Application of Hashing and Advanced Blockchain Technology for Digital Transactions in the Modern Era (Forensic Accounting and Auditing Perspective)

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Abstract

This study examines the role of cryptographic hashing as a foundational security primitive in blockchain-based digital transaction systems, with particular emphasis on integrity, transparency, auditability, and long-term cryptographic resilience. The research evaluates how hash-linked block structures, Merkle tree constructions, and decentralised consensus mechanisms enhance transaction immutability and resistance to unauthorised data modification when compared with traditional centralised architectures. Special attention is given to the implications of emerging quantum computing threats on classical public-key cryptographic schemes and the suitability of hash-based and post-quantum signature approaches, such as XMSS and SPHINCS+, for future-proof blockchain security. Using analytical comparison and conceptual system modelling, the study demonstrates that hashing-centred blockchain architectures significantly improve evidential integrity, traceability, and non-repudiation, making them particularly valuable for forensic accounting and auditing applications. The findings confirm that distributed hash verification eliminates single points of failure, strengthens audit trails, and supports transparent, tamper-evident financial recordkeeping. While hash-based and post-quantum mechanisms introduce additional computational and storage overhead, their resilience against projected quantum adversaries provides substantial long-term security benefits. Above all, the study concludes that the integration of cryptographic hashing, Merkle tree structures, and post-quantum–aware signature schemes offers a robust and sustainable framework for secure digital transactions. These mechanisms not only enhance current blockchain performance but also position blockchain systems as reliable infrastructures for future digital economies, regulatory compliance, and forensic assurance in increasingly complex and adversarial computational environments.

Keywords:
Blockchain, Cryptographic Hashing, Digital Transactions, Hash-Based Signatures, Post-Quantum Cryptography, Distributed Ledger Technology.

1. Introduction

The rapid growth of digital platforms has fundamentally transformed how financial and non-financial transactions are conducted in the modern economy. Contemporary society has experienced accelerated digitalisation of economic, social, and institutional systems, reshaping how transactions are created, verified, stored, and trusted. From electronic payment platforms and digital identity systems to e-governance applications and smart contracts, digital transactions now form the backbone of global economic activity. This transformation has significantly expanded transaction volumes across sectors such as finance, healthcare, logistics, and public administration.

As digital transactions increasingly occur over open, interconnected, and distributed networks, concerns relating to data integrity, authenticity, transparency, and trust have intensified. Traditional centralised digital transaction systems depend heavily on trusted intermediaries; such as banks, payment processors, and regulatory institutions; to enforce authentication, integrity, and accountability. While these intermediaries have

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historically provided confidence and oversight, they also introduce structural inefficiencies, single points of failure, and escalating operational costs.

Moreover, centralised transaction infrastructures are increasingly vulnerable to cyber-attacks, insider threats, data manipulation, and systemic outages. High-profile breaches and service disruptions have eroded public trust in centralised data custodians, particularly in environments where participants lack pre-existing trust relationships. These limitations have generated a global demand for decentralised, transparent, and cryptographically secured transaction frameworks capable of operating without reliance on central authorities.

In response to these challenges, blockchain technology has emerged as a critical infrastructure for secure digital transactions. Blockchain enables decentralised, tamper-resistant, and verifiable transaction records through distributed ledger mechanisms. By distributing transaction validation and storage across multiple nodes, blockchain eliminates single points of failure while enhancing transparency and auditability. Mehta *et al.* [1] observed that blockchain’s decentralised architecture, combined with cryptographic hashing and distributed consensus mechanisms, significantly improves transaction security and immutability.

A defining feature of blockchain systems is their reliance on cryptographic hashing. Hash functions convert transaction data into fixed-length outputs that are computationally infeasible to reverse or manipulate without detection. Through block chaining and Merkle tree constructions, hashing ensures that even minor alterations to transaction data propagate detectable inconsistencies throughout the ledger. Consequently, blockchain systems can maintain data integrity and transparency without centralised oversight.

At the technical core of blockchain architecture, cryptographic hashing underpins essential components such as block linking, Merkle trees, proof-of-work or proof-of-stake mechanisms, and transaction verification processes. These mechanisms collectively enable distributed consensus and trustless verification across network participants. Once transaction data are recorded and hashed, any unauthorized modification becomes computationally detectable, thereby reinforcing immutability and accountability across the system.

Despite these strengths, most operational blockchain platforms rely extensively on traditional public-key cryptographic (PKC) schemes, particularly Rivest–Shamir–Adleman (RSA) and Elliptic Curve Cryptography (ECC), for user authentication and digital signatures. These cryptographic systems derive their security from mathematical problems that are computationally infeasible for classical computers to solve. However, their continued reliability is increasingly uncertain in the face of emerging computational paradigms.

The advancement of quantum computing presents a fundamental threat to classical cryptographic systems. Quantum algorithms, most notably Shor’s algorithm, have demonstrated the theoretical capability to efficiently solve the integer factorization and discrete logarithm problems that underpin RSA and ECC [**2**]. As quantum computing matures, blockchain systems dependent on classical PKC may face significant long-term security risks, potentially compromising transaction authentication and digital signatures.

In response to this emerging threat, cryptographic research has shifted toward post-quantum cryptography (PQC), which aims to develop algorithms secure against both classical and quantum adversaries. Among various PQC approaches, hash-based cryptographic techniques have gained prominence due to their reliance on the security of cryptographic hash functions rather than number-theoretic assumptions. Hash-based signature schemes are widely regarded as among the most conservative and well-understood post-quantum solutions [**3**].

International standards bodies have begun formalising post-quantum cryptographic frameworks. The U.S. National Institute of Standards and Technology (NIST), for example, has advanced several post-quantum algorithms—including hash-based and lattice-based schemes, through its standardisation process to ensure long-term cryptographic resilience [**4**]. These developments have intensified interest in integrating post-quantum techniques into blockchain infrastructures to future-proof digital transaction systems.

Within this evolving technological landscape, it is increasingly important to reassess how cryptographic hashing and modern blockchain technologies can be systematically leveraged to

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strengthen digital transaction systems. Contemporary blockchain architectures are progressively exploring the integration of hash-centric and post-quantum cryptographic techniques as a means of future-proofing digital transaction infrastructures against emerging computational threats. Accordingly, this study is motivated by the need to examine both the theoretical foundations and practical applications of cryptographic hashing and modern blockchain technologies for securing digital transactions in the contemporary and post-quantum era.

The primary objective of this study is to empirically evaluate the extent to which cryptographic hashing and modern blockchain mechanisms enhance the security, integrity, and reliability of digital transactions. A secondary objective is to assess the effectiveness of hash-centric and post-quantum cryptographic approaches in mitigating emerging quantum-related security risks in digital transaction systems. In line with these objectives, the study is designed to specifically achieve the following objectives:

(i) To examine the impact of cryptographic hashing on transaction integrity and immutability in blockchain-based digital transaction systems.

(ii) To evaluate the comparative security performance of decentralised blockchain architectures relative to traditional centralised transaction systems.

(iii) To assess the long-term security advantages of hash-based and post-quantum cryptographic methods for sustaining secure digital transactions in the presence of emerging quantum threats.

(iv) To evaluate the applicability of blockchain hashing mechanisms for forensic accounting and auditing**,** particularly in enhancing audit trails, evidential integrity, traceability, and non-repudiation in digital financial records.

Based on the stated objectives, the study is guided by the following null hypotheses:

H_{01}: Cryptographic hashing does not significantly improve the integrity and immutability of digital transactions in blockchain systems.

H_{02}: Modern blockchain architectures do not significantly enhance transaction security compared to traditional centralised systems.

H_{03}: Hash-based and post-quantum cryptographic approaches do not provide significant long-term security advantages for digital transaction systems.

H_{04}: Blockchain-based hashing mechanisms do not significantly enhance the reliability, traceability, and evidential value of digital records for forensic accounting and auditing purposes.

