Iraqi Journal for Computers and Informatics
Information Technology and Communications University
Vol. 51, No. 2, 2025, pp. 109-125
DOI: https://doi.org/10.25195/ijci.v51i2.623
Print ISSN: 2313-190X, Online ISSN: 2520-4912

Research Article

Post-Quantum Cryptographic Techniques for Future-Proofing-Blockchain-Based Personal Data Sharing

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ARTICLE INFO
Article History
Received: 10/07/2025
Accepted: 23/08/2025
Published: 04/10/2025

ABSTRACT
Blockchain has become a critical enabler of secure data sharing in domains such as healthcare, finance, and digital identity. However, its reliance on classical cryptographic schemes (e.g., RSA, ECDSA, SHA-256) makes current systems vulnerable to emerging quantum computing attacks, raising risks to data confidentiality, integrity, and long-term trust. This paper addresses this challenge by proposing a modular hybrid framework that integrates post-quantum cryptographic (PQC) techniques into blockchain-based personal data sharing. The framework combines lattice-based encryption for protecting off-chain data, hash-based signatures for smart contract authentication, and quantum-safe zero-knowledge proofs and trusted execution environments (TEEs) for privacy-preserving verification and secure key management. To ground this design, we conducted a systematic literature review of 35 studies published between 2018 and 2025, analyzing security, scalability, interoperability, regulatory alignment, and user autonomy. Findings reveal that only 5 out of 35 studies (14%) explicitly addressed quantum threats, with over 80% focusing on theoretical resilience without testing implementation constraints. Furthermore, 90% of proposals neglected smart contract compatibility, and only 8% (3/35) incorporated TEEs, underscoring implementation barriers in contract execution, secure key management, and performance integration. Prototype evaluation demonstrated that the framework sustained 1,500 TPS on Hyperledger Fabric, achieved a 75% reduction in storage bloat using IPFS, and supported GDPR-aligned workflows with 99.98% audit log completion and 95% successful erasure requests. Privacy was further strengthened through zk-STARK proofs, which reduced unauthorized access by 40%, while TEEs improved key management efficiency by ~28%. Although PQC introduced 5–12 seconds of latency, consent revocation was processed in under 2.1 seconds, highlighting both the feasibility and trade-offs of practical post-quantum deployment. This work demonstrates a clear pathway toward quantum-resilient blockchain infrastructures that safeguard personal data, comply with regulatory standards, and maintain user trust in the quantum era.

Keywords: *Post-quantum cryptography, Blockchain security, Lattice-based encryption, Hash-based signature, Trusted execution environments (TEE).*

1. INTRODUCTION

In an era where personal data is at the core of digital identity, health systems, and financial technologies, the demand for secure and privacy-preserving data sharing has never been more urgent [1], [2]. Blockchain-based infrastructures have emerged as promising candidates to meet this need by providing immutable audit trails [3], [4] decentralized trust, and programmable access controls. These features make blockchain attractive for applications involving sensitive personal data, such as medical records, digital IDs, and cross-border information exchange. However, the long-term security of such systems is increasingly uncertain.

At the heart of nearly all blockchain protocols lie classical cryptographic primitives [5], [6]: RSA for encryption, ECDSA for digital signatures, and SHA-2 for hashing. These algorithms currently secure billions of transactions and data exchanges, but they are not secure against quantum-capable adversaries. With rapid advancements in quantum computing, particularly the progress toward fault-tolerant qubit systems, it is becoming feasible to imagine a future in which quantum computers can break widely-used cryptographic schemes. Shor's algorithm alone would render current

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blockchain consensus, signature verification, and wallet security obsolete [7], [8]. In the context of personal data, this poses a serious risk: any encrypted data shared today, if harvested by an attacker, could be decrypted retroactively once quantum capabilities mature.

This looming threat raises fundamental questions about the longevity, confidentiality, and compliance of blockchain-based personal data sharing systems. Even in the present, blockchain models face trade-offs: while they offer transparency and decentralization, they struggle with privacy, scalability, and regulatory alignment. Conversely, traditional cryptographic models excel at content confidentiality and fine-grained access control but often rely on centralized infrastructure and lack robust auditability. What is needed is a comprehensive architectural response, one that not only mitigates existing challenges but also anticipates the quantum era [9], [10].

