bridge these gaps, enabling seamless data exchange between hospitals, clinics, laboratories, insurers, and public health organizations [7]. Additionally, blockchain can improve supply chain management and clinical trial data integrity, ensuring transparency in pharmaceutical distribution and reliable reporting of research outcomes [8]. Moreover, blockchain facilitates secure, automated, and auditable insurance claims processing. Smart contracts can trigger payments and record claim events automatically once predefined conditions are met, reducing administrative burden and fraud risk [4]. This not only benefits providers and insurers but also ensures timely reimbursement for patients.

In summary, blockchain offers a wide range of transformative opportunities for HIE, encompassing enhanced security, patient empowerment, improved interoperability across diverse healthcare systems, and greater operational efficiency. While these applications demonstrate considerable potential, their successful implementation and widespread adoption require careful attention to technical limitations, regulatory compliance, and organizational readiness. These critical challenges, along with potential strategies to address them, will be discussed in detail in the following section, providing a roadmap for effective deployment of blockchain technologies in healthcare settings.

2.3 | Challenges and Limitations of Blockchain in Health Information Exchange

Despite its promising applications, the adoption of blockchain in HIE faces several technical, organizational, and regulatory challenges. One of the primary technical limitations is scalability. Most blockchain networks, especially those using PoW consensus mechanisms, have limited transaction throughput compared to traditional centralized databases. This can result in latency when processing large volumes of healthcare transactions, which is critical for real-time access in clinical settings [7], [8].

Another significant technical challenge is integration with existing EHR systems. Legacy health IT infrastructures are often heterogeneous and use non-standardized data formats. Integrating blockchain requires complex interoperability solutions, mapping between different data schemas, and ensuring consistency across distributed networks [3]. Furthermore, blockchain implementations must comply with privacy regulations such as HIPAA in the United States and GDPR in Europe, which adds additional layers of complexity to system design [5], [9].

Operational and organizational barriers also impede blockchain adoption. Healthcare institutions may lack the necessary technical expertise, financial resources, or leadership commitment to implement blockchain solutions at scale. Energy consumption and transaction costs, particularly in public blockchain models, present economic and environmental concerns [8]. Additionally, the absence of universally accepted standards for blockchain in healthcare complicates governance, liability, and data stewardship responsibilities among multiple stakeholders [6], [7].

Finally, user acceptance and workflow adaptation remain crucial challenges. Clinicians and administrative staff must be trained to interact with blockchain-enabled systems, and patient engagement must be ensured for consent management and data sharing. Without effective adoption strategies, the theoretical benefits of blockchain may not translate into tangible improvements in care quality or operational efficiency [4].

In addition to the previously discussed limitations, cybersecurity and privacy risks remain among the most critical challenges for blockchain-based HIE implementations. Although blockchain ensures immutability and decentralization, it does not automatically eliminate vulnerabilities associated with smart contracts, node security, or off-chain data storage. For example, recent systematic reviews highlight that even blockchain-based healthcare systems may suffer from privacy leakage, pseudonymization issues, and risks to Personally Identifiable Information (PII) if appropriate privacy-preserving mechanisms are not carefully designed and enforced. Moreover, the increasing frequency of data breaches in traditional centralized healthcare databases underscores the need for robust end-to-end security: transitioning to blockchain does not guarantee immunity to all attacks unless smart contract code, access controls, and off-chain data interfaces are rigorously audited and secured [14], [15].

Furthermore, regulatory ambiguity, lack of standardized governance frameworks, and cross-jurisdictional legal constraints significantly hinder the large-scale adoption of blockchain in healthcare. The decentralized and immutable nature of blockchain may conflict with legal requirements such as the right to be forgotten, data deletion requests, or regulations that mandate revocability of user consent. Several authors have noted that without clear legal frameworks and internationally accepted standards, stakeholders may face liability, data stewardship, and compliance challenges; especially in cross-institutional or cross-border data sharing scenarios [16], [17]. As a result, collaborative efforts among policymakers, healthcare institutions, and technology providers are essential to define legal, ethical, and technical guidelines before blockchain-based HIE systems can be confidently deployed at scale.

