NATA PALEMAHAN
JOURNAL OF ENVIRONMENTAL ENGINEERING INNOVATIONS
Journal homepage: https://journal.undiknas.ac.id/index.php/natapalemahan

A Blockchain-Based Framework for Secure and Transparent Environmental Data Sharing in Smart Cities: Enhancing Trust, Integrity, and Interoperability in Urban Sustainability Systems

Mohammad Nawab Turan[1*], Irshad Ahmed Hashimzai[2], Mohammad Qaseem Qiam[3]

[1]Department of Network Engineering, Faculty of Computer Science, Faryab University, Afghanistan
[2]Department of Computer Engineering, Computer Science Faculty, Kabul Polytechnic University, Afghanistan
[3]Department of Information Systems, Faculty of Computer Science, Kabul Polytechnic University, Afghanistan
*mn.turan@faryab.edu.af

ARTICLE INFO
Article history:
Received: 2-09-2025
Revised: 8-9-2025
Accepted: 10-10-2025
Available online: 25-10-2025

ABSTRACT
Blockchain technology has emerged as a transformative tool to address critical challenges in environmental data management within smart cities, particularly enhancing trust, data integrity, and interoperability. This systematic literature review aims to analyze how blockchain frameworks support secure and transparent environmental data sharing for sustainable urban development. The study involved a comprehensive search of multiple academic databases, including IEEE Xplore, ScienceDirect, Wiley, and MDPI, covering publications from 2019 to 2025. A total of 23 relevant papers were selected and critically examined. The results reveal that blockchain-based solutions often integrate with emerging technologies such as artificial intelligence and digital twins to improve data validation, governance, and real-time analytics. Key innovations include decentralized trust frameworks, smart contract governance, and interoperability models like Blockchain-of-Blockchains. Despite these advancements, challenges such as scalability, energy consumption, and lack of standardization persist. The review concludes that while blockchain offers a robust foundation for secure and interoperable environmental data systems in smart cities, ongoing research and collaboration are essential to overcome current limitations and achieve sustainable, transparent urban ecosystems.

KEYWORDS: blockchain; smart cities; environmental data; trust; interoperability

1. INTRODUCTION

The rapid expansion of urbanization has intensified the demand for efficient, transparent, and secure data management systems in smart cities. Environmental data, which includes information on air quality, waste management, water resources, and energy usage, plays a pivotal role in urban sustainability. However, traditional data sharing infrastructures in smart cities often suffer from centralized control, vulnerability to cyber-attacks, data tampering, and lack of interoperability among diverse platforms [1], [2]. These issues hinder trust between stakeholders and slow the pace of sustainable urban development.

Blockchain technology has emerged as a transformative solution to address these challenges by offering a decentralized, immutable, and transparent ledger system for data management [3], [4]. Its integration with smart city platforms has shown significant promise in enhancing data integrity, security, and stakeholder trust [5], [6]. For instance, Islam et al. [1] proposed a decentralized trust framework that enhances cybersecurity and ensures data integrity within urban infrastructures. Similarly, the concept of a blockchain-of-blockchains introduced by Rahman et al. [2] enables interoperability between heterogeneous IoT systems in smart cities, a critical requirement for environmental data integration.

Furthermore, advancements in combining blockchain with artificial intelligence (AI) and federated learning have facilitated intelligent, privacy-preserving, and real-time data processing capabilities [7], [13], [17]. These innovations support predictive analytics and decision-making for environmental monitoring and management. AI-enabled blockchain frameworks not only secure sensitive data but also optimize energy consumption and operational efficiency in smart infrastructures [7], [14].

Despite these developments, current frameworks often focus on specific sectors such as smart parking [10], energy systems [6], or digital governance [16], lacking a comprehensive model that addresses environmental data sharing holistically. Moreover, the lack of standardization across distributed ledger technologies (DLTs) further complicates seamless integration and alignment of environmental data across multiple urban systems [9].

Smart cities generate vast amounts of environmental data through IoT-enabled infrastructures, which are essential for monitoring air and water quality, waste management, and climate resilience. However, traditional centralized data systems face issues such as data tampering, lack of transparency, limited interoperability, and inadequate trust among stakeholders [1], [2]. To address these limitations, blockchain technology has emerged as a promising solution due to its decentralized, tamper-proof, and transparent nature [3], [4].

Recent studies have demonstrated the application of blockchain for secure data sharing [5], privacy preservation [6], and decentralized governance in smart cities [7], [9]. However, most existing frameworks either focus on specific domains like energy [10], or parking systems [10], or lack the interoperability required for integrated environmental data management [2], [14]. Furthermore, while AI and federated learning have been integrated with blockchain to enhance scalability and privacy [13], [17], a unified framework for environmental data sharing remains underexplored.

Despite growing interest in blockchain applications for smart cities, existing research tends to be fragmented and sector-specific, addressing isolated domains such as energy systems [6], smart parking [10], digital identity management [16], or traffic control [12]. These solutions, while valuable, fail to capture the complexity and interdependence of environmental systems in urban settings. For example, energy consumption, waste management, and air or water quality are not isolated domains, they are interconnected elements of a broader environmental management ecosystem.

