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Blockchain-Based Decentralized Security for Internet of Things Applications

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Abstract

The rapid advancement of the Internet of Things (IoT) has posed significant security and privacy challenges because of its centralized architecture and resource-constrained devices. Moreover, because traditional security solutions require scaling and decentralized mechanisms immune to tampering, they cannot satisfy the requirements of IoT ecosystems. The distributed ledger technology in the form of blockchains fits the bill, with decentralized architecture, immutability, and cryptographic assurance. This review provides a thorough analysis of blockchain-augmented IoT security, examining various security models based on blockchains, consensus protocols, and smart contracts. Blockchains are the basis for security architectures, access control models, and threat mitigation strategies proposed in 15 cutting-edge research papers. A comparative analysis of key features was conducted, contrasting blockchain architectures across several performance axes: scalability, energy efficiency, latency, and security effectiveness. Finally, the challenges, future research avenues, and barriers to the full-scale application of blockchains in IoT environments are discussed. It comprehensively surveys blockchain-enabled decentralized security for IoT applications and provides directions for researchers and practitioners for developing robust security frameworks for IoT ecosystems.

***Keywords**:* Blockchain, IoT Security, Decentralization, Access Control, Smart Contracts, Cybersecurity, Consensus Mechanisms.

1. Introduction

IoT has transformed industries through real-time data collection, computerization, and interconnectivity within various applications, such as intelligent cities, healthcare, and industrial automation (Gupta et al., 2022; Yousif & Saini, 2020). The rapid expansion of IoT is prompting significant worries about security and data privacy, with traditional system security approaches struggling to adapt to its immense size and complexity, as well as the limitations of energy-efficient devices (Alajlan et al., 2023). Some of the security attacks common to IoT are unauthorized access, data corruption, distributed denial-of-service (DDoS) attacks, and trust management problems (Kotela et al., 2023).

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Therefore, a decentralized, tamper-proof, and scalable security framework is urgently needed to secure IoT networks (Sharma et al., 2021; Hasan et al., 2022).

Traditional security systems are being increasingly replaced by blockchain technology, which shifts trust from a central authority to a network of interconnected devices (Bao et al., 2021; Niazi et al., 2021). Blockchain is involved in the security of the Internet of Things (IoT), such as access control, trust management, secure data exchange, and counteracting attacks (Mahto et al., 2025; Chowdhury et al., 2023). In this regard, a smart contract ensures the automated and verifiable interaction between IoT nodes to enable policy execution and perform the secure transaction itself (Rathee et al., 2023).

IoT systems employing blockchain technology exhibit a dual characteristic, balancing advantages and disadvantages, which encompass scalability problems, considerable computational and energy expenses, slow transaction processing, and regulatory hurdles, as noted by Dhieb et al. (2020) and Moniruzzaman (Miaz & Ali, 2020). The primary goal of this conversation is to determine which architectural style meets the security requirements of IoT systems, with several issues raised regarding the advantages and disadvantages of public, private, and consortium blockchain solutions (Khan et al., 2021; Min et al., 2022). These factors underscore the pressing need for a comprehensive assessment of block-based security solutions tailored to specific IoT environments (Kumar et al., 2022; Aljabri & Yousif, 2023).

Reviews of 15 state-of-the-art research papers that present different blockchain-based security mechanisms for IoT. This will further contribute to the literature by

1. Classification of blockchain-based security mechanisms in IoT networks, such as access control, authentication, and integrity protection mechanisms.
2. Comparison of the 15 selected research papers on a set of key attributes, such as scalability, security efficiency, and computational overhead.
3. Determining the key obstacles faced in integrating blockchain technology for IoT security purposes.
4. Proposing some future research directions to address these limitations and consequently strengthen the adoption of blockchain in IoT applications.

The paper consists of seven separate sections, with Section 2 providing a thorough examination of 15 blockchain-based IoT security research studies, Section 3 offering a comparative analysis, Section 4 evaluating the effectiveness of blockchain, Section 5 discussing challenges and potential future research avenues, Section 6 conducting a critical evaluation of the current limitations of blockchain-based IoT security solutions, and Section 7 outlining potential future research paths.

2. Literature Review

Considering that the Internet of Things security is highly important in the aftermath of some catastrophes, as mentioned by Alam and coworkers in 2021, and Zhou et al. in 2021, blockchain has started to capture a greater share of consideration as a potential solution. As presented by Feng et al., regular security mechanisms fail to deliver sufficient protection against cyber threats. Therefore, this section presents a review of 15 important research papers on blockchain-based security mechanisms for IoT applications, analyzing each paper with respect to the objectives, methodology, findings, strengths, and limitations. Blockchain technology has gained a vast amount of recognition as

a potential solution for securing these Internet of Things networks (Gong et al., 2021; Zhang et al., 2022). IoT is unable to provide enough protection against any fabrication by standard security mechanisms because of its inherent weaknesses. This discussion analyzes 15 leading research papers on blockchain-based security mechanisms for IoT applications. Each of these papers has been analyzed based on its objectives, methodology, findings, strengths, and limitations.

Cheng et al. (2022) recommended a new blockchain access control mechanism for the Internet of Things (IoT) that solves the security issues associated with traditional centralized access control systems. Using Hyperledger Fabric as the blockchain framework, key components of access control, including the PDP, ACP, and ATM, are deployed in smart contracts (chain codes) on-chain, whereas policy administration points (PAP), Policy Enforcement Points (PEP), and Policy Information Points (PIP) click here are controlled through off-chain systems to reduce storage overheads. This hybrid architecture improves the transparency, non-manipulation, and auditability of the ACC process to tackle imminent challenges of data privacy and protection against cyberattacks in IoT environments. A feasibility study shows that it maintains a sufficient throughput for different transaction volumes, hence demonstrating its scalability and efficiency for vast IoT ecosystems. In addition, it lays the ground for integration with more complex blockchain applications in IoT access control, which provides a springboard for future research in decentralized identity management and secure resource access.