2. Literature Review

Blockchain technology has become a foundational infrastructure for securing digital transactions across distributed networks, primarily through cryptographic hashing mechanisms that ensure integrity, immutability, and transparency. These properties allow distributed ledgers to operate without centralised control while maintaining verifiable and tamper-resistant transaction histories. However, most deployed blockchain systems still rely on classical public-key cryptography (PKC), notably RSA and Elliptic Curve Cryptography (ECC), for authentication and transaction validation. While secure under classical assumptions, these schemes face significant long-term risks from quantum computing. Shor's algorithm demonstrates that sufficiently powerful quantum computers can efficiently break the number-theoretic foundations of RSA and ECC, threatening the security of existing blockchain architectures [**5**].

This emerging threat has intensified research into post-quantum cryptography (PQC), which seeks cryptographic primitives resilient to both classical and quantum attacks. Among PQC candidates, hash-based cryptography has attracted sustained attention due to its reliance on well-understood hash function properties rather than vulnerable mathematical assumptions. Paar and Pelzl [6] describe cryptographic hash functions as deterministic, one-way mappings that satisfy pre-image resistance, second-pre-image resistance, and collision resistance such properties that are particularly well suited to distributed systems requiring strong data integrity and tamper detection. In blockchain environments, hashing underpins block formation, transaction chaining, and Merkle tree construction, ensuring that any data modification propagates detectable inconsistencies across the network.

The broader security implications of quantum computing for cryptographic infrastructures have been extensively analysed. Bernstein, Buchmann, and Dahmen [5] argue that number-

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theoretic cryptography will inevitably degrade as quantum technologies mature, necessitating a structural shift toward quantum-resistant alternatives. Hash-based digital signature schemes represent one of the most mature and theoretically robust PQC classes. Buchmann, Dahmen, and Hülsing [7] show that the security of hash-based signatures depends solely on the strength of underlying hash functions. While early constructions such as Lamport signatures were limited to one-time use, later developments—including Winternitz signatures and Merkle tree-based schemes—enabled scalable multi-signature functionality.

Standardisation efforts have further accelerated practical adoption. The NIST post-quantum cryptography standardisation programme formally recognises hash-based signature schemes such as XMSS and SPHINCS+ as viable post-quantum standards [4], reinforcing their relevance for future digital infrastructures. Blockchain-focused studies confirm their applicability within distributed ledger systems. Chen, Jordan, and Moody [8] demonstrate that integrating hash-based signatures into blockchain architectures enhances long-term security without compromising decentralisation, although challenges related to signature size, computational overhead, and state management remain.

Governance and protocol-level considerations are also critical. Buterin [9] cautions that abrupt cryptographic transitions may disrupt consensus mechanisms in public blockchains and advocates hybrid cryptographic models combining classical and post-quantum techniques as a pragmatic migration strategy. Further studies emphasise the need for standardisation, optimisation, and coordinated adoption frameworks to ensure interoperability and scalability of hash-based systems [1].

Advances in stateless hash-based cryptography further strengthen feasibility. Hülsing, Rijneveld, and Song [10] introduce SPHINCS+, eliminating state-management complexities while preserving strong post-quantum guarantees. Comparative surveys by Perlner and Cooper [11] conclude that hash-based approaches offer superior maturity and conservative security assumptions relative to other PQC families. From an architectural perspective, Merkle tree-based hash aggregation enables efficient and immutable verification of large datasets, a principle central to blockchain auditability and transparency. By eliminating single points of failure, blockchain systems outperform centralised models in integrity assurance and trust distribution. Consistent with Gahlod and Bhanse [12], hash-driven, Merkle-based blockchain designs significantly enhance the security and resilience of cloud-integrated digital transaction systems.

In general, the literature establishes cryptographic hashing as the cornerstone of blockchain security and identifies hash-based post-quantum cryptography as a leading pathway for safeguarding future digital transaction systems. Nonetheless, gaps remain in integrating hashing, blockchain architecture, distributed trust, and post-quantum security into a unified applied framework, particularly within financial and forensic investigative contexts. This gap motivates the present study.

Hash-Based and Classical Signature Schemes in Blockchain Systems

Several cryptographic signature schemes have played notable roles in blockchain-based digital transaction systems, particularly with respect to authentication, integrity assurance, and long-term security. Hash-based signature scheme in blockchains technology is considered blockchain system that uses cryptographic hashes as the backbone of trust, linking transactions, securing blocks, enabling decentralised verification, and preserving an immutable and auditable transaction history. A hash-based blockchain system is a blockchain architecture in which cryptographic hash functions form the core security and integrity mechanism for transaction processing, data storage, and verification, rather than relying primarily on traditional public-key cryptography alone. In such a system, *hashing is the foundational trust primitive* used to link transactions, validate blocks, secure audit trails, and ensure immutability across a distributed ledger. The following are related core concepts:

RSA (Rivest–Shamir–Adleman) is a classical public-key cryptographic algorithm whose security relies on the computational difficulty of integer factorization. In early blockchain and distributed ledger implementations, RSA was employed for digital signatures and transaction authentication, allowing users to sign transactions and verify key ownership. However, RSA is fundamentally vulnerable to quantum computing attacks. Shor’s algorithm enables efficient factorization of large integers on a sufficiently powerful quantum computer,

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thereby undermining RSA's security assumptions. Consequently, RSA is increasingly viewed as unsuitable for long-term blockchain security, especially in post-quantum threat environments [2], [5].

In contrast, **XMSS (eXtended Merkle Signature Scheme)** is a stateful, hash-based digital signature scheme explicitly designed to achieve post-quantum security. XMSS derives its security entirely from the properties of cryptographic hash functions and Merkle tree constructions, rather than from number-theoretic hardness assumptions. Within blockchain systems, XMSS can be applied to quantum-resistant transaction signing and block validation, ensuring ledger integrity even in the presence of quantum adversaries. Although its stateful design requires careful key and state management, XMSS offers provable security guarantees that make it a strong candidate for future blockchain authentication mechanisms [7], [13].

SPHINCS (Stateless Practical Hash-Based Incredibly Nice Cryptographic Signatures) represents a stateless alternative within the family of hash-based post-quantum signature schemes. Unlike XMSS, SPHINCS eliminates the need for signer state tracking, which is particularly advantageous in decentralised and large-scale blockchain environments where state management is operationally challenging. Although SPHINCS signatures are comparatively larger and computationally more intensive, they provide strong quantum resistance and high operational flexibility, making them well suited for future-proof blockchain transaction authentication [4], [10].

Table 1: Comparative Context in Blockchain Systems

Scheme	Full Meaning	Blockchain Role	Quantum Resistance
RSA	Rivest–Shamir–Adleman	Classical transaction signing and authentication	✗ No
XMSS	eXtended Merkle Signature Scheme	Stateful post-quantum transaction authentication	✓ Yes
SPHINCS	Stateless Practical Hash-Based Incredibly Nice Cryptographic Signatures	Stateless post-quantum blockchain signatures	✓ Yes

The table above indicated the comparative analysis of RSA, XMSS and SPHINCS. Summarily, while RSA historically supported blockchain authentication, its susceptibility to quantum attacks significantly limits its long-term viability. By contrast, XMSS and SPHINCS embody hash-based, post-quantum alternatives that align closely with blockchain's decentralised trust model, offering resilient security for future digital transaction systems.