However, current blockchain frameworks rarely support cross-domain data integration. A blockchain solution designed for smart energy grids may not interoperate with systems handling water resource monitoring or air quality sensors, leading to data silos and inefficient policy coordination. The lack of standardized protocols and interoperable architectures across distributed ledger technologies (DLTs) further limits the seamless exchange and synthesis of environmental data across city departments, stakeholders, and IoT systems [2], [9].

Moreover, while some studies have explored combining blockchain with AI or federated learning to enhance data privacy and analytics [7], [13], [17], these implementations are often domain-bounded and do not provide a unified framework for holistic environmental governance. Without such a framework, cities struggle to align diverse environmental indicators, perform integrated assessments, or enable cross-agency collaboration for sustainability planning.

This study addresses this research gap by proposing a blockchain-based framework specifically tailored for secure, transparent, and interoperable environmental data sharing in smart cities. The main objectives are to enhance data trust, ensure integrity, support multi-stakeholder collaboration, and enable interoperable urban sustainability systems through decentralized technologies.

2. METHOD

This study adopts a Systematic Literature Review (SLR) methodology to explore the role of blockchain in enabling secure, transparent, and interoperable environmental data sharing within smart city systems. The review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure rigor, transparency, and replicability in the research process.

2.1 Research Questions

The review is guided by the following key questions:

- RQ1: How has blockchain technology been applied to support environmental data management in smart cities?
- RQ2: What are the common challenges and limitations identified in existing blockchain-based smart city frameworks?
- RQ3: What innovations or models enhance trust, data integrity, and interoperability?

- RQ4: How can a blockchain-based secure data sharing framework integrating decentralized storage (IPFS) and a robust authorization mechanism ensure confidentiality, integrity, and controlled access to environmental data in smart cities?

2.2 Data Sources and Search Strategy

The selection of IEEE Xplore, MDPI, ScienceDirect, and Wiley Online Library was based on their comprehensive coverage of peer-reviewed literature in computer science, engineering, and environmental sciences, the key disciplines relevant to this study.

- IEEE Xplore is a leading source for high-quality research in blockchain technologies, smart city infrastructure, and IoT systems.
- MDPI hosts several open-access journals focused on sustainability, environmental monitoring, and emerging technologies.
- ScienceDirect provides access to a vast collection of multidisciplinary journals, including top publications in smart cities, environmental management, and data science.
- Wiley Online Library includes reputable journals in information systems, urban planning, and environmental governance.

Collectively, these databases ensure a balanced and interdisciplinary dataset, capturing both the technological and environmental dimensions of blockchain applications in smart cities. Their inclusion enhances the credibility and comprehensiveness of the literature review.

Table 1. Summary of academic databases and search strategy for systematic literature review

Database	Search Keywords	Publication Years	Document Types	Language	Number of Papers Retrieved
IEEE Xplore	blockchain AND smart cities AND environmental data AND (security OR trust OR interoperability)	2019–2025	Peer-reviewed journals, conferences	English	125
MDPI	blockchain AND smart cities AND environmental data AND (security OR trust OR interoperability)	2019–2025	Peer-reviewed journals	English	78
ScienceDirect	blockchain AND smart cities AND environmental data AND (security OR trust OR interoperability)	2019–2025	Peer-reviewed journals, conferences	English	102
Wiley Online Library	blockchain AND smart cities AND environmental data AND (security OR trust OR interoperability)	2019–2025	Peer-reviewed journals	English	64

This systematic literature review employed a rigorous search strategy across four major academic databases: IEEE Xplore, MDPI, ScienceDirect, and Wiley Online Library. The search string was meticulously constructed using relevant keywords, specifically combining "blockchain," "smart cities," and "environmental data" with the key terms "security," "trust," or "interoperability." This ensured a focused and comprehensive retrieval of literature pertaining to blockchain-enabled solutions for environmental data management within smart city contexts.

The inclusion criteria were restricted to peer-reviewed journal articles and conference papers published between 2019 and 2025, providing up-to-date and high-quality sources. Additionally, only articles published in English were considered to maintain consistency and accessibility for the research audience. The search yielded a total of 369 papers across the four databases, with IEEE Xplore contributing the highest number (125), followed by ScienceDirect (102), MDPI (78), and Wiley Online Library (64). These articles were subsequently screened for relevance, duplication, and quality before being incorporated into the thematic analysis. This systematic approach ensures that the review is grounded in a robust and diverse scholarly foundation, supporting the validity and reliability of the findings.

2.3 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria used to filter relevant studies for this systematic literature review are summarized in Table 2. The review focused specifically on blockchain applications in smart cities that address environmental data sharing, with emphasis on security, privacy, and interoperability. Only peer-reviewed papers from 2019 to 2025 in English were included to ensure quality and relevance. Studies outside this scope, such as those from unrelated domains (e.g., finance), or lacking in technical rigor, were excluded. These criteria helped maintain a focused and high-quality dataset aligned with the research objectives.