The work presented by Kotel et al. (2023) is concerned with a novel blockchain-based platform utilizing Hyperledger Fabric to promote security and privacy features in smart home systems, which are expected to be embraced within a burgeoning IoT tradition. The relevance and timeliness of this work arise from the fact that smart homes face common weaknesses intrinsic to traditional IoT architectures, which involve unauthorized access and exposure to data breaches, due to their increasing incorporation into everyday life. The proposed framework consists of a structured four-layer architecture comprising a cloud storage layer, a blockchain platform layer, an application layer, and IoT Devices Layer-making use of the cloud storage efficiency and resource availability for smart devices. The system incorporates strong identity management, user authentication, and access control to safeguard the integrity and confidentiality of sensitive information and device communication. This implementation not only enhances data integrity and transaction transparency but also counters risks owing to a single point of failure with the decentralized ledger technology of blockchain. The results indicate that implementing this architecture significantly enhances the security of smart homes, thereby making large-scale adoption a feasible prospect. The authors further recommend that identity management solutions be investigated for their implementation in real settings, thus giving a flourish to substantial research grounds for further endeavors in this area.

IoTChain is the architecture proposed by Zijian Bao et al. (2021) as the first solution designed to incorporate aspects of security into IoT systems that have faced acute challenges since time immemorial, particularly with respect to vulnerability and data integrity. This framework has three-tier authentication: authentication layer, blockchain layer, and application layer, which, together, can provide core features much expected, like identity authentication, access control, and privacy protection. The architecture uses a consensus algorithm for regional node fault tolerance and denial-of-service (DoS) attack resistance. Furthermore, it entails data verification efficiency through Merkle trees along with hashing techniques to ensure blockchain transactions' immutability. Simulation was utilized under Contiki

OS to evaluate performance in a resource-limited setting, focusing on key metrics such as communication delay and transaction dependability, thereby confirming the lightweight nature and operational effectiveness of IoTChain. This enables IoTChain to handle pressing security issues and, therefore, lay the groundwork for continued research toward real-world implementation and rigorous evaluation toward drastically enhancing IoT security.

According to Dhieb et al. (2020), the increasing security vulnerabilities in the Internet of Things (IoT) ecosystem are expected to exceed 20 billion devices by 2022, as illustrated by the DDoS attacks from the Mirai malware. Therefore, a strong architecture combining AI with permissioned blockchain technology has been proposed to further strengthen the security and efficiency of IoT systems. The solution implements useful ML algorithms—namely, artificial neural networks, XGBoost, decision trees, and naive Bayes—applied at the level of the gateway for real-time detection and classification of malware and suspicious actions. This novel architecture allows for decentralized data storage with respect to IoT devices that do not have enough computational capacity for the mining processes; this ensures that performance is not compromised. Moreover, data integrity and secure communication in IoT environments can be improved using well-defined access control and AI modules capable of identifying anomalies. The simulation results also reflect how the newly proposed system enhances privacy and data sharing while protecting against various cyber threats; thus, it really catalyzes stronger efforts towards the realization of secure IoT ecosystems.

Miaz and Ali (2020) define the integration of Blockchain technology and the Internet of Things (IoT) in IoT ecosystems for security and privacy purposes. The paramount aim of their investigation is to verify whether Blockchain could be employed in alleviating some of the known vulnerabilities that exist in IoT security, particularly the risk arising from machine-to-machine communication that has no human supervisory concern. Using a survey method, the authors assess current research articles and existing applications in order to understand the practical implementations of Blockchain for IoT security while identifying events related to this purpose. They discuss the cryptographic methods of hashing and asymmetric encryption that fortify the integrity and confidentiality of data broadcast through a distributed ledger. Some of the novel applications discussed include smart contracts and a protocol, Telehash, that can decentralize and self-manage devices, thus eliminating single points of failure. Even though Blockchain has great prospects for enhancing data privacy, security, and traceability, the work highlights certain critical challenges like computational intensity and huge scalability issues that create impediments to its deployment in resource-constrained environments. Therefore, Miaz and Ali, therefore, advocate for research addressing the optimization of blockchain solutions to meet the specific requirements within the IoT backdrop, which demands extremely efficient and scalable solutions.

The work presented by Sargsyan and co-authors (2022) discussed providing a blockchain security framework meant only for the IoT, as the need of the hour for providing sophisticated security mechanisms to tackle the intricacies of vulnerabilities inherent in a variety of IoT networks. The company has outlined clear objectives; its primary goal is to determine how businesses can implement blockchain technology, combining strong security measures with continuously evolving data protection standards. It pushes for a "security by design" strict approach in such a unit, emphasizing the importance of making security considerations from the outset of electronic development. Specific methodologies include the Risk-and Cost-Driven Architecture (RCDA) for cycles of iterative decisions and the Blockchain Trilemma, which illustrates the balancing act between scalability, decentralization, and security. The

Cyber-Trust project, which is already under construction, acts as an example of how it can be used within the framework by demonstrating the building of a cyber-threat intelligence platform to integrate blockchain technology for improved security of IoT ecosystem environments against cyber threats. This brand-new framework draws a detailed itinerary between theoretical principles and practical implementation, equipping technology managers and decision-makers with all the tools necessary to create trust and protect their organizations from increasingly happening shifts in the digital world.

Rathee et al. (2023) propose an extensive security framework pertaining to the Industrial Internet of Things (IIoT) using blockchain technology to address major security loopholes in conventional IIoT architectures as shown in Figure 1. The framework relies on a Coordinator IoT Device (CID) to compute the Trust Factor (TF) for connected devices, ensuring that only authenticated and legitimate devices are permitted to form part of the network. Moreover, a novel blockchain-based data model has been incorporated in the schema to ensure data integrity and transparency by barring any changes and allowing quicker detection of malicious activities. Performance evaluations are conducted rigorously through MATLAB simulations using key areas of security metrics like attack strength, false authentication rates, and message alteration. The results demonstrate a 91% reduction in malicious device detection compared to traditional methods, which lack blockchain. Even though the proposed solution greatly robustifies IIoT security, constraints remain, as noted by the authors, with respect to verified delays that may be introduced by the blockchain. These findings present opportunities for future research. This synergy, when taken alongside trust management and blockchain does not only ensures network security but also it is a stolen leap against secure data handling in industrial applications.