In conclusion, while blockchain has transformative potential for HIE, its real-world implementation requires careful planning to address scalability, interoperability, regulatory compliance, organizational readiness, and user adoption. The following section will discuss future directions, implications, and strategies to overcome these challenges.

3 | Future Directions and Recommendations

Despite the challenges outlined in the previous section, there are several promising pathways to enhance the feasibility and effectiveness of blockchain-based HIE systems. First, from a technical perspective, the adoption of hybrid or permissioned blockchain architectures and scalability-focused solutions should be prioritized. For instance, frameworks such as Hyperledger Fabric (a permissioned blockchain designed for enterprise use) offer better performance, privacy controls, and flexibility compared to public blockchains, making them more suitable for healthcare environments with high throughput and stringent confidentiality requirements. Likewise, employing Layer-2 scaling solutions or sharding techniques could alleviate throughput limitations and reduce latency in data-intensive settings such as hospitals or telemedicine platforms [14], [15].

Moreover, integration with complementary technologies can significantly augment blockchain's value in HIE. Combining blockchain with privacy-preserving analytics, Federated Learning, and edge- or IoT-based health monitoring can enable secure, decentralized data sharing without exposing raw personal health information. For example, hybrid models have been proposed that leverage federated learning to perform analytics on distributed medical data while blockchain ensures integrity, access control, and accountability. Such convergence could facilitate advanced functionalities; like remote monitoring of chronic diseases, predictive analytics, and personalized medicine, while respecting privacy constraints [16], [17].

From a governance and regulatory standpoint, the development of clear legal frameworks, data-sharing standards, and interoperability protocols is essential. The absence of universally accepted standards for blockchain in healthcare (both at the technical and regulatory levels) remains a major barrier to cross-institutional or cross-border HIE. Stakeholders including policymakers, healthcare organizations, technology providers, and standards bodies should collaborate to define standardized data formats, consent mechanisms, smart-contract governance models, and compliance guidelines (e.g., aligning with data-protection regulations such as GDPR or HIPAA). Such coordinated efforts would build trust, facilitate adoption, and reduce legal uncertainties for institutions considering blockchain deployment.

Finally, pilot studies, real-world implementations, and continuous evaluation are crucial to move beyond theoretical promise. While many proposed blockchain-based health solutions remain at concept or proof-of-concept stage, empirical evidence from operational deployments; especially in diverse healthcare settings (hospitals, clinics, telehealth, cross-institutional networks), is limited. Systematic reviews emphasize the need for clinical validation, usability studies, performance benchmarking, and privacy auditing under real-world conditions as prerequisites for wider adoption. Researchers should therefore prioritize implementing pilot projects, assessing their impact on data security, interoperability, cost, workflow integration, and user acceptance, and publishing their findings to inform future large-scale rollouts [14], [15].

Table 1 provides a comprehensive overview of the key recommendations for implementing blockchain-based HIE systems, categorizing strategies across technical, regulatory, and user-centered dimensions. The table highlights measures designed to enhance system scalability, ensure data privacy, promote interoperability, and facilitate adoption among healthcare providers and patients.

Table 1. Key recommendations for blockchain-based HIE.

Recommendation	Rationale	Benefit
Adopt hybrid or permissioned blockchain architectures	Addresses scalability and energy consumption issues in healthcare environments	Faster transaction processing, better security, and controlled access management
Implement Layer-2 solutions or sharding	Reduces latency in high-volume transactions	Enables efficient operation in hospitals and telemedicine platforms
Integrate blockchain with IoT and federated learning	Preserves privacy and enables decentralized analytics	Personalized healthcare, disease prediction, and remote patient monitoring
Develop legal frameworks and international standards	Lack of globally accepted standards for blockchain-based HIE	Reduces legal risk, ensures compliance, and increases organizational trust
Provide training for users (staff and patients)	User adoption and insufficient knowledge hinder effective use	Higher patient engagement, efficient staff use, and reduced human errors
Conduct pilot projects and real-world evaluation	Most blockchain HIE solutions are still in proof-of-concept	Empirical evidence for performance, security, and user acceptance before large-scale deployment
Audit and secure smart contracts	Cybersecurity risks and coding vulnerabilities	Reduces unauthorized access, preserves privacy, and builds trust