Table 2: Hash-Based Signature Schemes for Blockchain Applications and Quantum Resistance

Signature Scheme	Full Meaning	State Type	Primary Blockchain Use	Quantum Resistance	Ref.
Lamport OTS	Lamport One-Time Signature	Stateful (one-time)	Conceptual blockchain authentication; foundational research	Yes	[14], [3]

Winternitz OTS (WOTS)	Winternitz One-Time Signature	Stateful (one-time)	Efficient transaction signing with reduced signature size	Yes	[14], [3]
WOTS+	Enhanced Winternitz One-Time Signature	Stateful (one-time)	Improved efficiency and security for blockchain signing	Yes	[14], [3]
Merkle Signature Scheme (MSS)	Merkle Tree–Based Signature Scheme	Stateful	Aggregation of multiple one-time keys in blockchains	Yes	[11]
XMSS	eXtended Merkle Signature Scheme	Stateful	Post-quantum blockchain transaction authentication	Yes	[7], [13]
XMSS-MT	XMSS Multi-Tree	Stateful	Scalable blockchain signing with reduced tree height	Yes	[7], [13]
SPHINCS	Stateless Practical Hash-Based Incredibly Nice Cryptographic Signatures	Stateless	Large-scale decentralised blockchain environments	Yes	[4], [10]
SPHINCS+	Improved SPHINCS Signature Scheme	Stateless	Standardised post-quantum blockchain authentication	Yes	[4], [10]

The table demonstrates that hash-based signature schemes uniformly provide quantum resistance because their security depends on cryptographic hash functions rather than vulnerable number-theoretic assumptions. Early schemes such as Lamport and Winternitz signatures established the theoretical foundations of hash-based cryptography but are constrained by one-time usage limitations [14], [3]. Merkle-tree-based constructions, including XMSS and XMSS-MT, address scalability challenges and enable practical blockchain deployment, albeit with state-management requirements [7], [13], [11]. Stateless schemes such as SPHINCS and SPHINCS+ remove these constraints entirely, making them particularly suitable for decentralised blockchain environments where signer state tracking is impractical [4], [10].

Blockchain Hashing and Security Framework

Blockchain is a decentralised and distributed digital ledger in which transactions are grouped into chronologically linked blocks and maintained collectively by network participants rather than a central authority. Each block contains a set of validated transactions, a timestamp, and a cryptographic hash of the preceding block, creating an immutable chain structure. This design, combined with decentralised consensus mechanisms, enhances fault tolerance, auditability, and resistance to single-point-of-failure attacks, making blockchain particularly suitable for secure financial, accounting, and public-sector systems [15], [16]. Figure 1 illustrates a fully distributed blockchain ledger network in which all nodes maintain synchronised copies of the ledger and jointly validate transactions.

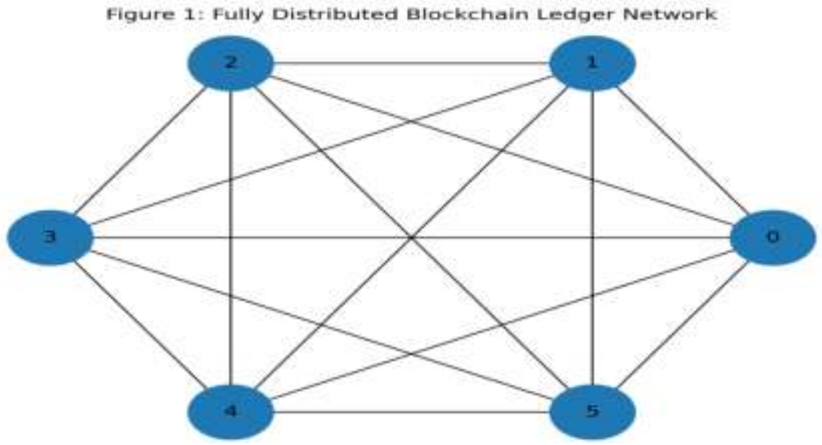

Figure 1. Fully distributed blockchain ledger network in which all participating nodes maintain synchronised copies of the ledger and collectively validate transactions through decentralised consensus mechanisms [15], [16].

Cryptographic hashing constitutes the core security primitive underpinning blockchain architectures. A cryptographic hash function maps input data of arbitrary length to a fixed-length output in a deterministic yet computationally irreversible manner. Secure hash functions such as SHA-256 and SHA-3 exhibit pre-image resistance, second pre-image resistance, and collision resistance, which are essential for ensuring data integrity. In blockchain systems, hashing links blocks through hash pointers, structures transaction data using Merkle trees, and supports consensus mechanisms such as Proof of Work. Any alteration to transaction data results in a radically different hash value, thereby immediately exposing tampering attempts and preserving ledger integrity [17], [18]. Figure 2 contrasts this distributed trust model with traditional centralised architectures.

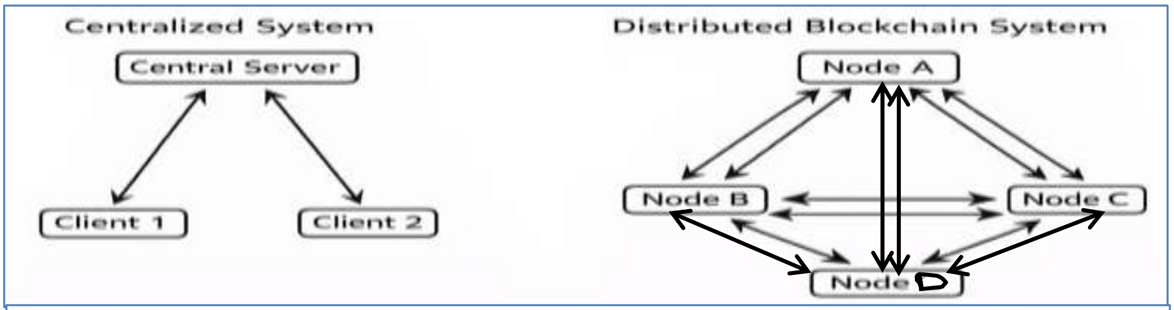

Figure 2. Comparison of centralized and distributed ledger architectures highlighting decentralization, fault tolerance, and improved auditability in blockchain systems.

While hashing secures data integrity, transaction authenticity and non-repudiation are achieved through digital signatures. Hash-based signature (HBS) schemes represent a class of digital signature mechanisms whose security relies exclusively on cryptographic hash functions rather than number-theoretic assumptions. Unlike conventional public-key cryptography, which depends on factorisation or discrete logarithm problems that are vulnerable to quantum algorithms, HBS schemes derive their security from the one-way and collision-resistant properties of hash functions. As a result, HBS schemes are regarded as inherently resistant to known quantum attacks and are increasingly explored as post-quantum alternatives for blockchain security [19], [20].

Several HBS schemes have been proposed for practical deployment and developed to support secure and efficient blockchain operations, including Lamport signatures, Winternitz One-Time Signatures (WOTS), the Leighton–Micali Signature Scheme (LMS), and the eXtended Merkle Signature Scheme (XMSS). These schemes employ Merkle tree constructions to enable efficient public-key verification while preserving strong security

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guarantees. Recent studies, including Mehta *et al.* [1], highlight the suitability of HBS schemes for blockchain environments that require long-term cryptographic resilience, particularly in applications where ledger immutability must be preserved over decades.

Mehta *et al.* [1] further identify critical future research directions under *The Future of Blockchain Hashing: Hash-Based Signatures and Beyond*. These include signature optimisation techniques such as Merkle tree compression to reduce authentication path sizes, adaptive parameter selection to balance security and performance, and aggregate signature constructions that minimise verification overhead. Additional challenges relate to HBS state management, with proposed solutions including decentralised key-tracking mechanisms, ephemeral key pools, and hybrid stateful–stateless models. Hardware acceleration using ASIC-optimised hashing units, GPU-based parallel verification, and secure enclave integration is also emphasised to enhance performance and key protection. Finally, hybrid cryptographic frameworks combining HBS with other post-quantum cryptographic techniques, such as lattice-based and threshold signatures, are proposed to support adaptive, multi-layered blockchain security architectures [13], [21].