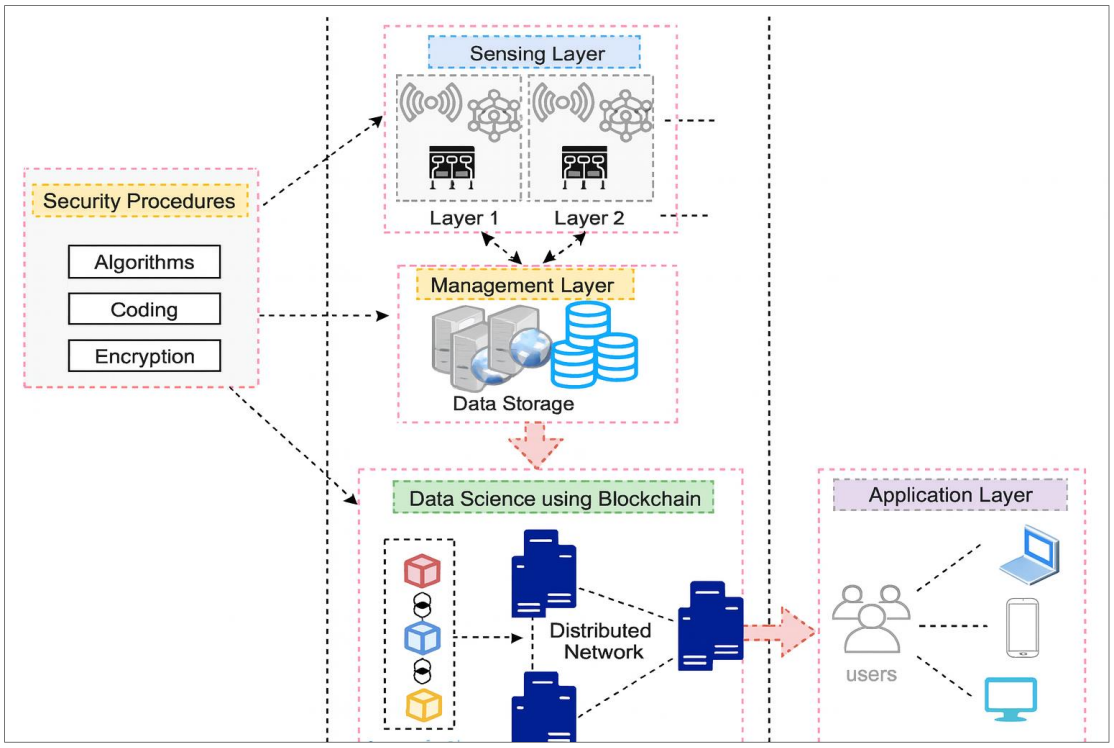

Figure 1: DS-IoT Blockchain in Industrial Internet of Things (IoT) (Rathee et al., 2023)

Chowdhury et al. (2023) conducted a comprehensive survey that encompasses all security arguments and vulnerabilities within the IoT ecosystem, as well as its potential application in blockchain technology for feasible access control and data integrity. Research suggests a substantial increase in the number of IoT devices, expected to total 29 billion by 2030, and highlights major security concerns such as physical breaches, unauthorized access, and data tampering. The authors employed a systematic review methodology to scrutinize 3,798 research papers, subsequently narrowing their focus to 195 relevant studies in order to categorize attack vectors and evaluate the suitability of existing blockchain frameworks, such as Hyperledger Fabric, in IoT environments. They further claim that while blockchain enables better security in IoT from the perspective of decentralized data management, issues such as scalability and latency have to be addressed. Their research not only reinforces the existing body of knowledge on blockchain and IoT but also highlights the areas that need further investigation and underscores the importance of exploring lightweight blockchain models and novel access control mechanisms. This exploration is pivotal for optimizing cybersecurity strategies in resource-constrained IoT environments.

Wang et al. (2021) noted that to implement an effective data management approach, industrial IoT systems must address numerous challenges, with one key issue being the need to balance the growth of IoT devices with sustainable data management practices. They proposed a blockchain-based DT management architecture with the potential to increase efficiency and lower information loss in a multi-agent framework wherein agents are actively vending data from physical assets. The proposed system employs a suitable, potentially fault-tolerant PBFT for securely processing requests and a modified Max-Weight-Delay algorithm to optimize sensing policies, thereby ensuring both energy sustainability and data fidelity. Decentralizing data through blockchain technology ensures its integrity by making it less dependent on a single source, which is vulnerable to failure, resulting in a more resilient data exchange system. The authors' analysis and simulation results demonstrate significant reductions in energy consumption and faster data availability, thereby validating the efficacy of their design in optimizing operational procedures across multiple sectors. This combined approach not only inculcates sustainability but also eradicates obsolescence and delinquent industrial processes through credible and timely data communication.

Alajlan et al. (2023) complete the assessment of cybersecurity arguments affecting blockchain-based Internet of Things (IoT) systems and their importance due to the increasing reliance on this technology being adopted in all industries. The authors identified three major areas of concern, such as IoT devices' security vulnerabilities, which include limited computational resources rendering them susceptible to attacks-inherent security issues of the blockchain, such as double spending and scalability constraints. To analyze these issues, the authors use a systematic literature review methodology following PRISMA guidelines to assess many studies to derive very insightful findings. The paper proposed innovative solutions like sharding and off-chain mechanisms to handle scalability and emphasized the importance of developing strong security measures, such as advanced encryption techniques, consensus algorithms, or access control schemas. In addition, the authors provide a taxonomy of blockchain-based IoT systems that highlights their key aspects of design; they also present future research directions focusing on the interoperability frameworks, regulatory compliance, as well as user adoption enhancement strategies. This review not only maps the current landscape but also makes it clear that there is a lot more space for future research to continue fortifying the cybersecurity framework of blockchain-enabled IoT applications, thus holding significant promise for the field.