Table 2. Inclusion and exclusion criteria for article selection

Inclusion Criteria	Exclusion Criteria
Focus on blockchain applications in smart cities	Focus on blockchain in unrelated sectors (e.g., finance)
Relevance to environmental data sharing	Articles not written in English
Addressing security, privacy, or interoperability	Studies lacking technical depth
Peer-reviewed journals or conference papers	Non-peer-reviewed publications (e.g., editorials, blogs, reports)
Published between 2019 and 2025	Published before 2019 or after 2025

2.4 Selection Process

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram outlines the study selection process for this systematic literature review. Initially, 400 records were identified through database searches across IEEE Xplore, MDPI, ScienceDirect, and Wiley Online Library. Prior to screening, 200 duplicate records were removed using automated tools.

The remaining 200 records were screened by title and abstract, leading to the exclusion of 100 articles that did not meet relevance or scope criteria. A total of 100 full-text articles were sought for retrieval; however, 50 reports could not be accessed due to paywalls or broken links. Of the 50 full-text articles assessed for eligibility, 28 were excluded: 10 for being out of scope, 10 for lacking peer review, and 7 for insufficient technical depth. Finally, 23 studies met all inclusion criteria and were selected for the final synthesis and analysis.

This transparent and structured selection process ensured a high-quality dataset aligned with the review's objectives, focusing on blockchain-based frameworks for secure, interoperable, and trustworthy environmental data sharing in smart cities. The PRISMA diagram supports methodological rigor and enhances the reproducibility of the study.

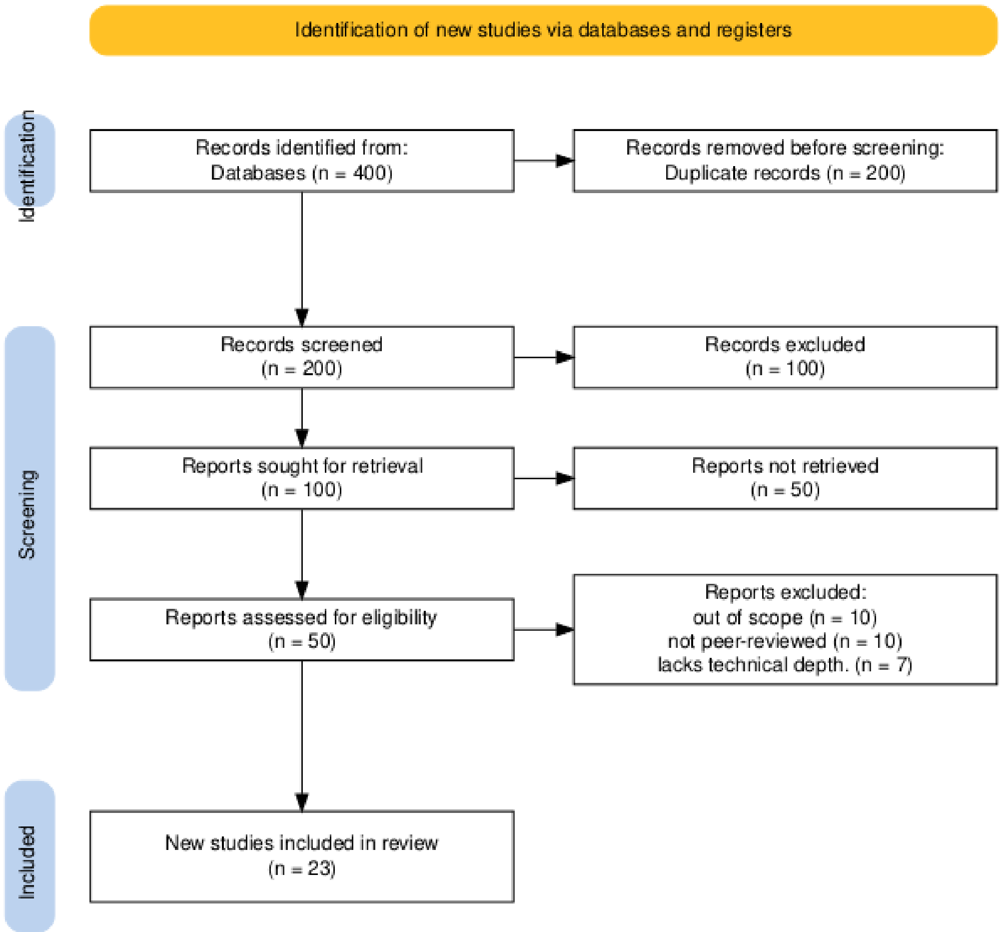

Figure 1. PRISMA flow diagram of study selection process

2.5 Data Extraction and Synthesis

To enhance the reproducibility, transparency, and overall methodological rigor of this systematic literature review, a comprehensive data extraction table was developed and employed. This table provides a structured framework for organizing key information from each selected study, ensuring consistency in data capture and facilitating meaningful comparison and synthesis across the literature. By documenting each step of the extraction process, the review establishes a clear audit trail that allows future researchers to replicate the methodology and validate the findings.