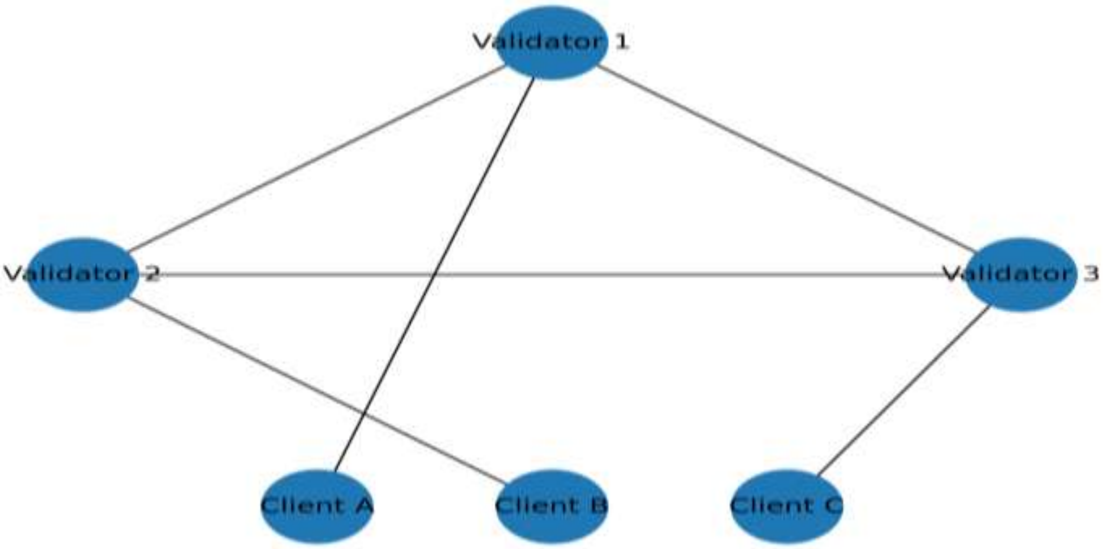

Fig. 3 Permissioned blockchain architecture showing authorised validator nodes responsible for transaction validation and block creation, while client nodes submit and query transactions [22], [23]

Figure 3 presents a permissioned blockchain architecture in which authorised validator nodes perform transaction validation and block creation, while client nodes submit and query transactions. Such architectures improve scalability, governance, and throughput, making them suitable for enterprise and public-sector blockchain deployments.

Types of Hash-Based Signature Schemes

1) Lamport Signatures: Lamport signatures represent one of the earliest digital signature schemes and are based entirely on one-way hash functions. They are one-time-use schemes in which a private key consists of a set of random values

$sk_0,sk_1,\ldots\ldots,sk_n$,

while the public key is formed by hashing each private value:

$pk_i=H(sk_i)$.

To sign a message, selected elements of the private key are revealed based on the message's bit representation. While highly secure, Lamport signatures suffer from large key sizes and limited practicality for large-scale blockchain systems [19].

2) Winternitz One-Time Signatures (WOTS): WOTS improves upon Lamport signatures by reducing key size and signature length through a hash-chain construction. Instead of revealing key elements for each message bit, WOTS applies iterative hashing, significantly improving efficiency while retaining strong security guarantees, making it more suitable for blockchain environments [20].

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3) Leighton–Micali Signature Scheme (LMS): LMS extends one-time signatures by organizing them within a Merkle tree, allowing multiple signatures to be generated from a single public key [7]. The authentication path for each signature is derived from the Merkle tree root:

Root = $H(H(\text{leaf}_1) \| H(\text{leaf}_2) \| \ldots \| H(\text{leaf}_n))$.

This structure enhances scalability and makes LMS practical for real-world blockchain and distributed ledger applications [21].

4) eXtended Merkle Signature Scheme (XMSS): XMSS is a stateful hash-based signature scheme standardised by NIST and explicitly designed for long-term security. By combining Merkle trees with robust state management, XMSS enables efficient generation of multiple signatures while maintaining strong post-quantum security guarantees, making it particularly attractive for blockchain-based financial and transactional systems [4], [13].

Theoretical Underpinnings

This study is anchored by well-established digital and systems technology theories that collectively explain the security, resilience, and future sustainability of blockchain-based digital transaction systems. These include cryptographic hash function theory, distributed systems theory, trustless systems and institutional trust theory, and post-quantum cryptographic theory. Together, these theoretical lenses provide the conceptual foundation for evaluating hash-centric blockchain architectures and the post-quantum signature schemes summarised in Table 2 above.

Cryptographic Hash Function Theory provides the mathematical foundation for blockchain security by explaining how hash functions ensure data integrity, immutability, and tamper detection. Hash functions map arbitrary-length inputs to fixed-length outputs while exhibiting properties such as pre-image resistance, second-pre-image resistance, and collision resistance. In blockchain systems, these properties ensure that once transaction data are hashed and recorded, any modification becomes computationally detectable across the distributed ledger. This theory directly underpins blockchain immutability and explains why hash-based signature schemes, such as XMSS and SPHINCS summarised in Table 2 are suitable candidates for post-quantum security mechanisms [25], [26].

Distributed Systems Theory explains how blockchain networks achieve coordination and consistency without centralised control. The theory addresses how independent nodes communicate, replicate data, and reach consensus despite latency, faults, or adversarial behaviour. Blockchain systems apply core distributed systems principles—including replication, fault tolerance, and consensus protocols—to maintain synchronised and trustworthy transaction records across nodes. This theoretical lens is essential for evaluating the comparative security and resilience of decentralised blockchain architectures relative to centralised transaction systems, particularly in hostile network environments [27], [28].

Trustless Systems and Institutional Trust Theory challenges traditional reliance on centralised intermediaries by replacing institutional trust with cryptographic proof and algorithmic verification. In blockchain environments, trust is established through transparent protocols, cryptographic hashing, and consensus mechanisms rather than through banks, regulators, or other centralised authorities. This theory explains how blockchain enables secure digital transactions among participants without pre-existing trust relationships and provides a conceptual basis for the superiority of hash-centric blockchain security models discussed in Table 2**,** especially in low-trust or adversarial digital ecosystems [15], [29].

Post-Quantum Cryptography Theory addresses the limitations of classical cryptographic systems in the context of advancing quantum computing capabilities. Traditional public-key cryptographic schemes rely on mathematical problems that are vulnerable to quantum algorithms, thereby creating long-term security risks for digital infrastructures. Post-quantum cryptography proposes alternative constructions—such as hash-based, lattice-based, and code-based schemes—that remain secure against both classical and quantum adversaries. This theoretical framework directly supports the

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study’s focus on hash-based signature schemes, including XMSS and SPHINCS+, as sustainable long-term security solutions for blockchain-based digital transaction systems, as empirically and comparatively illustrated in Table 2 [4], [30].

3. Methodology

Research Design

This study adopts a technology-oriented analytical research design grounded in science- and systems-based inquiry, consistent with methodologies commonly employed in cryptographic and blockchain security research. The approach integrates theoretical modelling, cryptographic system analysis, blockchain architecture evaluation and security and performance benchmarking to assess the role of cryptographic hashing and modern blockchain technologies support secure digital transactions.

The study is non-empirical and does not involve primary data collection. Instead, it relies on structured analysis of established cryptographic standards, peer-reviewed technical literature, and documented blockchain implementations, and system analyses. This design is consistent with technology-focused security research and appropriate for evaluating system robustness, security properties, and architectural suitability rather than behavioural or user-level outcomes. The mixed-method technical analysis framework employed, comprising: conceptual blockchain system modelling; cryptographic architecture analysis; security and performance benchmarking and comparative systems evaluation enables systematic examination of both cryptographic primitives and system-level architectures, in line with IEEE and Springer expectations for security and systems research.

Analytical Procedure

Stage 1: Structural Analysis of Blockchain Hashing Mechanisms: A structural examination of blockchain transaction workflows was conducted to identify how cryptographic hashing supports data integrity, immutability, and transaction verification. Hash function usage was mapped across **t**ransaction creation and validation, block formation, Merkle tree construction, digital signature validation, and consensus processes of hashing in blockchain security. This stage established the functional role of hashing within blockchain systems and its contribution to tamper detection and data consistency.

Stage 2: Comparative Cryptographic Evaluation: A comparative cryptographic framework was applied to contrast classical public-key–based transaction systems with hash-centric and post-quantum alternatives. Security assumptions, scalability and **r**esistance to quantum adversaries, computational and storage overhead, and implementation complexity of schemes such as ECDSA, XMSS, and SPHINCS+ were synthesised from prior studies, technical standards documentation, and documented implementations, ensuring methodological rigor and reproducibility.