The main challenge in smart homes is the security and privacy concerns inherent in the Internet of Things (IoT), which Dorri et al. (2022) addressed using a lightweight blockchain framework that does not need Proof-of Work or cryptocurrencies, which are incompatible with resource-constrained devices. This architecture comprises three key tiers: cloud storage, an overlay network, and one for the smart home, where a "miner" device provides secure communication and manages transactions among IoT devices. At this stage, a local private blockchain is presumed to ensure secure access management, maintaining an unalterable transaction log, and supports diverse transaction types including store, access, monitor, genesis, and remove transactions. These transactions use symmetric encryption and a lightweight hashing method meant to guarantee confidentiality, integrity, and availability at minimum overhead cost. The simulation results demonstrate that these findings are sufficient to eliminate potential threats like attachments and DDoS attacks. The novelty of this development for security practices within smart homes contributes to the dynamic potential offered by extending a similar possibility to other IoT applications and underscores the requirement for adaptive and efficient security schemes in an environment characterized by numerous connected devices.

Rattanawiboomsom et al. (2023) presented an overview of IoT devices in the healthcare spectrum that facilitate real-time monitoring and analysis of patient data for the improvement of monitoring and care. However, we contend that centralized processing of data faces grave difficulties in this regard, such as those arising from data manipulation and privacy. We undertook a systematic review of relevant literature on blockchain technology's potential for decentralized e-healthcare systems, conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We focused on how blockchain aids in establishing data integrity and security through smart contracts, relating to secure user authentication to access IoT devices, using data from the Scopus database. Our major findings suggest that blockchain technology is vital to pharmaceutical supply chain management, with direct implications for patient safety and welfare amid disruptions. Among others, cloud computing, fog computing, and medical services come out as considerable research themes, although the literature was found to be deficient concerning smart contracts as applied in healthcare settings. The integration of blockchain and IoT technology in healthcare is expected to result in more accurate diagnoses, tailored treatments, and more efficient administrative processes, which could ultimately lead to enhanced patient outcomes and create further opportunities for research in this rapidly evolving healthcare sector.

Sreelakshmi et al. (2020) thoroughly examines the convergence of Internet of Things (IoT) and blockchain technology to resolve pressing security and privacy issues in IoT systems. As the number of unified devices continues to increase, traditional centralized structures become somewhat incompetent against threats such as data breaches. The authors demonstrate how the decentralized character of the blockchain would enhance data integrity and privacy via immutable records and consensus algorithms. Use of smart contracts would automate the transactions, and they put forward the blockchain of things architecture to optimize the performance of IoT. The authors highlight the use of lightweight blockchain algorithms to address energy constraints along with security measures, such as intrusion detection systems (IDS), to further strengthen resilience. Specific case studies on smart healthcare and supply chain management show that significant integration benefits can accrue, stressing the need for further research to resolve security vulnerabilities in blockchain-lead IoT applications. Table 1 shows the solutions offered by blockchain in various IoT applications (Sreelakshmi et al., 2020).

No.	IoT Application Domains	Identification & Isolation of Malicious	Provenance	Security	Privacy	Traceability	Trust	Transparency	Non-Repudiation	Accountability
1	Smart city	✓	✓	✓			✓	✓		
2	Smart Grid		✓			✓	✓	✓	✓	✓
3	Smart Healthcare		✓	✓	✓	✓	✓	✓	✓	✓
4	Supply chain management		✓	✓		✓	✓	✓	✓	✓
5	Intelligent Transport Systems	✓	✓	✓	✓		✓	✓	✓	✓
6	Smart homes & Buildings	✓	✓		✓		✓		✓	
7	Industrial IoT & Smart Manufacturing		✓				✓		✓	

Table 1: Solutions offered by blockchain in various IoT applications (Sreelakshmi et al., 2020)

Chen et al. (2024) focus on the pressing question of security on the Internet of Things (IoT) because existing security mechanisms usually do not provide adequate protection against unauthorized access, identity spoofing, and data integrity breach challenges. A proposed architecture integrates BaaS to enhance hybrid IoT security with supplementary security management and increased functionality. Their investigation indicates and classifies the security threats in the settings of edge and fog computing, which stress the deficits of traditional solutions that are generally fragmented and resource-intensive. One of their key contributions is the development of a blockchain-based security framework that incorporates ZKP authentication, with experimental testing using the web3.js library to show its effectiveness in real IoT scenarios and achieve high-performance efficiency. The findings demonstrated that their mechanism can efficiently thwart specific attacks like identity spoofing and data manipulation, thus paving the way for decentralized security solutions that adhere to Web 3.0 standards. This work will have far-reaching potential, providing due support for the advancement of IoT security frameworks, a platform for future findings, and their implication in an ever-dynamic field. Figure 2 presents the classification of blockchain-based IoT solutions (Chen, 2024).

Alzoubi (2024) discussed the combination of Blockchain technology with the Internet of Things (IoT) to provide enhancement of security, privacy, and trust. The systematic literature review, which constituted the research methodology with frameworks such as PRISMA, highlighted critical encounters, including data privacy, security vulnerabilities, and interoperability issues related to IoT applications. The paper showed how Blockchain, by virtue of its decentralization, immutability, and transparency, could address problem areas through secure data transactions and automated device authentication. Specification 22a, which demonstrates interaction among IoT devices, edge nodes, and Blockchain networks, has also been provided. Nevertheless, challenges such as scalability, energy consumption, and regulatory complexities are mentioned. Alzoubi concluded that integrating blockchain technology with IoT brings security and efficiency opportunities, but there is a need for strategic approaches to deal with obstacles.