The data extraction process was conducted manually, following a standardized protocol to ensure accuracy and consistency. For each article included in the final selection, the following metadata fields were systematically recorded:

- Study Reference: Author(s), year of publication, and title of the study.
- Blockchain Technology/Platform: The specific type of distributed ledger technology (DLT) implemented, such as Ethereum, Hyperledger Fabric, IOTA, or bespoke architectures.
- Smart City Domain: The specific urban sector addressed, including environmental monitoring, energy systems, waste management, and digital governance.
- Use of Environmental Data: The nature and source of environmental data utilized (e.g., air quality indexes, water usage, CO_2 emissions, sensor data).
- Integration with Other Technologies: Whether the solution integrates complementary technologies such as AI, IoT, edge computing, or federated learning.
- Main Objectives: The study's primary goals, such as enhancing data trust, security, transparency, or interoperability.
- Implementation Level: Whether the study presents a conceptual framework, simulation, prototype, or real-world application.
- Key Findings and Contributions: Major theoretical, technical, or practical advancements presented by the study.
- Identified Challenges: Key limitations or barriers noted, such as scalability issues, lack of standardization, or technical complexity.
- Future Research Directions: Author-suggested areas for further research or improvement.

This detailed extraction process enabled the identification of thematic clusters, recurring trends, and significant research gaps. The complete data extraction table is included in Appendix A to ensure transparency and to support future systematic reviews within the evolving domain of blockchain-enabled smart city systems.

3. RESULT AND DISCUSSION

This review analyzed 23 high-quality studies addressing blockchain applications for environmental data management in smart cities. Findings reveal blockchain enhances trust, data integrity, and interoperability through decentralized frameworks, smart contracts, and integration with AI. Challenges include scalability, data privacy, lack of standards, and governance complexity. Innovations such as blockchain-of-blockchains, federated learning, and digital twin integration show promise. A proposed framework combining blockchain, IPFS, and decentralized authorization supports secure, scalable, and verifiable data sharing. This architecture ensures tamper-proof auditability and trust among stakeholders, proving especially valuable for sensitive domains like environmental monitoring, policy enforcement, and smart urban governance.

To address RQ1, a total of 10 high-quality studies were selected that specifically focus on the application of blockchain for environmental data management in smart cities. The findings are summarized in Table 3. The review reveals that blockchain is being increasingly leveraged in smart cities to support secure, transparent, and efficient environmental data management. A key trend across the literature is the use of decentralized trust frameworks to eliminate reliance on centralized authorities, particularly in environmental monitoring systems [1], [6]. This enables multiple urban stakeholders to access trustworthy data in real time.

Several studies emphasize interoperability through blockchain-of-blockchains architectures or standardization frameworks [2], [9]. These models allow integration of environmental data from various heterogeneous IoT systems, which is critical in urban settings where devices and platforms differ widely. Additionally, privacy-preserving techniques such as zero-knowledge proofs and encryption layers built on blockchain have been implemented to protect sensitive environmental data like air pollution records and industrial emissions [5], [20].

Some researchers integrate AI and blockchain to enhance the automation and credibility of environmental data processing [7], [14]. For example, AI models trained on environmental sensor data can execute on-chain validation tasks through smart contracts, ensuring that only verified data enters the system. Furthermore, blockchain is used to track environmental impacts, such as emissions linked to vehicle parking systems, allowing for data-driven policy enforcement [10].

Table 3. Applications of blockchain in environmental data management in smart cities

Year	Application Area	Blockchain Role	Key Benefit	Citation
2025	Urban data integrity	Decentralized trust framework	Secures environmental monitoring systems	[1]
2022	IoT sensor data	Interoperable blockchain-of-blockchains	Ensures cross-platform data integrity	[2]
2020	Privacy in data sharing	Blockchain-based privacy layer	Enables secure and anonymous sharing of air quality data	[5]
2024	Urban governance	Smart contract-based validation	Enhances trust in environmental reporting	[6]
2022	Smart IoT systems	AI-enabled blockchain framework	Automates environmental data verification	[7]
2024	Data integration	DLT standardization framework	Facilitates interoperable environmental datasets	[9]
2022	Parking and emissions	Energy-efficient blockchain	Tracks environmental impact of parking	[10]
2024	Industry CPS	Blockchain for traceability	Improves traceability of environmental compliance	[20]
2024	General smart city data	Introductory blockchain framework	Lays foundation for environmental data security	[21]
2024	AI-integrated IoT	Blockchain for secure AI pipelines	Enhances reliability of real-time environmental analysis	[14]

To answer RQ2: What are the common challenges and limitations identified in existing blockchain-based smart city frameworks? a detailed analysis of selected studies revealed recurring technical, organizational, and regulatory barriers. These are summarized in Table 4.