Stage 3: Scenario-Based Blockchain System Evaluation and Application Analysis: To assess practical applicability, representative blockchain application scenarios, including financial and payment transactions, smart contracts execution, Internet-of-Things (IoT) micro-transactions, distributed identity systems, and forensic accounting and audit trail management were analysed to evaluate the operational suitability, resilience, and long-term viability of hashing-oriented and post-quantum blockchain architectures. Particular emphasis was placed on forensic accounting and audit-related use cases, such as immutable audit trails, transaction traceability, and non-repudiation.

System Architecture Framework

A modular blockchain transaction architecture was conceptualised, consisting of the following layers:

1. Transaction Layer – user authentication, digital signatures, and identity verification
2. Hashing Layer – cryptographic hash functions ensuring data integrity and immutability
3. Consensus Layer – distributed validation and agreement protocols
4. Ledger Layer – decentralised data storage and synchronisation
5. Application Layer – financial systems, governance platforms, healthcare records, IoT, and audit applications and systems

This layered abstraction facilitates systematic evaluation of security and performance across blockchain components.

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Cryptographic Security Metrics

The hashing architecture was evaluated using three core cryptographic security properties:

- Collision resistance
- Pre-image resistance
- Second pre-image resistance

These properties were assessed in relation to their effectiveness in preventing data manipulation, unauthorised data modification, and evidential compromise thereby preserving evidential integrity..

Performance Evaluation Metrics

System performance was analysed using the following commonly adopted blockchain performance indicators:

a) Transaction throughput
b) Verification latency
c) Storage efficiency
d) Computational overhead

These metrics enable objective comparison between centralised systems and decentralised, hashing-based blockchain architectures.

Analytical Tools and Evaluation Methods

Conceptual models, architectural diagrams, cryptographic performance models, and comparative evaluation matrices were employed to assess the operational efficiency, security robustness, and forensic suitability of hashing-based blockchain systems. The analysis emphasises deterministic verification and reproducibility, aligning with IEEE Transactions and Springer expectations for technical validity.

Methodological Alignment with Research Objectives

The methodology adopted supports the objectives of this study directly by enabling:

a) Evaluation of hashing on transaction integrity and immutability
b) Comparative assessment of decentralised and centralised security architectures
c) Analysis of post-quantum cryptographic sustainability
d) Assessment of blockchain applicability for forensic accounting and auditing

4. **Results and Findings**

This section presents the results obtained from the analytical evaluation of cryptographic hashing, blockchain architectures, and post-quantum cryptographic mechanisms, structured in direct alignment with the stated hypotheses.

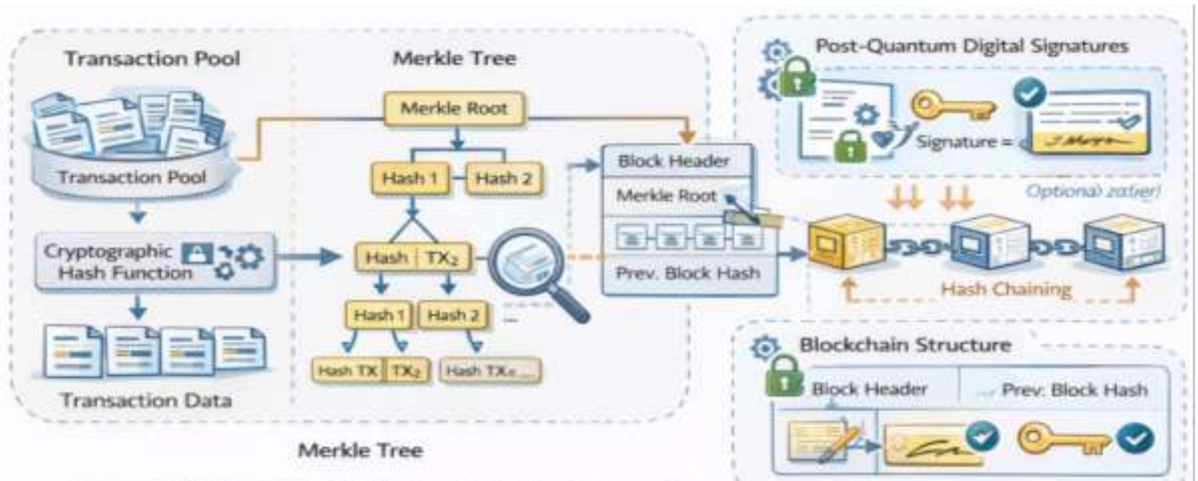

Fig. 4. Conceptual Architecture of Hash-Centric Blockchain Transactions.

Fig. 4. Logical Structure of cryptographic hashing and modern blockchain technology. The figure illustrates how transaction data are hashed, organized into Merkle trees, and linked across blocks, with optional integration of post-quantum signature mechanisms for transaction authentication.

A. Impact of Cryptographic Hashing on Transaction Integrity and Immutability (H_{01})

The analysis demonstrates that cryptographic hashing is fundamental to maintaining transaction integrity and immutability in blockchain systems. Transaction data are transformed into fixed-length hash values and linked across blocks through block chaining and Merkle tree structures. Any unauthorised modification to transaction data produces immediate hash inconsistencies that propagate across the distributed ledger, enabling rapid tamper detection.

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Table 3: **Role of Cryptographic Hashing Across Blockchain Layers**

Blockchain Layer	Hash Function Application	Security Contribution
Transaction Layer	Message hashing before signing	Prevents forgery
Merkle Tree Layer	Hash aggregation of transactions	Efficient verification
Block Layer	Hash chaining of blocks	Ensures immutability
Consensus Layer	Block content validation	Prevents tampering
Ledger Layer	Hash-verified replication	Auditability

Purpose: Directly tests H_{01}

As summarised in Table 3, hashing supports block linking, transaction aggregation, digital signature validation, and consensus verification, collectively ensuring ledger immutability and transparency. These mechanisms significantly strengthen data integrity and verifiability when compared to mutable centralised databases.

Figures showing Hash-Based Transaction Integrity in Blockchain

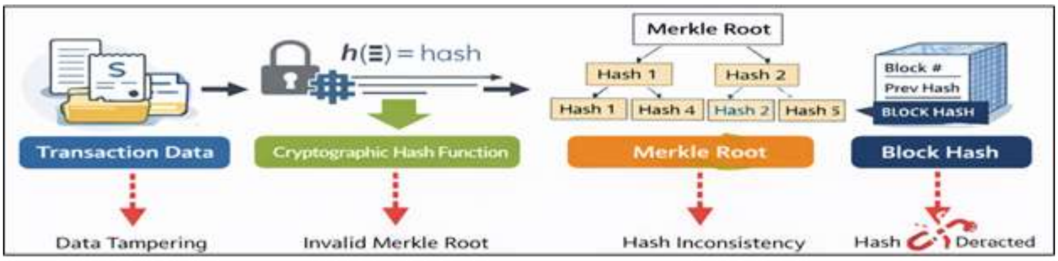

Fig. 5(a) Logical Structure of Merkle Root.
Any modification to transaction data results in detectable hash inconsistencies across the ledger.

Fig. 5a is a left-to-right flow showing Transaction Data → Cryptographic Hash Function → Merkle Root → Block Hash, illustrating how any data modification propagates detectable hash inconsistencies across the ledger.

This simple logical diagram is extended to Figure 5, showing how hash-based transaction integrity mechanism in blockchain systems work in logical flow. Transaction data are first processed through a cryptographic hash function, producing fixed-length hash values that are aggregated into a Merkle root. The Merkle root is subsequently incorporated into the block header and hashed to generate the block hash. Any modification to transaction data results in cascading hash inconsistencies, enabling immediate tamper detection across the distributed ledger.