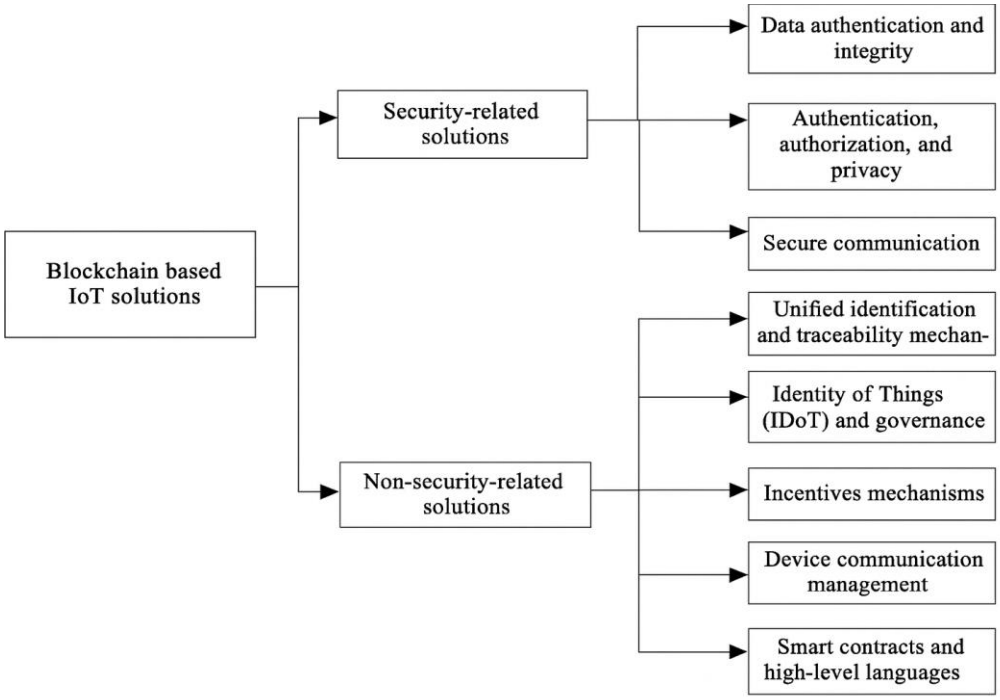

Figure 2: Classification of blockchain-based IoT solutions (Chen, 2024)

2.1. Comparison Table of the Literature Review

An overview of the current literature is presented in this comparison. As described in the table of comparison, the parameters include the proposed blockchain model with IoT, originality, addressed problem, advantages, and disadvantages. With the help of Table 2, innovations, challenges, and effectiveness are presented for comparison in regard to blockchain-based security solutions for IoT applications. As additional insights emerge from the remaining papers, the table will receive further revisions.

Table 2: Comparison of all the literature reviews

Paper author/s	Proposed Model	Novelty	Problem Addressed	Strengths	Weaknesses
Cheng et al. (2022)	Blockchain-based access control utilizing on-chain PDP and off-chain PAP.	Combination of smart contracts and off-chain components for improved performance.	Difficulty in deploying and securing IoT access control.	High throughput; improved transparency, traceability, and non-tampering.	Potential complexities and reliance on blockchain infrastructure.
Kotela et al. (2023)	Blockchain-integrated ABAC framework	Fine-grained access control via blockchain	Unauthorized device access and replay attacks	Transparent access control, improved security	High transaction fees and latency in Ethereum

Bao et al. (2021)	IoTChain: Three-tier blockchain security architecture	Integration of blockchain with edge computing	Mitigating security threats while maintaining low latency	Distributed computation, optimized for IoT	Requires optimization for large-scale deployments
Dhieb et al. (2020)	Scalable blockchain-based architecture with sidechains	Off-chain storage for improved efficiency	High computational costs in traditional blockchain	Low latency, improved scalability	Complexity in implementing interoperability
Miaz & Ali (2020)	Hybrid blockchain for IoT security	Combination of blockchain with security protocols	Secure device authentication and communication	Energy-efficient consensus mechanism	Regulatory challenges and protocol standardization needed
Sargsyan et al. (2022)	Security-by design blockchain framework	Automated security policy enforcement	Trust management and end-to-end encryption	Enhanced trust and security management	Compliance and integration complexity
Rathee et al. (2023)	Consortium blockchain for Industrial IoT	Smart contract automation for industrial security	Data integrity and transparency in industrial networks	Reduced human intervention, improved security	Network latency and scalability concerns
Chowdhury et al. (2023)	Survey on blockchain for IoT threats	Comparative analysis of security solutions	Scalability, regulatory compliance, interoperability	Insights on multiple blockchain mechanisms	Lacks experimental validation
Wang et al. (2021)	Blockchain-based digital twin management	Secure synchronization for IoT devices	Ensuring data integrity in digital twin architectures	Tamper-proof records, lifecycle management	Storage efficiency and data processing overhead
Alajlan et al. (2023)	Blockchain cybersecurity assessment	Systematic review of blockchain risks	51% attacks, Sybil attacks, consensus vulnerabilities	Proposes hybrid security models	Lack of standardized security frameworks
Dorri et al. (2022)	Blockchain-enabled smart home security	Privacy-preserving authentication	Unauthorized access in smart home networks	Decentralized control, improved user privacy	Blockchain latency affecting real-time operations
Rattanawiboomsom et al. (2023)	Blockchain applications in healthcare IoT	Systematic review of healthcare security	Securing patient data using blockchain	Enhance privacy and data integrity	Regulatory challenges and interoperability issues
Sreelakshmi et al. (2020)	Securing IoT applications using blockchain	Comprehensive survey on blockchain integration	Enhancing security in IoT networks	Provides an overview of multiple blockchain mechanisms	Lacks detailed experimental validation
Chen et al. (2024)	Blockchain-as-a-Service for IoT security	Exploring BaaS for securing IoT ecosystems	Simplifying blockchain deployment for IoT security	Reduces the complexity of blockchain adoption	High dependency on third-party BaaS providers

Alzoubi, 2024	Blockchain in IoT: Security, Applications, Technologies, and Challenges	Broad analysis of blockchain applications in IoT	Addressing multiple security challenges in IoT	Comprehensive coverage of security, applications, and trends	Generalized findings, lacks specific implementation details

3. Methodology

This paper relies on a systematic review to analyze where research currently stands regarding the integration of blockchain technology into securing IoT ecosystems. The aim is to highlight key security challenges, innovative blockchain-based solutions, and potential areas for further research. The research proceeded through stages of literature search, selection criteria, data extraction, comparative analysis, and synthesis of insight into the research topic. Below is a detailed exposition of the entire methodology is provided below:

3.1. Literature search and selection criteria

A complete literature search was performed across relevant databases: Google Scholar, Web of Science, Scopus, ResearchGate, and IEEE Xplore. The key interest was on articles published in peer-reviewed journals, conference proceedings, and prominent studies on blockchain security in IoT. The literature being reviewed was confined to publications that appeared between 2021 and 2024 to consider only the recent developments in this area.