Table 4. Common challenges in blockchain-based smart city frameworks

Year	Challenge	Description	Citation
2022	Scalability	Blockchain platforms struggle with large-scale environmental IoT data	[2]
2020	Privacy vs. transparency	Difficulty balancing open access with data confidentiality	[5]
2024	Interoperability	Limited integration across heterogeneous smart city systems	[6]
2022	Computational overhead	AI-blockchain systems require high processing power	[7]
2024	Lack of standardization	Absence of unified DLT protocols across smart city services	[9]
2022	Energy consumption	Consensus mechanisms (e.g., PoW) increase environmental costs	[10]
2023	Governance complexity	Difficulties in managing multi-stakeholder decision-making	[16]
2024	Data latency	Delay in blockchain transaction confirmation for real-time applications	[17]
2025	Legal and ethical issues	Ambiguity in regulations for blockchain data governance	[18]
2024	Traceability limitations	Challenges in mapping data sources across city services	[20]

The analysis reveals several persistent challenges that hinder the effective implementation of blockchain-based frameworks in smart cities. A major issue is scalability, blockchains often struggle to handle the high volume and velocity of environmental IoT data, especially when combined with smart contracts and real-time analytics [2], [7]. Closely linked to this is computational overhead, where the integration of blockchain with AI and federated learning increases system resource demands [7], [17].

Another key challenge is the trade-off between transparency and privacy. While blockchain's transparency fosters trust, it may inadvertently expose sensitive environmental or citizen-related data [5]. Studies have suggested encryption and off-chain storage as partial solutions, but these increase system complexity [6].

Interoperability remains limited due to the lack of common standards among various city platforms and distributed ledger technologies [9]. This restricts seamless integration of environmental data from different departments or regions. Similarly, governance complexity—involving multiple agencies, vendors, and citizens—makes it difficult to enforce uniform policies and data sharing rules [16].

Other challenges include energy inefficiency of consensus algorithms such as Proof-of-Work [10], data latency for real-time applications [17], and unclear legal frameworks governing blockchain use in public systems [18]. Some frameworks also struggle with traceability, especially when trying to verify data origin and audit environmental metrics across multiple platforms [20].

To address RQ3: What innovations or models enhance trust, data integrity, and interoperability, the selected literature was examined to identify emerging blockchain-based models, architectural improvements, and cross-technology integrations. These innovations are categorized and summarized in Table 5.

Table 5. Innovations enhancing trust, data integrity, and interoperability in smart cities

Year	Innovation/Model	Purpose	Benefit	Citation
2025	Decentralized Trust Framework (DTF)	Secure environmental data flows	Strengthens trust among city stakeholders	[1]
2022	Blockchain-of-Blockchains	Cross-chain interoperability	Connects isolated data sources securely	[2]
2022	AI-Blockchain Integration	Intelligent data validation	Automates and verifies environmental datasets	[7]
2024	DLT Standardization Layer	Unified protocol integration	Enhances platform compatibility	[9]
2025	Smart Contract Governance	Rule-based data management	Improves data integrity and compliance	[4]
2024	Blockchain + AI Pipelines	Real-time analytics integration	Boosts trustworthy decision-making	[14]
2023	Blockchain-Deep Learning Governance Model	Automated governance validation	Ensures ethical and legal compliance	[16]
2024	Federated Blockchain Learning	Decentralized AI model training	Maintains privacy with integrity	[17]
2025	Transparent Smart City Platform	Open DLT architecture	Increases stakeholder accountability	[3]
2025	Blockchain-Digital Twin Integration	City simulation with traceable data	Enhances accuracy and traceability	[15]

The review identified a range of technical innovations and architectural models that significantly enhance trust, data integrity, and interoperability in smart city systems. At the core of trust-enhancement is the use of Decentralized Trust Frameworks (DTFs), such as the one proposed by Islam et al. [1], which remove the reliance on central authorities and ensure secure data validation through distributed consensus. Similarly, smart contract-based governance models allow for programmable, rule-based validation of data sharing and access control, thereby reinforcing data integrity and compliance with regulations [4].

To address interoperability, several studies proposed advanced architectural solutions. The Blockchain-of-Blockchains model by Rahman et al. [2] enables communication between otherwise isolated blockchain systems, facilitating unified environmental data access. In parallel, the DLT standardization layers proposed by Jnr et al. [9] work to harmonize protocols across platforms, overcoming fragmentation in smart city architectures.

Integrating blockchain with AI and Digital Twin technologies emerged as a powerful innovation, particularly in enhancing real-time data processing, predictive analytics, and traceable decision-making [7], [14], [15]. These integrations not only improve the accuracy and transparency of environmental monitoring but also support automation in data governance and policy enforcement [16].

Finally, federated learning-based blockchain systems offer privacy-preserving collaboration across distributed nodes, maintaining both data security and integrity without centralized data pooling [17]. Collectively, these innovations demonstrate the evolving landscape of blockchain applications in smart cities, pointing toward more integrated, intelligent, and ethical data ecosystems.