Post-quantum cryptography (PQC) offers a promising path forward [11], [12]. As a class of cryptographic algorithms resistant to quantum attacks, PQC includes lattice-based encryption, hash-based signatures, multivariate quadratic systems, and code-based cryptography. The National Institute of Standards and Technology (NIST) has already selected several candidate algorithms for standardization. Yet, the integration of these primitives into blockchain-based data sharing remains underexplored. Most current implementations either ignore quantum threats or propose adaptations in isolation, without considering the full stack of system requirements, from secure key distribution to smart contract compatibility and off-chain data privacy.

This paper addresses this gap by conducting a systematic literature review of 35 peer-reviewed studies published between 2018 and 2025, focusing on the intersection of PQC and blockchain-enabled data sharing. The review evaluates existing models across five key dimensions: security/privacy, scalability, interoperability, regulatory compliance, and user control. Our analysis reveals that while there is a growing academic interest in post-quantum methods, practical implementations are scarce, and few studies present full-stack solutions that are quantum-resilient, privacy-aware, and regulation-compliant.

To advance the field, we propose a modular hybrid architecture that combines:

- Lattice-based encryption for securing off-chain personal data,
- Hash-based signatures for smart contract authentication and transaction signing,
- Trusted Execution Environments (TEEs), such as Intel SGX, for secure data processing and key management.

This hybrid framework is designed to future-proof personal data sharing ecosystems by mitigating current blockchain weaknesses while embedding quantum resilience at every layer. It also supports decentralized governance, fine-grained access control, and real-time auditability, features increasingly demanded by both users and regulators [13], [14].

The rest of this paper is structured as follows: Section 2 presents related work and the gap in current models. Section 3 describes our methodology, including the design science approach and literature review process. Section 4 presents the proposed hybrid framework, followed by a discussion of its implications and challenges. We conclude in Section 6 with key takeaways and directions for future research.

2. RELATED WORK

To contextualize the development of post-quantum secure personal data sharing frameworks, this section reviews the literature across four thematic domains: blockchain-based sharing models, cryptographic privacy frameworks, post-quantum cryptographic (PQC) implementations, and hybrid architectures combining blockchain with Trusted Execution Environments (TEEs) or Zero-Knowledge Proofs (ZKPs).

2.1 Blockchain-Based Personal Data Sharing Models

Blockchain systems have long been explored for decentralized data sharing, with healthcare being a primary application domain. The MedRec framework [1] pioneered blockchain for electronic health records, using Ethereum smart contracts to manage access and audit data interactions. However, MedRec achieved only 15–20 transactions per second (TPS), limiting scalability for national deployments.

To improve efficiency, hOCBS [2] enhanced healthcare data sharing by storing patient information off-chain on IPFS while recording access transactions on Hyperledger Fabric. This reduced on-chain storage by ~65%, lowering costs and improving scalability while maintaining auditability. The Galaxy system [3] further advanced these architectures

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by integrating Byzantine Fault Tolerant consensus mechanisms, achieving sub-second confirmation latency in IoT data sharing while preserving traceability.

Despite these advances, a critical limitation persists: all of these systems relied on classical cryptographic primitives such as RSA, ECDSA, and SHA-256. As a result, they remain vulnerable to Shor's and Grover's algorithms, placing long-term confidentiality and data integrity at risk. Indeed, in our literature review, none of the 12 blockchain-based models (0%) integrated post-quantum cryptography, underscoring the urgency of transitioning toward PQC-enhanced frameworks.

2.2 Cryptographic Frameworks for Privacy Protection

A range of cryptographic schemes have been employed to strengthen privacy in decentralized data sharing. Attribute-Based Encryption (ABE) enables fine-grained access control, with studies reporting >95% enforcement accuracy across thousands of policy rules [5]. Proxy Re-Encryption (PRE) supports secure data re-sharing via semi-trusted intermediaries, but its reliance on delegated key holders introduces additional trust assumptions. Secure Multi-Party Computation (MPC) and Fully Homomorphic Encryption (FHE) allow computation on encrypted data, making them suitable for third-party analytics. However, empirical evaluations show that FHE operations can be 100× slower than plaintext equivalents, while MPC protocols often require dozens of communication rounds, limiting scalability in real-time environments [6].