The following keywords were employed during the search:

- “Blockchain technology in IoT security”
- “Security challenges in the IoT”
- “Access control mechanisms using the blockchain”
- “Decentralized security solutions for the IoT”
- “Smart contracts in Internet of Things applications”

3.1.1. Inclusion Criteria

- Research addressing blockchain-based security measures specifically designed for IoT
- Research papers outlining methods, architectures, or approaches designed to mitigate security weaknesses in Internet of Things networks.
- Comprehensive Analyses of challenges and security threats posed by IoT environments are summarized in this paper.

3.1.2. Exclusion Criteria

- Studies that do not explicitly focus on the intersection of blockchain technology and IoT security.
- Publications before 2021, unless they present essential foundational knowledge crucial for understanding contemporary advancements.

The selection process adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which were accompanied by a visual depiction of the selection process presented in a PRISMA flow diagram as shown in Figure 3.

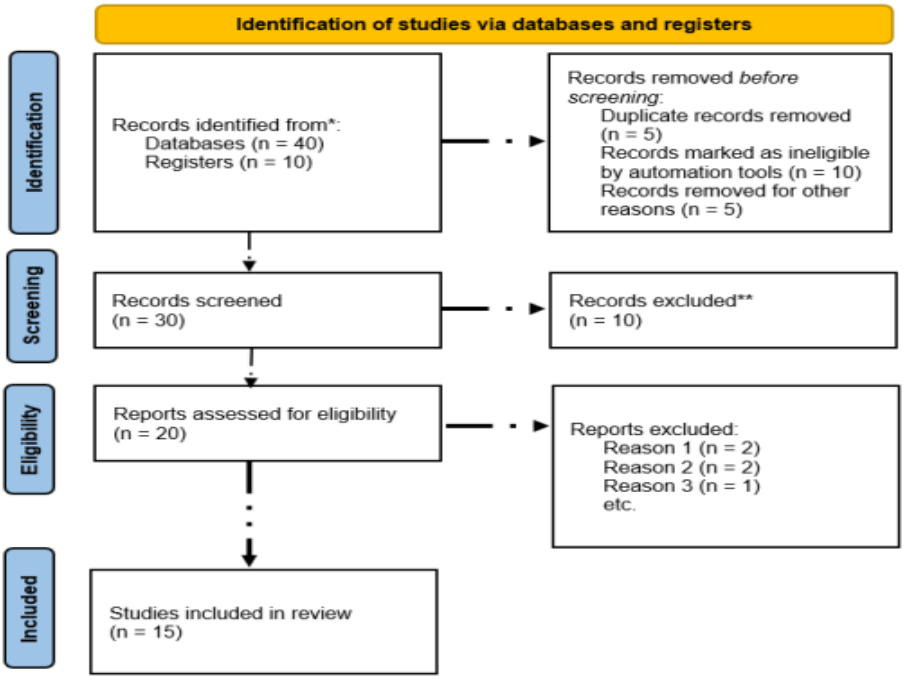

Figure 3: PRISMA flow diagram.

3.2. Data extraction and categorization

Critical data points were extracted from the selected studies, concentrating on blockchain techniques, methodologies, security challenges, and countermeasures within the IoT context. The extracted data included specifics such as:

- Blockchain Models Used: Types of blockchain frameworks (public, private, and hybrid).
- Security Threats Addressed: Common IoT threats include unauthorized access, data breaches, and DoS attacks.
- Proposed Solutions: Access control model types, consensus mechanisms, and smart contract applications.
- Identified vulnerabilities: weaknesses within IoT deployments and potential attack vectors.
- Strengths and Limitations: Evaluations of the methodologies' effectiveness and practical drawbacks.

The data were organized into the following thematic categories:

1. Blockchain Models for Internet of Things Security: Use Cases of Various Blockchain Frameworks.

2. Challenges and Threats in IoT: Key vulnerabilities and attack vectors specific to IoT devices.
3. Mitigation Strategies: Proposed Countermeasures and Frameworks for Enhancing Security
4. Areas requiring additional investigation or verification include research gaps and challenges.

3.3. Comparative Analysis

A comparative analysis was conducted to assess the strengths and weaknesses of the methodologies and frameworks proposed in the reviewed studies. Comparisons were based on the following criteria:

- The originality and importance of the proposed solutions in addressing IoT security vulnerabilities.
- Methodological Rigor: Robustness of research designs, including theoretical frameworks and empirical validation.
- The effectiveness of solutions is evaluated in real-world applications across various domains, such as smart homes and industrial IoT.
- Enumerated Challenges and Limitations: Key obstacles identified in previous research, such as scalability and resource consumption issues, were identified.

A comparative analysis table was constructed to evaluate these aspects across the studies systematically.

3.4. Synthesis and interpretation of the findings

The findings of the comparative analysis were synthesized to uncover emerging trends, recurring challenges, and prospective research avenues. The synthesis revealed the following key insights:

- Benefits of Decentralized Security: Blockchain technology has the potential to provide enhanced security through its decentralized framework.
- The Critical Need for Innovative Access Control: The growing importance of implementing robust access control measures to prevent unauthorized access in Internet of Things systems.
- Integration with Existing Protocols: Blockchain solutions must coexist with existing compliance and regulatory frameworks.
- Research gaps: identified areas lacking empirical validation or real-world deployment.

3.5. Research gaps and future directions

The review culminated with a discussion of significant research gaps and proposed future directions:

- Enhanced Consensus Mechanisms: The pursuit of novel consensus algorithms that can offer improved efficiency and scalability for Internet of Things applications.
- Interoperability Solutions: Standard protocols that facilitate seamless interaction between diverse IoT devices and blockchain ecosystems are needed.

- Robustness of Smart Contracts: Further research on optimizing smart contract execution for real-time applications within Internet of Things networks is required.
- Regulatory Compliance: Investigating how blockchain solutions can be aligned with global data protection regulations to ensure market readiness.

By systematically employing this methodology, this study contributes meaningful insights into the evolving intersection of blockchain technology and IoT security.