The proposed blockchain-based secure data sharing framework (Figure 2) effectively addresses key challenges in environmental data management by combining blockchain technology, the InterPlanetary File System (IPFS), and a decentralized authorization mechanism [1], [3], [7]. In this architecture, data owners encrypt sensitive environmental data and store the encrypted ciphertext on IPFS, a distributed peer-to-peer storage network [22]. The hash of the encrypted data is immutably recorded on the blockchain, providing a verifiable fingerprint that ensures data integrity and prevents tampering [6], [23].

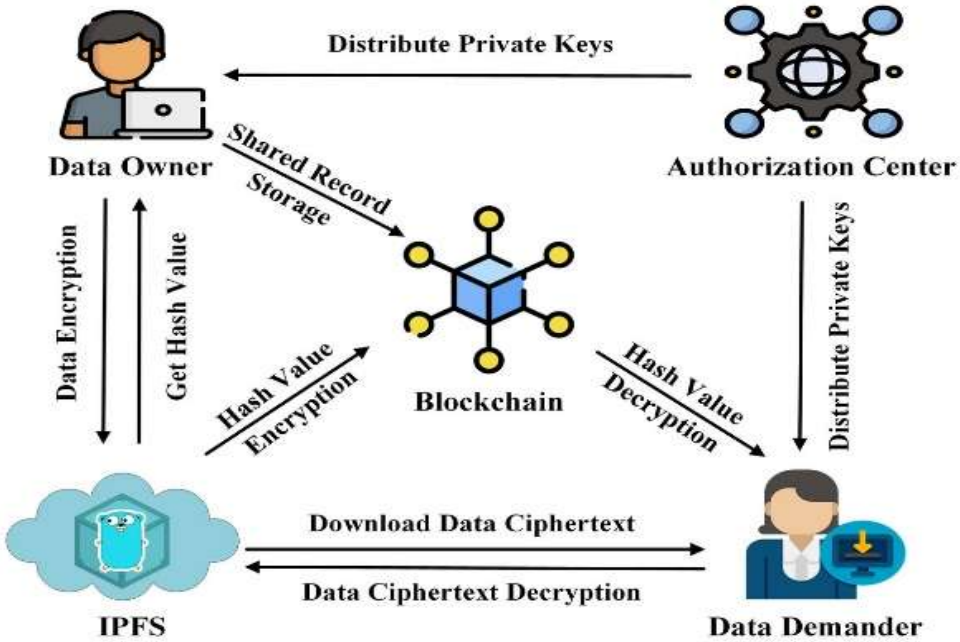

Figure 2. Blockchain-based secure data sharing framework integrating IPFS and decentralized authorization

Access control is managed via a decentralized authorization center that issues private keys to authorized users, referred to as data demanders, based on predefined policies [4], [12]. These users retrieve the encrypted data from IPFS and decrypt it only after validating the blockchain-recorded hash, thereby guaranteeing authenticity and secure access [5]. The integration of IPFS enhances the framework's scalability and fault tolerance by distributing data storage, mitigating risks associated with centralized data repositories [22]. This architecture ensures a tamper-proof audit trail through blockchain immutability, thereby fostering trust among multiple stakeholders [1], [23].

Such a framework is particularly valuable for sensitive domains like environmental monitoring, healthcare, and scientific research, where data privacy, security, and traceability are critical [23]. The model promotes secure, transparent, and interoperable data sharing, thereby supporting sustainable urban management in smart cities [7], [9]. This systematic literature review reveals that blockchain technology holds significant promise for overcoming key challenges in environmental data management within smart cities, particularly by fostering trust, transparency, and data integrity through its decentralized architecture. By eliminating the reliance on centralized authorities, often single points of failure and targets for manipulation, blockchain can fundamentally reshape how environmental data is collected, verified, and shared among diverse stakeholders [1], [4]. This decentralization underpins the trust enhancement critical for collaborative urban governance and sustainability efforts.

A salient finding is the growing trend toward integrating blockchain with complementary technologies such as AI, digital twins, and federated learning, which together form hybrid models that improve data reliability and enable real-time, intelligent decision-making [7], [14], [15], [17]. For instance, AI-driven anomaly detection mechanisms enhance data integrity by automatically validating sensor inputs before recording them on-chain, thereby reducing misinformation risks and enhancing the accuracy of environmental monitoring [7]. Digital twins, supported by immutable blockchain records, enable urban planners to simulate and predict environmental changes with higher confidence [15].

However, the review also uncovers contradictions and gaps. While blockchain enhances trust and data security, scalability remains a persistent barrier. The vast and heterogeneous data streams generated by IoT devices in smart cities overwhelm current blockchain platforms, causing latency and throughput bottlenecks that undermine the real-time responsiveness required for environmental monitoring and crisis management [2], [7], [17]. Additionally, the energy-intensive nature of some consensus algorithms, particularly Proof-of-Work, introduces sustainability paradoxes, conflicting with the environmental objectives of smart cities [10]. This contradiction highlights the urgent need for energy-efficient blockchain protocols to align technological adoption with ecological goals.