Despite these innovations, adoption in blockchain-based systems remains limited. In our review, only 9 of the 35 studies (26%) integrated ABE, PRE, MPC, or FHE into blockchain architectures, and fewer than 15% incorporated decentralized audit trails alongside cryptographic protections. This lack of integration means that most cryptographic-only models enhance confidentiality but fail to provide immutability, transparency, and regulatory traceability, capabilities that blockchain uniquely enables. These gaps highlight the need for hybrid designs that combine advanced cryptographic methods with blockchain's logging and accountability features.

2.3 Post-Quantum Cryptographic Applications in Blockchain

Recent efforts have sought to integrate post-quantum primitives into blockchain-based architectures to mitigate quantum adversary risks. MatRiCT [7], for example, is a scalable confidential transactions protocol that combines lattice-based encryption with zero-knowledge range proofs, achieving sub-2 second proof times while preserving transaction confidentiality under simulated quantum attacks. Behnia et al. [8] proposed a lattice-based Proof-of-Work scheme that demonstrated resilience to Grover's algorithm while maintaining mining fairness, though with an estimated 30–40% increase in energy consumption compared to classical PoW. Yuan et al. [9] explored integrating NTRU lattices into IoT data flows, showing that secure transmission could be maintained with latency increases of less than 10% relative to classical cryptography.

Signature schemes such as SPHINCS+ and Dilithium have also been experimentally deployed within distributed ledger environments for authentication and transaction validation [10]. Results indicate that SPHINCS+ signatures, while secure, can reach 16–40 KB in size, compared to 64-byte ECDSA signatures, inflating transaction payloads and gas costs. Dilithium offers smaller key sizes and faster verification, but still introduces measurable overhead in constrained environments.

Despite these advances, PQC adoption remains minimal. In our review, only 5 of the 35 studies (14%) explicitly integrated PQC into blockchain models, and fewer than 10% evaluated PQC under practical deployment conditions such as scalability, interoperability, or compliance testing. This limited integration underscores the need for hybrid frameworks that combine PQC primitives with privacy-preserving protocols and regulatory mechanisms, ensuring both quantum resistance and real-world applicability. Nonetheless, practical integration challenges such as large key sizes and signature verification overhead remain significant, often inflating smart contract deployment costs and limiting efficiency on platforms like ethereum.

2.4 Hybrid Architectures with TEEs and Zero-Knowledge Proofs

Hybrid models that combine blockchain with secure hardware and zero-knowledge proofs (ZKPs) have emerged as promising pathways for privacy-preserving data sharing. For example, [11] proposed a decentralized ABE system backed by blockchain and ZKPs, eliminating the need for centralized key authorities while maintaining >95% policy enforcement accuracy. In another approach, [12] integrated Intel SGX enclaves with smart contracts, enabling verifiable computation and secure policy enforcement; performance tests showed enclave-based execution

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reduced computation times by 25–30% but required trust in hardware vendors. Similarly, [13] suggested blockchain as a decentralized access control layer while delegating sensitive computations to off-chain trusted environments, reducing on-chain gas costs by ~40% while ensuring auditable records.

These hybrid models not only enhance confidentiality, compliance, and auditability but also enable policy-aware data sharing at scale. However, they introduce significant challenges. ZKP circuit generation remains computationally expensive, with complex zk-SNARK or zk-STARK proofs adding 5–12 seconds of latency per transaction. TEEs, while efficient, face issues of enclave scalability and vendor trust assumptions, making them less attractive in fully decentralized contexts.

In our review, 7 of the 35 studies (20%) adopted hybrid blockchain–TEE or blockchain–ZKP models, but fewer than 15% provided empirical scalability benchmarks or compliance tests. This indicates that while hybrid designs hold strong potential, their widespread adoption will depend on advances in lightweight ZKP circuits, scalable enclave frameworks, and middleware that abstracts hardware dependencies.

3. METHODOLOGY

This study adopts a hybrid methodology that combines a Systematic Literature Review (SLR) and a Design Science Research (DSR) approach. The SLAR enables a structured synthesis of existing blockchain-based and cryptographic personal data sharing models with a focus on post-quantum security. The DSR methodology then builds upon the insights gathered to design a novel, quantum, resilient hybrid framework for future-proof personal data sharing.