4. Discussion

A comparative study outlined in Section three highlights the advantages and disadvantages of using blockchain-based security solutions in IoT systems. This section expands on the key findings from the literature, focusing on IoT security issues, the research contributions of various studies, and the hurdles that need to be overcome.

4.1. Key Insights from the Literature

4.1.1. Decentralization-Enhanced Security

A few papers regarding blockchain, for instance, Cheng et al. (2022) and Kotela et al. (2023), show how the proposed blockchain access control mechanisms keep the system free from SPOF. This can be done by the adoption of smart contracts that ensure secure authentication and data integrity (Cheng et al., 2022; Kotela et al., 2023). Despite its potential, the scalability of this approach still requires improvement due to high transaction costs and latency concerns.

4.1.2. Improved Data Integrity and Privacy

The abovementioned studies, among many others, emphasize on the importance of blockchain technology in ensuring that data remains of high integrity and privacy within IoT networks (Bao et al. 2021; Wang et al. 2021). Digital twin management-offload synchronization in their respective storage solutions has a unique specificity in such a way that sensitive IoT data would be tamper-proof. Although, on the other side, most of these mechanisms are associated with data storage overhead and some processing delays.

4.1.3. Consensus Mechanisms and Optimization of Performance

Several papers have investigated consensus mechanisms that differ from the traditional Proof-of-Work (PoW) consensus for improving performance. For example, Miaz and Ali (2020) proposed energy-efficient consensus schemes with significantly reduced computation, and Sargsyan et al. (2022) proposed security by design frameworks. However, the implementations are too complex and face interoperability issues, making them difficult to adopt across the board (Miaz & Ali, 2020; Sargsyan et al., 2022).

4.1.4. Blockchain for Industrial IoT and Smart Homes

Numerous articles are devoted to domain-specific applications of blockchain, such as manufacturing IoT (Rathee et al., 2023) and intelligent homes (e.g., Dorri et al, 2022). They show how transparency is vastly enhanced by blockchain, while a smart contract drives security automation processes, as well as security against unauthorized access (Rathee et al., 2023; Dorri et al., 2022). However, blockchain latency and network congestion cause

performance issues in real-time. Figure 4 shows the results of security benefits and Figure 5 shows the results of adaptation of blockchain models.