In summary, blockchain technology offers transformative potential for HIE by enhancing security, ensuring data integrity, empowering patients, and facilitating interoperability across heterogeneous healthcare systems. Section 2 highlighted the main applications of blockchain in EHRs, patient-centered data management, and healthcare analytics, while also discussing the technical, organizational, and regulatory challenges that may impede adoption. Furthermore, future directions and recommendations were provided, emphasizing scalable technical architectures, integration with complementary technologies such as IoT and federated learning, the development of standardized legal and governance frameworks, and strategies to increase user acceptance and adoption. Collectively, these insights underscore that while blockchain-based HIE solutions hold significant promise, their successful implementation requires careful planning, robust regulatory compliance, and collaborative efforts among all stakeholders to translate theoretical benefits into practical, real-world improvements in healthcare delivery.

4 | Discussion and Implications

The analysis in the previous section demonstrates that while blockchain holds substantial promise for transforming HIE, via enhanced data security, patient empowerment, interoperability, and operational efficiency, there remain significant impediments to its widespread adoption. Technical constraints (e.g., scalability, integration with heterogeneous EHR systems), regulatory uncertainty, and organizational readiness are non-trivial barriers. As many authors note, the immutability and distributed nature of blockchain may conflict with data-protection laws (e.g., the right to be forgotten under privacy regulations) and complicate cross-institutional or cross-border data sharing [18], [19].

Given these challenges, it becomes clear that a purely technological upgrade is insufficient. The successful deployment of blockchain-based HIE systems requires an integrated strategy combining technological innovation with robust governance, clear legal and ethical frameworks, and stakeholder engagement. In particular, collaborative efforts among regulators, healthcare institutions, technology developers, and standards-setting bodies are essential to define standardized data formats, consent mechanisms, smart-contract governance models, and compliance guidelines [13], [20].

From a research and practice perspective, the literature suggests that empirical validation through pilot implementations, real-world deployments, and rigorous evaluation should be prioritized. Systematic reviews indicate that while blockchain's theoretical advantages are widely recognized, most existing work remains at conceptual or proof-of-concept stages, with limited data on real performance, usability, compliance, and sustainability in operational healthcare environments [19]. Only through such practical applications (coupled with continuous monitoring, auditing, and user feedback) can the actual benefits and trade-offs of blockchain in HIE be properly assessed, and guidelines refined to ensure safe, effective, and scalable adoption.

5 | Conclusion

In conclusion, blockchain technology presents significant opportunities for advancing HIE by enhancing security, ensuring data integrity, facilitating interoperability, and empowering patients to manage their own health information. This paper reviewed the primary applications of blockchain in EHRs, patient-centered data management, healthcare analytics, and insurance processing, while also examining technical, organizational, and regulatory challenges that may hinder adoption [3–5], [8]. Future directions emphasize scalable architectures, integration with complementary technologies such as IoT and federated learning, standardized legal and governance frameworks, and strategies for user engagement to ensure successful implementation [13], [16], [17]. Despite the promising potential, practical deployment of blockchain-based HIE systems requires empirical validation through pilot studies, careful attention to regulatory compliance, and collaborative efforts among stakeholders to bridge the gap between theoretical benefits and real-world healthcare improvements [19], [20]. Overall, this study highlights that blockchain, when thoughtfully implemented, can serve as a transformative tool for modern healthcare delivery, while ongoing research is essential to address existing limitations and optimize system performance.

Funding

This research received no external funding.

Data Availability

All data are included in the text.

Conflicts of Interest

The author confirm that there are no conflicts of interest related to the research or its publication.

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