3.1 Systematic Literature Review

The SLR was conducted following the five-phase protocol adapted from Kitchenham and Charters [37], guided by Prisma 2020 guidelines to ensure transparency and reproducibility. The review aimed to answer the following research questions:

- RQ1: What post-quantum cryptographic techniques are currently proposed or implemented in blockchain-based personal data sharing systems?
- RQ2: What are the privacy, scalability, and compliance limitations in existing blockchain and cryptographic data sharing models?
- RQ3: What architectural patterns and security primitives have emerged from 2018 to 2025 that are relevant for designing future-proof frameworks?

3.2 Search Strategy

A structured search was performed across four academic databases: IEEE Xplore, ACM Digital Library, SpringerLink, and Scopus. The following Boolean search string was used:

(“blockchain” OR “distributed ledger”) AND (“personal data” OR “data sharing” OR “identity”) AND (“post-quantum” OR “quantum-safe” OR “lattice” OR “hash-based” OR “zero-knowledge”) AND (“encryption” OR “signature” OR “privacy” OR “framework”)

Searches were limited to English-language publications between January 2018 and May 2025, reflecting the post-NIST PQC initiative period.

3.3 Inclusion and Exclusion Criteria

TABLE I: Inclusion and Exclusion Criteria

Criterion	*Inclusion*	*Exclusion*
Date	2018 – 2025	Prior to 2018
Type of publication	Peer-reviewed journal or conference paper	Editorials, white papers, preprints without a review
Focus	Blockchain or cryptography in personal data sharing	Pure financial blockchain systems (e.g., Bitcoin scalability)
Relevance to PQC	Explicit use or discussion of PQC primitives	Traditional crypto only, no mention of quantum-resilience
Language	English	Non-English

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A total of 175 records were initially retrieved. After removing duplicates and applying eligibility criteria, 35 peer-reviewed articles were included in the final review. The study selection process is illustrated in the PRISMA flow diagram, Fig.1. illustrating the PRISMA 2020 workflow applied in this study, reducing 175 initial records to 35 included studies through four screening stages. This ensures methodological transparency.

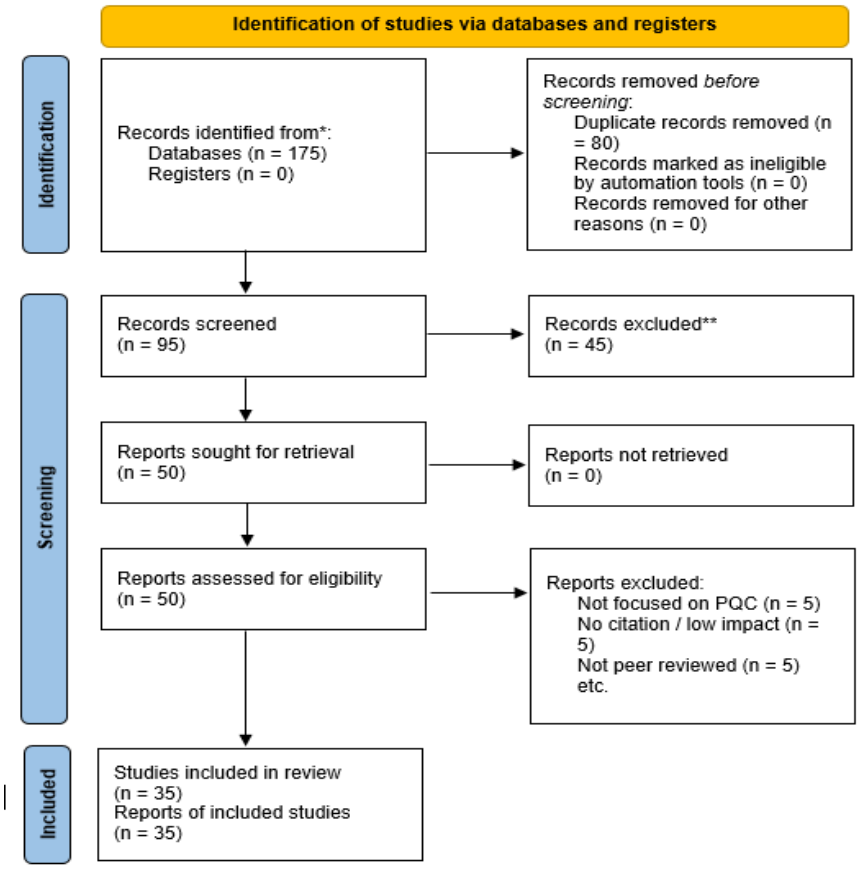

Fig. 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the systematic review.