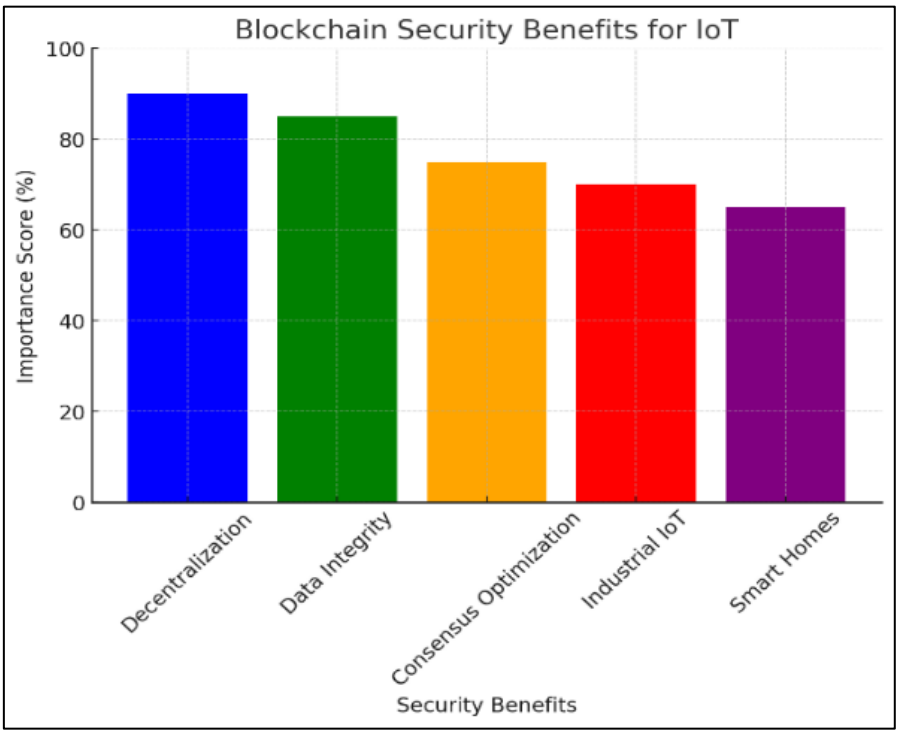

Figure 4: The importance of different blockchain security benefits for IoT

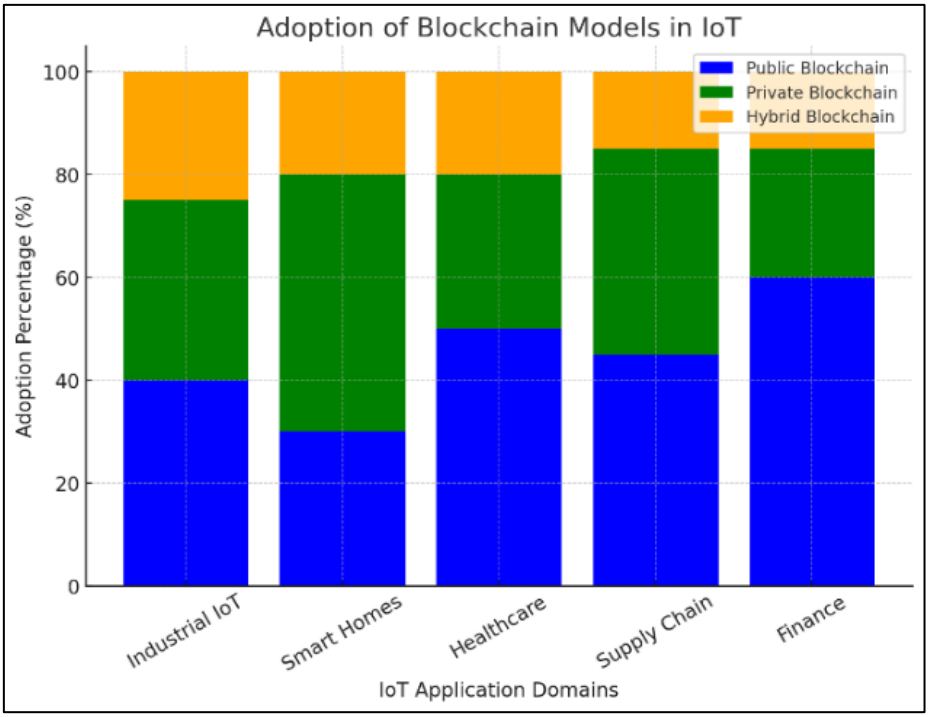

Figure 5: Adoption of Blockchain Models in IoT

4.2. Challenges and Open Issues

4.2.1. Scalability and transaction costs

Numerous academic research studies frequently reference scalability as a significant constraint. Performance bottlenecks in these networks emerge through high transaction costs, physical throughput restrictions, and external failures for sidechains and computing off-chain (Dhieb et al., 2020; Peterson et al., 2021). Nevertheless, improved solutions are pending further examination in this approach.

4.2.2. Regulatory and Compliance Issues

Blockchain-underpinning security models usually experience regulatory and compliance issues, especially in sensitive fields, such as healthcare (Dorri et al., 2022). A flexible blockchain framework ensuring the harmony of legal obligations with security is needed for compliance with data protection laws such as the General Data Protection Regulation (GDPR) and HIPAA (Dorri et al., 2022).

4.2.3. Interoperability between IoT Devices and Blockchain

Blockchain interoperability itself, therefore, becomes a hindrance in the adoption of blockchain in an IoT ecosystem. Different IoT devices operate on heterogeneous platforms, so their seamless integration into a blockchain network is difficult. Therefore, blockchain interoperability itself enables smooth communication between IoT systems and blockchain infrastructures (Chowdhury et al., 2023).

4.2.4. Use of Third-Party Backend as a Service (BaaS) Providers

Although blockchain-as-a-Service (BaaS)-type infrastructures (Wang et al., 2021) greatly facilitate deployments, they are responsible for dependencies on third parties, which could jeopardize security, lead to vendor lock-in, and incur operational costs (Wang et al., 2021). Figure 6 shows the distribution of challenges in blockchain-IoT integration.

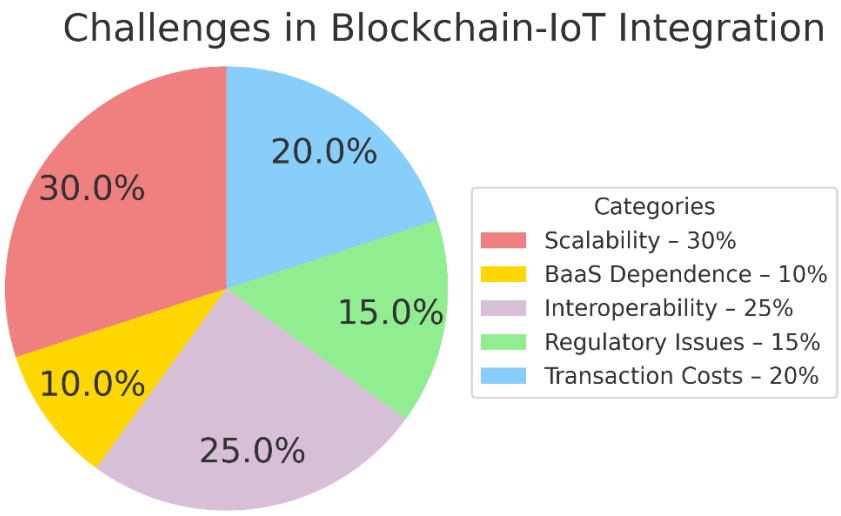

Figure 6: Distribution of challenges in blockchain-IoT integration

4.3. Future Directions

To address these challenges, future research should focus on the following:

- Scalability Solutions: Evolution towards more efficient consensus methods, such as proofs-of-stake (PoS) and directed acyclic graphs (DAGs), will result in better scalable blockchains.
- Regulatory Frameworks: Establishing a standardized framework for laws can ensure they are acceptable worldwide, thereby bringing global data protection laws into compliance.
- Interoperability Enhancements: Universal protocols are being developed for the unwavering integration of blockchain and various IoT gadgets.
- Implementing Smart Contracts with Optimization: This approach aims to boost the effectiveness of smart contracts, thus reducing execution costs and enhancing real-time processing capabilities (Hooda et al., 2024).

The presented discussion presents the strengths and weaknesses of some blockchain-based security solutions for IoT applications. Implementing blockchain technology does enhance security, however, issues such as scalability, regulatory constraints, and interoperability need to be resolved for it to be widely accepted (Yousif et al., 2025). The next section proposes a methodology for implementing a blockchain-based security framework for IoT systems.

5. Conclusion

This paper examines various blockchain-integrated models, which aim to address persistent security issues in IoT applications by implementing blockchain-based decentralized security solutions. A comparative literature review was conducted to analyze existing frameworks, investigate key challenges, and compare their strengths and weaknesses.

The study demonstrates that blockchain technology could greatly enhance the security of IoT systems through decentralized identity management, smart contract-based access control, and immutable data storage. Challenges, including scalability, transaction latency, and power consumption, continue to pose substantial problems requiring thorough examination. The proposed method incorporates an optimized blockchain framework that employs lightweight consensus mechanisms and off-chain storage solutions to address these issues.

In the future, research should be directed towards improving blockchain scalability for large-scale IoT networks, developing energy-efficient consensus algorithms, and ensuring interoperability with existing IoT infrastructure. Additionally, actual applications and case studies will play an important role in proving the feasibility of blockchain-based security models in real-world IoT applications.

In summary, despite offering a robust security framework for IoT applications via blockchain technology, ongoing innovations and interdisciplinary collaborations are required to address their limitations and unlock their full potential for creating secure, scalable, and efficient IoT systems.

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Author contribution

All authors have contributed, read, and agreed to the published version of the manuscript results.

Conflict of interest

The authors declare no conflict of interest.

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