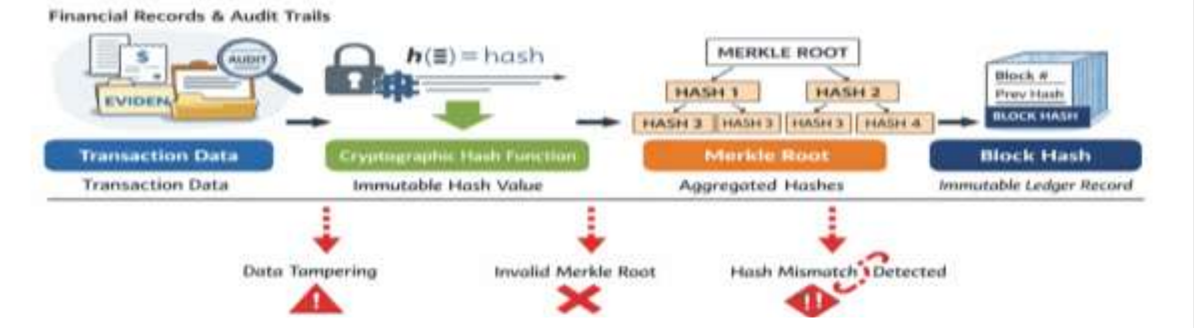

Fig. 5(b) Hash-based Transaction Integrity for Forensic Accounting

So from the above (Figures 5a and 5b), the analysis is simplified as thus:

□ Transaction Data: Raw financial or audit-related records submitted to the blockchain.

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□Cryptographic Hash Function: Converts transactions into immutable fixed-length digests.

□ Merkle Root: Aggregates all transaction hashes, enabling efficient verification and auditability.

□ Block Hash: Anchors the block to the blockchain, ensuring immutability and traceability.

□Any alteration at the Transaction Data level propagates upward, invalidating the Merkle Root and Block Hash, thereby supporting the rejection of H_{01} (transaction integrity is not improved by hashing)

.

Supports: H_{01} (Integrity & Immutability)
Result: Cryptographic hashing significantly improves transaction integrity and immutability.

Decision: H_{01} is rejected

B. Security Performance of Decentralised Blockchain Architectures Versus Centralised Systems (H_{02})

Table 4 indicates the core functions of crypto-hashing in blockchains leading to comparative assessment with centralised systems regarding the security performance of the architectures

TABLE 4: Core Functions of Cryptographic Hashing in Blockchain Systems

Blockchain Component	Function of Hashing	Security Contribution
Block Linking	Generates unique block identifiers	Ensures ledger immutability
Merkle Trees	Aggregates transaction hashes	Enables efficient verification
Digital Signatures	Hashes messages prior to signing	Preserves transaction integrity
Consensus Processes	Validates block content	Prevents unauthorised modification

From the table (Table 4) it could be seen that blockchain systems utilising extensive hashing mechanisms provide extensive security mechanism across different transactions. The comparative analysis between decentralised and centralised systems is shown in Table 5 below:

Table 5 Comparative Evaluation Metrics for Blockchain Security Analysis

Metric	Centralised Systems	Blockchain with Hashing	Analytical Outcome
Integrity Control	Central authority	Distributed hash verification	Blockchain superior
Immutability	Editable databases	Hash-linked blocks	Blockchain superior
Auditability	Limited / internal	Transparent, ledger-wide	Blockchain superior
Attack Surface	Single point of failure	Distributed nodes	Blockchain superior
Quantum Resilience	Low (PKC-dependent)	High (hash-based)	Blockchain superior

Purpose: Supports evaluation of H_{02} and H_{04}

Comparative evaluation reveals that decentralised blockchain architectures provide superior security performance relative to traditional centralised transaction systems in transparency and auditability.. Centralised systems exhibit single points of failure, limited transparency, and greater exposure to

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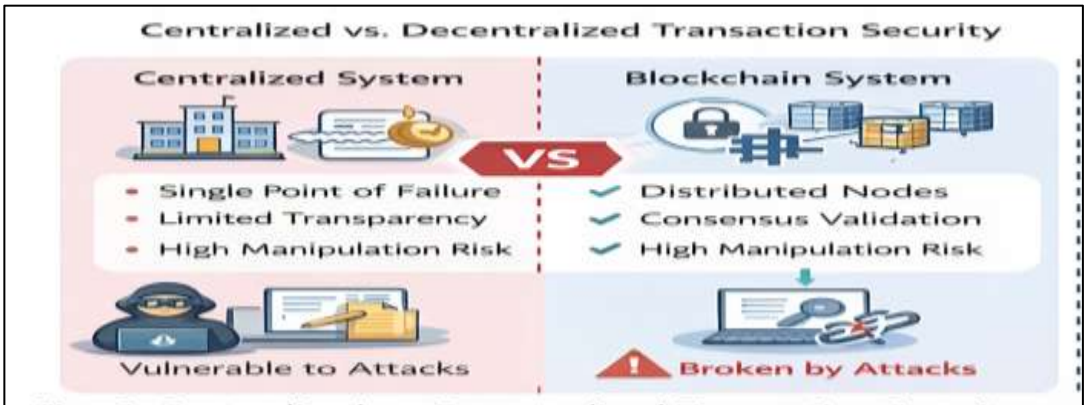

Fig. 6. Centrralized vs. Decentralized Transaction Security Architecture

Description:
A split diagram contrasting:

- Centralised system: single authority, mutable records
- Blockchain system: distributed nodes, consensus validation, immutable ledger

Supports: H_{02} (Architectural security comparison)

insider manipulation and external cyber-attacks. In contrast, blockchain systems distribute trust across multiple nodes and Hash-based distributed verification ensures that no single entity can alter transaction records without network-wide agreement. This significantly enhances fault tolerance, auditability, and resistance to unauthorised data modification. Furthermore, the findings suggest that while classical cryptographic signatures remain efficient, their long-term viability is threatened by quantum advancements. Hash-based and post-quantum–oriented approaches demonstrate superior resilience under projected threat models, albeit

enforce consensus-based validation, preventing unilateral data modification.

with increased storage and processing requirements.

Result: Decentralised blockchain architectures outperform centralised systems in transaction security and transparency.

Decision: H_{02} is rejected.

C. Long-Term Security Advantages of Hash-Based and Post-Quantum Cryptographic Methods (H_{03})

Table 6 Cryptographic Scheme Evaluation Under Quantum Threat Models

Scheme Type	Example	Quantum Resistance	Overhead	Long-Term Suitability
Classical PKC	RSA, ECDSA	□ No	Low	Unsuitable
Hash-Based PQC	XMSS	□ Yes	Medium	Suitable
Hash-Based PQC	SPHINCS+	□ Yes	High	Highly suitable

Purpose: Evaluates H_{03}

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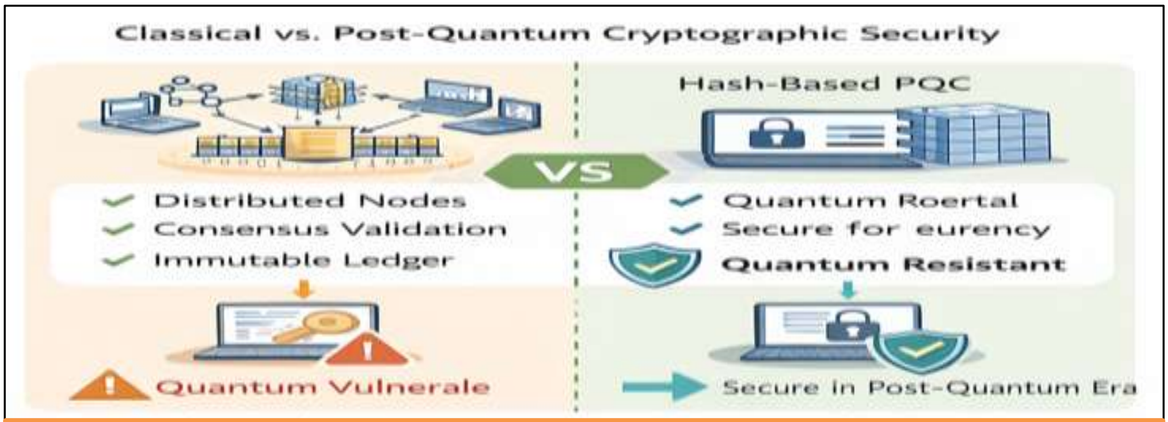