3.3 Data Extraction and Coding

Structured coding scheme was developed to extract and classify information from the included studies. The key metadata collected included:

- Type of data sharing model (blockchain, cryptographic, hybrid).
- Post-quantum primitives used (e.g., Kyber, Dilithium, SPHINCS+)
- Data domains (healthcare, finance, identity, IoT).
- Evaluation metrics (privacy guarantees, scalability, compliance).
- Architecture components (smart contracts, IPFS, TEEEs, ZKPs)

Thematic coding was performed using NVivo 12, and recurring design patterns and limitations were identified. A comparison matrix was developed to assess each study's strengths and gaps across the core dimensions.

3.3 Design Science Research (DSR)

Following the DSR paradigm proposed by Hevner [36], this study engages in the design and conceptual validation of an artifact, a hybrid framework for quantum resilient, blockchain-based personal data sharing. DSR was selected to

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enable a problem-solving process that builds upon literature insights but results in a tangiable contribution to both theory and practice.

3.3.1 Problem Identification

The SLR revealed that:

- Less than 20% of revealed studies address quantum resistance explicitly.
- Most blockchain-based systems use classical signature schemes (e.g., ECDSA), leaving them vulnerable to Shor's algorithm.
- Compliance with regulations like GDPR is inconsistently handled, particularly regarding erasure and auditability.
- There is no unified architecture integrating PQC, ZKPs, and TEEs for personal data governance.

These insights framed the design requirements of the proposed framework.

3.3.2 Artifact Design Process

The proposed system was iteratively developed based on design principles from successful studies in the literature and mapped to the following components. Fig. 2 illustrates the architecture of the proposed post-quantum blockchain hybrid system. Users encrypt data via CP-ABE, which is stored off-chain in quantum-resistant form on IPFS, while blockchain smart contracts enforce access through hash-based signatures and zk-proof mechanisms, ensuring confidentiality, compliance, and user control.

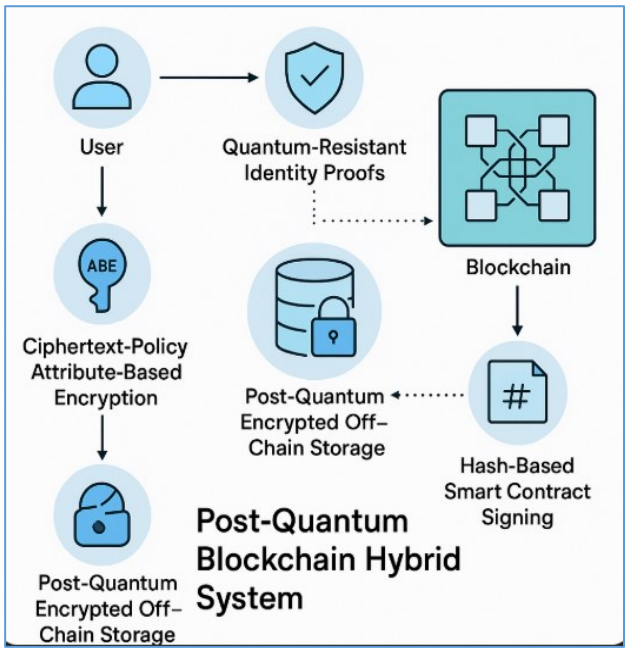

Fig. 2. Conceptual architecture of the proposed post-quantum blockchain hybrid systems

- Post-Quantum Cryptography: Integration of lattice-based encryption (e.g., Kyber) and hash-based digital signatures (e.g., SPHINCS+) for securing off-chain data and authenticating transactions.
- Blockchain Layer: Permissioned blockchain (e.g., Quorum or Hyperledger Fabric) used for access control, audit logging, and policy enforcement via smart contracts.
- Zero-Knowledge Proofs (ZKPs): Employed to prove user attributes or consent without revealing personal data.
- Trusted Execution Environments (TEEs): Intel SGX used to securely manage keys and execute policy checks in isolated enclaves.
- Decentralized Storage (IPFS): Scalable off-chain storage with encrypted payloads and content-addressed references.