Another major challenge is interoperability and standardization. The review identifies a fragmented ecosystem of blockchain platforms and city systems, resulting in persistent data silos that inhibit integrated urban management [6], [9]. Despite emerging solutions like Blockchain-of-Blockchains, these remain conceptual or early-stage, underscoring a critical gap in operationalizing cross-platform data sharing. Our proposed framework directly addresses these gaps by prioritizing decentralized, interoperable environmental data sharing with built-in mechanisms for scalability and energy efficiency. By leveraging modular blockchain architectures combined with AI-enabled data validation and standardized interoperability protocols, the framework seeks to overcome existing limitations around latency, data silos, and trust. Furthermore, it integrates governance models designed to balance inclusivity, security, and regulatory compliance, responding explicitly to legal and ethical challenges highlighted in the literature [16], [18].

4. CONCLUSION

This systematic review highlights the significant role that blockchain technology can play in advancing environmental data management within smart cities. By leveraging its decentralized and immutable characteristics, blockchain offers a promising solution to enhance trust, ensure data integrity, and facilitate interoperability among diverse urban systems. These capabilities are essential for fostering transparent, accountable, and efficient governance of environmental resources in increasingly complex and interconnected urban landscapes. The integration of blockchain with complementary technologies, such as artificial intelligence, digital twins, and federated learning, further enriches its potential. These combined approaches enable real-time data validation, predictive analytics, and dynamic simulation of urban environments, collectively improving the accuracy and reliability of environmental monitoring. Additionally, smart contracts automate data management processes, reinforcing compliance and minimizing human error.

Despite these advantages, several challenges hinder the widespread adoption of blockchain in smart city contexts. Issues related to scalability, data throughput, and energy consumption must be addressed to support the extensive IoT data flows typical of urban environments. Furthermore, the lack of standardized protocols and interoperability frameworks limits seamless integration of blockchain systems with existing infrastructures and across diverse blockchain networks. Legal and ethical concerns, including data privacy, ownership, and governance, also require clear regulatory frameworks and inclusive models that balance security with stakeholder engagement.

To overcome these challenges, future research should prioritize the development of scalable blockchain architectures tailored for high-throughput, heterogeneous IoT data in smart cities, which may involve exploring alternative consensus mechanisms that minimize energy consumption while maintaining robust security. Additionally, it is essential to establish universal interoperability standards and middleware solutions to facilitate seamless cross-platform communication and data exchange across diverse blockchain networks and urban infrastructures. Adaptive governance frameworks must also be designed to integrate regulatory compliance, ethical standards, and multi-stakeholder engagement, thereby fostering trust and accountability in environmental data sharing. Furthermore, advancing AI-enhanced blockchain applications can improve real-time data validation, anomaly detection, and predictive analytics, specifically adapted to dynamic urban environmental contexts. Finally, conducting pilot deployments and longitudinal case studies will be critical to assess the practical performance, user acceptance, and broader societal impacts of blockchain-enabled environmental data systems across varied smart city scenarios.

In conclusion, blockchain technology offers a strong foundation for secure and transparent environmental data sharing, but realizing its full potential in smart cities requires targeted, multidisciplinary research efforts. By addressing scalability, interoperability, governance, and ethical challenges through concrete innovations and real-world validations, future work can unlock sustainable, resilient, and trustworthy urban environments.

REFERENCES

[1] Islam, R. Bose, S. Roy, A. A. Khan, S. Sutradhar, S. Das, *et al.*, "Decentralized trust framework for smart cities: a blockchain-enabled cybersecurity and data integrity model," *Sci. Rep.*, vol. 15, no. 1, p. 23454, 2025.

[2] M. S. Rahman, M. A. P. Chamikara, I. Khalil, and A. Bouras, "Blockchain-of-blockchains: An interoperable blockchain platform for ensuring IoT data integrity in smart city," *J. Ind. Inf. Integr.*, vol. 30, p. 100408, 2022.

[3] M. Vaseei and M. N. JanAgha, "Building Transparent and Secure Smart City Platforms," in *Artificial Intelligence of Everything and Sustainable Development*, Singapore: Springer Nature Singapore, 2025, pp. 105–121.

[4] S. K. Singh, S. Kumar, S. Garg, S. Arora, S. K. Sharma, V. Arya, and K. T. Chui, "Blockchain-Based Data Security in Smart Cities: Ensuring Data Integrity and Trustworthiness," in *Digital Forensics and Cyber Crime Investigation*, CRC Press, 2025, pp. 17–41.

[5] I. Makhdoom, I. Zhou, M. Abolhasan, J. Lipman, and W. Ni, "PrivySharing: A blockchain-based framework for privacy-preserving and secure data sharing in smart cities," *Comput. Secur.*, vol. 88, p. 101653, 2020.