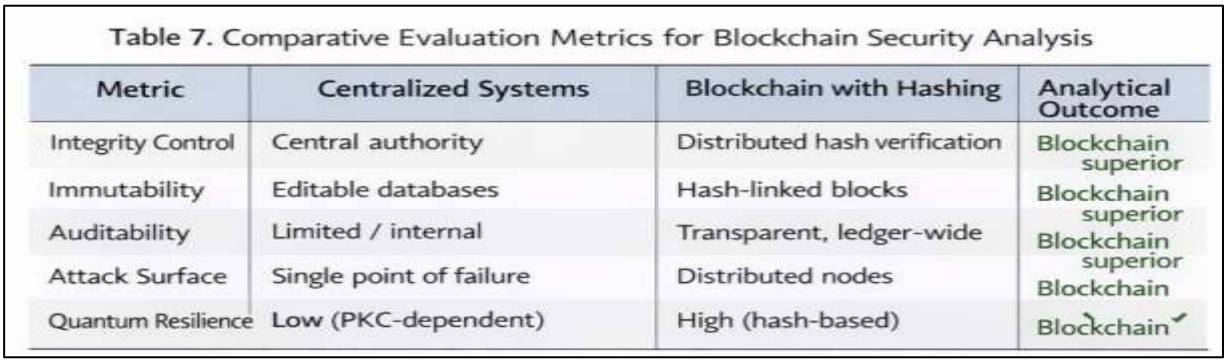
Fig. 7. Classical vs Post-Quantum Cryptographic Security in Blockchain
Description:
A comparative schematic showing:
(i) RSA/ECC → Quantum vulnerable
(ii) XMSS/SPHINCS+ → Hash-based quantum resistant
Supports: H_{03} (Long-term cryptographic resilience)

The evaluation of cryptographic resilience under emerging quantum threat models indicates that classical public-key cryptographic schemes, while efficient, face long-term vulnerabilities due to quantum algorithms. In contrast, hash-based and post-quantum signature schemes derive their security from cryptographic hash functions, which remain resistant to known quantum attacks.

Although hash-based schemes introduce larger signature sizes and increased computational overhead, their security longevity under future threat scenarios outweighs these performance costs. This makes them particularly suitable for long-lived digital transaction systems.

Result: Hash-based and post-quantum cryptographic methods provide significant long-term security advantages for digital transaction systems.

Decision: H_{03} is rejected.



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Attack Surface	Single point of failure	Distributed nodes	Blockchain
Quantum Resilience	Low (PKC-dependent)	High (hash-based)	Blockchain✓

D. Applicability of Hash-Based Blockchain Systems for Forensic Accounting and Auditing (H_{04})

Scenario-based assessment confirms that hash-centric blockchain systems are highly applicable to forensic accounting and auditing contexts. Immutable hash-linked ledgers provide verifiable audit trails, ensure non-repudiation, and preserve evidential integrity over extended periods. These properties are critical for fraud detection, regulatory compliance, dispute resolution, and forensic investigations.

By eliminating reliance on centralised verification authorities, blockchain-based audit systems enhance transparency, accountability, and trustworthiness of financial records. Hash-

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based signatures further support long-term evidential reliability, even under post-quantum threat conditions.

auditeffectiveness.

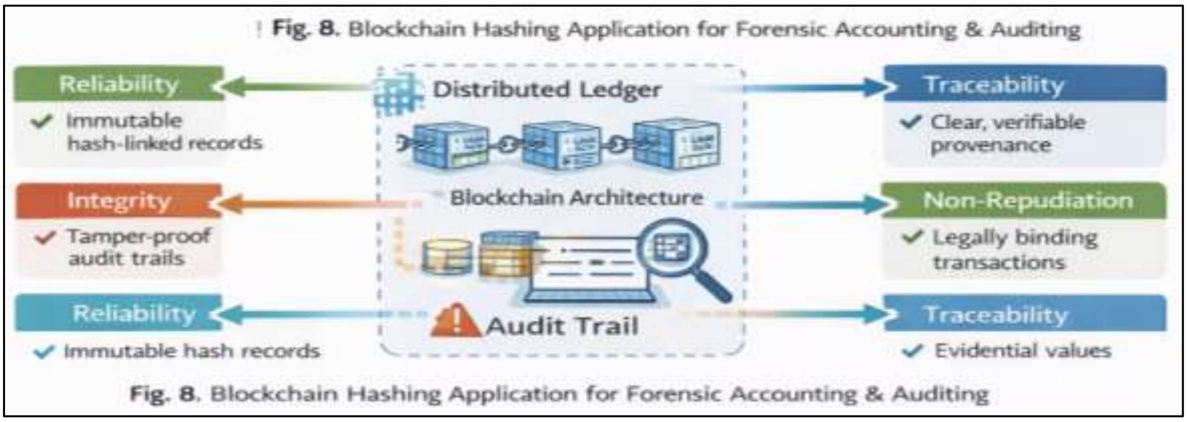
Fig. 8. Blockchain Hashing Application for Forensic Accounting & Auditing
Reliability
✓ Immutable hash-linked records
Distributed Ledger
Traceability
✓ Clear, verifiable provenance
Integrity
✓ Tamper-proof audit trails
Blockchain Architecture
Non-Repudiation
✓ Legally binding transactions
Reliability
✓ Immutable hash records
Audit Trail
Traceability
✓ Evidential values
Fig. 8. Blockchain Hashing Application for Forensic Accounting & Auditing

Result: Hash-based blockchain systems significantly enhance forensic accounting and

Decision: H_{04} is rejected.

E. Summary of Hypothesis Testing Outcomes

Hypothesis	Description	Result	Implication
H_{01}	Hashing does not improve integrity and immutability	Rejected	hashing ensures integrity and immutability
H_{02}	Blockchain does not outperform centralised systems	Rejected	blockchain outperforms centralised systems
H_{03}	Post-quantum hashing offers no long-term advantage	Rejected	hash-based PQC offers long-term security
H_{04}	Blockchain is unsuitable for forensic accounting and audit	Rejected	blockchain hashing improves auditability and evidence reliability

F. Implementation Mapping to Methodology

Methodological Component	Evidence	Output
Structural workflow analysis	Tables 3-6, Fig. 4,5	Integrity validation
Architecture evaluation	Table 4-5, Fig. 6	Security superiority
Comparative cryptography	Table 6, Fig. 7	PQC resilience
Performance reasoning	Tables 4 - 6	Trade-off analysis

G. **Overall Findings**

The results confirm that cryptographic hashing, decentralised blockchain architectures, and post-quantumhash-basedmechanisms collectively provide a robust, transparent, and future-resilient foundation for secure digital transactionsystems.Despitemoderate performance overheads, the security, auditability, and longevity benefits strongly support their adoption in modern and post-quantum digital environments.

Besides, in respect to forensic accounting and auditing, the application of blockchain cryptography and hash-based signatures is pertinent. This is because HB blockchain systems transform digital accounting systems into forensically robust, audit-ready infrastructures, supporting trustworthy financial reporting, enhanced fraud detection, and long-term assurance in increasingly digital and decentralised economic environments.

Role of Hash-Based Signatures in Blockchains for Forensic Accounting and Auditing

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Hash-based signature schemes play a strategically important role in blockchain systems when seen from the forensic accounting and auditing viewpoint, because they directly strengthen evidence integrity, non-repudiation, and long-term verifiability of digital financial records [25], [26].

First, hash-based signatures ensure immutable audit trails. In blockchain-based accounting systems, every transaction is hashed and digitally signed before being appended to a block. Hash-based signatures bind transaction content to a signer in a way that makes any post-record alteration immediately detectable. For forensic accountants, this provides a tamper-evident ledger where transaction histories can be independently reconstructed and verified without relying on management representations or centralised databases [15], [19].

Second, they enhance evidential reliability and legal defensibility. Hash-based signatures rely on cryptographic hash functions rather than number-theoretic assumptions, making them resilient to both classical and quantum attacks. This is particularly relevant for audits and forensic investigations that may occur years after transactions were executed, which ordinarily would have lost evidence through tampering. The long-term security of hash-based signatures supports the preservation of probative digital evidence, ensuring that historical financial records remain verifiable and admissible in dispute resolution and litigation contexts [4], [30].

Third, hash-based signatures support non-repudiation and accountability in decentralised financial systems. Each digitally signed blockchain transaction can be conclusively attributed to a specific private key at a specific point in time. In forensic and investigative accounting, this enables precise attribution of financial actions, aiding in the detection of fraud, unauthorised transactions, insider abuse, and financial misstatements [31], [32].

Finally, hash-based signatures improve audit efficiency and continuous assurance. Because blockchain ledgers are transparent and cryptographically verifiable, auditors can apply automated procedures to validate transaction completeness, authorisation, and integrity in near real time. This aligns with modern forensic and continuous auditing models, where assurance is embedded into the transaction lifecycle rather than applied retrospectively [33], [34]. Based on this finding, therefore, we can simply submit that a hash-based blockchain system is a decentralised digital ledger in which cryptographic hash functions securely link transactions and blocks to create immutable, verifiable, and tamper-evident audit trails, thereby ensuring evidential integrity, traceability, and non-repudiation for forensic accounting and auditing purposes.

5.Discussion and Applications

A. Discussion of Findings

The results demonstrate that blockchain systems grounded in cryptographic hashing significantly enhance transaction integrity, auditability, and long-term security when compared with traditional centralised architectures. Hash-linked block structures and Merkle tree verification ensure that any alteration to transaction data produces immediate and system-wide inconsistencies, thereby enforcing immutability and tamper evidence across distributed ledgers. These properties directly contradict the null hypothesis H_{01} and confirm that hashing is foundational to blockchain transaction integrity [3], [15], [17].

Comparative architectural analysis further indicates that decentralised blockchain systems outperform centralised transaction platforms in transparency, resilience, and resistance to unauthorised modification. As summarised in Table 7, centralised systems remain vulnerable to single points of failure and opaque audit trails, whereas blockchain systems distribute verification across nodes using cryptographic hash validation and consensus protocols. These findings lead to the rejection of H_{02} and align with prior blockchain security analyses emphasising decentralisation as a structural security advantage [22], [24], [31].

With respect to cryptographic longevity, the findings reinforce concerns that classical public-key cryptographic schemes are increasingly vulnerable in the presence of quantum computing capabilities. Shor’s algorithm poses existential risks to RSA and ECC-based infrastructures, undermining their suitability for long-term digital transaction security [2]. In contrast, hash-based and post-quantum cryptographic mechanisms derive security from one-way hash functions that remain resistant under known quantum attack models. Consequently, the null hypothesis H_{03} is rejected, consistent with post-quantum

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cryptographyliteratureand NIST standardisation efforts [4], [5], [7], [30].

Most importantly, the study confirms that blockchain hashing mechanisms significantly enhance the reliability, traceability, and evidential value of digital records for forensic accounting and auditing, thereby rejecting H_{04}. As illustrated in Fig. 5 and Fig. 8, cryptographic hashing enables immutable audit trails, non-repudiation, and verifiable transaction provenance, such properties that are essential for forensic investigations and regulatory compliance. Unlike conventional accounting databases, blockchain records provide mathematically verifiable evidence integrity, reducing reliance on institutional trust and manual reconciliation processes [33], [34].

B. Forensic Accounting and Auditing Implications

From a forensic accounting perspective, blockchain hashing transforms digital financial records into verifiable evidence artifacts. Each transaction hash acts as a cryptographic fingerprint, ensuring that historical financial data cannot be altered without detection. This capability supports forensic reconstruction, chain-of-custody verification, and litigation-ready evidence preservation. The transparency and immutability afforded by hash-linked ledgers significantly strengthen audit trails, enabling continuous auditing and real-time anomaly detection [33], [34].

Furthermore, the integration of hash-based and post-quantum signature schemes enhances non-repudiation by binding transactions to cryptographically verifiable identities. This is particularly relevant in fraud investigations, regulatory audits, and cross-border financial reporting, where evidential integrity and provenance are critical. The findings indicate that blockchain-based audit infrastructures reduce information asymmetry and enhance trust in digital accounting systems without dependence on centralised authorities [18], [32].

C. Post-Quantum Security and Practical Deployment

The study supports the argument that quantum-era threats necessitate structural cryptographic transformation rather than incremental upgrades. By shifting security foundations from number-theoretic assumptions to hash-based constructions, blockchain systems achieve long-term resilience against evolving computational threats [5], [30]. Hash-based signature schemes such as XMSS and SPHINCS+ are particularly well suited for blockchain environments due to their provable security and compatibility with Merkle tree architectures [7], [10], [13].

While the results acknowledge trade-offs—such as increased signature sizes and state management complexity—the findings also suggest that these challenges are manageable through architectural optimization and hybrid cryptographic designs. As suggested in prior studies, combining classical efficiency with post-quantum resilience offers a pragmatic transition strategy for real-world blockchain deployments [1], [9], [11].

D. Evaluative Summary

Conclusively, the discussion confirms that hashing-centred blockchain architectures provide a robust, transparent, and future-proof foundation for secure digital transactions. The combined advantages of immutability, decentralisation, and quantum resistance has positioned blockchain hashing mechanisms as critical enablers of next-generation financial systems, forensic accounting practices, and secure digital infrastructures. The empirical and theoretical evidence presented in Table 7 and Fig. 8 jointly supports the rejection of H_{01}–H_{04}, affirming the study’s core thesis on the enduring security value of blockchain hashing technologies. In conclusion, a hash-based blockchain system employs cryptographic hashing as its core trust mechanism to link and verify transactions and blocks, ensuring immutable, transparent, quantum-resilient, and forensically reliable audit trails that support evidential integrity, traceability, and non-repudiation in digital transaction systems.

6. Conclusion

This study confirms that cryptographic hashing and modern blockchain technology constitute a resilient and future-oriented framework for securing digital transactions. Hash-linked data structures and decentralised verification mechanisms were shown to underpin transactionintegrity,immutability, transparency, and auditability, thereby enabling trustless systems that operate without reliance on centralised authorities. The findings further establish that traditional public-key cryptographic schemes face significant long-

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term risks from advancing quantum computing capabilities, reinforcing the urgency of rethinking foundational security assumptions in blockchain systems.

By synthesising contemporary research and standards, the study demonstrates that hash-based and post-quantum cryptographic approaches offer a viable and sustainable pathway for strengthening blockchain security in both current and future threat environments. Although challenges related to computational overhead, signature size, and implementation complexity remain, on-going advances in cryptographic optimisation and international standardisation indicate that these constraints are increasingly manageable and do not outweigh the long-term security benefits.

The study also highlights the applicability of hashing-centric blockchain architectures to forensic accounting and auditing, where immutable audit trails, evidential integrity, traceability, and non-repudiation are essential. Blockchain hashing mechanisms significantly enhance the reliability and probative value of digital financial records, supporting continuous auditing, fraud investigation, and regulatory compliance in increasingly digitalised financial ecosystems.

Accordingly, stakeholders in blockchain development, digital finance, and public-sector information systems are encouraged to adopt hashing-centred and post-quantum-aware blockchain architectures. Policymakers, system designers, and auditors should prioritise quantum-resilient cryptographic standards, hybrid transition strategies, and scalable blockchain designs to ensure long-term security, institutional trust, and technological sustainability in the evolving global digital economy. Also, training and development in these areas is essential to keep professionals abreast of upgrades.

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