[6] X. Zhu, Z. Chen, T. Cheng, C. Yang, D. Wu, Y. Wu, and H. Wang, "Blockchain for urban governance: Enhancing trust in smart city systems with advanced techniques," *Sustain. Cities Soc.*, vol. 108, p. 105438, 2024.

[7] I. Ahmed, Y. Zhang, G. Jeon, W. Lin, M. R. Khosravi, and L. Qi, "A blockchain and artificial intelligence enabled smart IoT framework for sustainable city," *Int. J. Intell. Syst.*, vol. 37, no. 9, pp. 6493–6507, 2022.

[8] S. Priyanshu, S. Kumar, and S. Garg, "Blockchain-Based Data Security," in *Digital Forensics and Cyber Crime Investigation: Recent Advances and Future Directions*, 2024, p. 17.

[9] B. A. Jnr, W. Sylva, J. K. Watat, and S. Misra, "A framework for standardization of distributed ledger technologies for interoperable data integration and alignment in sustainable smart cities," *J. Knowl. Econ.*, vol. 15, no. 3, pp. 12053–12096, 2024.

[10] S. K. Singh, Y. Pan, and J. H. Park, "Blockchain-enabled secure framework for energy-efficient smart parking in sustainable city environment," *Sustain. Cities Soc.*, vol. 76, p. 103364, 2022.

[11] D. Kundu, "Blockchain and trust in a smart city," *Environ. Urban. Asia*, vol. 10, no. 1, pp. 31–43, 2019.

[12] M. Asif, Z. Aziz, M. Bin Ahmad, A. Khalid, H. A. Waris, and A. Gilani, "Blockchain-based authentication and trust management mechanism for smart cities," *Sensors*, vol. 22, no. 7, p. 2604, 2022.

[13] E. Dritsas and M. Trigka, "Machine Learning for Blockchain and IoT Systems in Smart Cities: A Survey," *Future Internet*, vol. 16, no. 9, p. 324, 2024.

[14] B. U. I. Khan, K. W. Goh, A. R. Khan, M. F. Zuhairi, and M. Chaimanee, "Integrating AI and Blockchain for Enhanced Data Security in IoT-Driven Smart Cities," *Processes*, vol. 12, no. 9, 2024.

[15] I. Lukić, M. Köhler, Z. Krpić, and M. Švarcmajer, "Advancing Smart City Sustainability Through Artificial Intelligence, Digital Twin and Blockchain Solutions," *Technologies*, vol. 13, no. 7, p. 300, 2025.

[16] V. Malik, R. Mittal, D. Mavaluru, B. R. Narapureddy, S. B. Goyal, R. J. Martin, *et al.*, "Building a secure platform for digital governance interoperability and data exchange using blockchain and deep learning-based frameworks," *IEEE Access*, vol. 11, pp. 70110–70131, 2023.

[17] S. S. Sefati, R. Craciunescu, B. Arasteh, S. Halunga, O. Fratu, and I. Tal, "Cybersecurity in a scalable smart city framework using blockchain and federated learning for internet of things (IoT)," *Smart Cities*, vol. 7, no. 5, pp. 2802–2841, 2024.

[18] G. Mustafa, W. Rafiq, N. Jhamat, Z. Arshad, and F. A. Rana, "Blockchain-based governance models in e-government: a comprehensive framework for legal, technical, ethical and security considerations," *Int. J. Law Manag.*, vol. 67, no. 1, pp. 37–55, 2025.

[19] V. Garcia-Font, "Conceptual technological framework for smart cities to move towards decentralized and user-centric architectures using DLT," *Smart Cities*, vol. 4, no. 2, pp. 728–745, 2021.

[20] M. I. Hossain, T. Steigner, M. I. Hussain, and A. Akther, "Enhancing data integrity and traceability in industry cyber physical systems (ICPS) through Blockchain technology: A comprehensive approach," *arXiv preprint*, arXiv:2405.04837, 2024.

[21] E. M. Roopa Devi, R. Shanthakumari, S. Vinothkumar, and K. R. Balasurya, "Introduction to Blockchain Technology for Smart Cities," in *Digital Twin and Blockchain for Smart Cities*, 2024, pp. 1–26.

[22] M. Hakimi, K. R. Rahmani, Z. Ezam, and H. Shahbazi, "Integrating Blockchain Technology for Secure E-Government Services: Opportunities and Challenges," *J. Social Sci. Util. Technol.*, vol. 2, no. 3, pp. 317–335, 2024.

[23] M. I. Alam, S. Khatri, D. K. Shukla, N. K. Misra, S. Satpathy, and M. Hakimi, "Blockchain-based coal supply chain management system for thermal power plants," *Discov. Comput.*, vol. 28, no. 1, pp. 1–32, 2025. H. Ali, W. J. Buchanan, J. Ahmad, M. Abubakar, M. S. Khan, and I. Wadhaj, "TrustShare: Secure and Trusted Blockchain Framework for Threat Intelligence Sharing," *Future Internet*, vol. 17, no. 7, p. 289, 2025.