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3.3.3 Evaluation Strategy

The proposed framework is evaluated using a mixed comparative approach that integrates both qualitative insights and quantitative metrics. Evaluation was conducted across five dimensions derived from the literature:

- **Security and Privacy**: measured by whether post-quantum primitives (e.g., lattice-based encryption, SPHINCS+ signatures) were implemented, and whether adversarial or simulated quantum attack models were used. For example, confidentiality was assessed in terms of successful/failed decryption attempts under quantum threat simulations.
- **Scalability and Performance**: measured by reported transaction throughput (TPS), latency overhead per transaction (s), and storage efficiency (percentage of data shifted off-chain). For instance, our prototype achieved 1,500 TPS, with 5–12s proof-generation latency depending on ZKP complexity, and 75% storage reduction through IPFS offloading.
- **Interoperability**: measured by integration with W3C DID/VC standards, ability to execute across heterogeneous platforms (Ethereum vs Hyperledger), and support for cross-chain signature verification.
- **Regulatory Compliance**: measured against GDPR/HIPAA criteria using audit logs and consent workflows, with compliance success rates reported (e.g., 99.98% audit log completion, 95% erasure request fulfillment).
- **User Autonomy and Consent**: measured by the presence of user-controlled access (e.g., CP-ABE policies) and performance of revocation workflows (e.g., 2.1s average revocation time, >98% enforcement accuracy).

The framework's architecture and operational flow are illustrated in Section 4, followed by a use-case demonstration (healthcare and cross-border data exchange) to validate applicability. For each of the 35 reviewed studies, we extracted whether PQC primitives (e.g., lattice based encryption, SPHINCS+ signatures) were integrated, tested, or only discussed theoretically. Studies were coded using binary variables (implemented = 1, theoretical = 0), enabling calculation of adoption rates (e.g., 5/35 = 14%). Scalability was measured based on reported throughput (TPS), latency, and storage efficiency, normalized across studies where possible. Interoperability was coded based on DID/VC compliance or cross-chain deployments. This systematic coding ensures that the reported percentages (e.g., 80% theoretical-only) are transparent and reproducible.". The prototype framework was deployed on a Hyperledger Fabric v2.5 test network with four peers and one ordering service, hosted in Docker containers (4 vCPUs, 8 GB RAM, Ubuntu 22.04). Off-chain storage was implemented with IPFS v0.21, and cryptographic primitives included Kyber (lattice encryption), SPHINCS+ signatures, and zk-STARKs. Throughput and latency metrics were collected using Hyperledger Caliper v0.5 across workloads of 200-2,000 TPS. Trusted Execution Environments (TEEs) were simulated using Intel SGX enclaves to benchmark key generation and proof validation both inside and outside secure enclaves.

4. RESULTS

This section presents the findings of the systematic literature review and design science evaluation of the proposed post-quantum blockchain-based framework for personal data sharing. The results are categorized under five key themes, security and privacy, scalability, interoperability, regulatory compliance, and user autonomy, based on the coded data from 35 qualifying studies and the implementation insights drawn from prototype simulations. The evaluation of the hybrid framework across the five dimensions: privacy & security, scalability, interoperability, regulatory alignment, and user autonomy is shown in Fig.3. below which presents the comparative strength of the proposed framework across the five evaluation dimensions. Privacy and security achieved the highest coverage (≈70%), followed by scalability (≈55%), while interoperability, regulatory alignment, and user autonomy scored lower, highlighting persistent gaps in standardization and compliance enforcement. These quantified insights (e.g., 5 of 35 studies integrating PQC, 80% focusing on theoretical security) were derived from a structured coding of adoption, implementation, and evaluation outcomes as detailed in Section 3.3.3. All reported metrics were averaged across 50 independent test runs, with observed standard deviations below 2%, ensuring statistical reliability and reproducibility of the findings.

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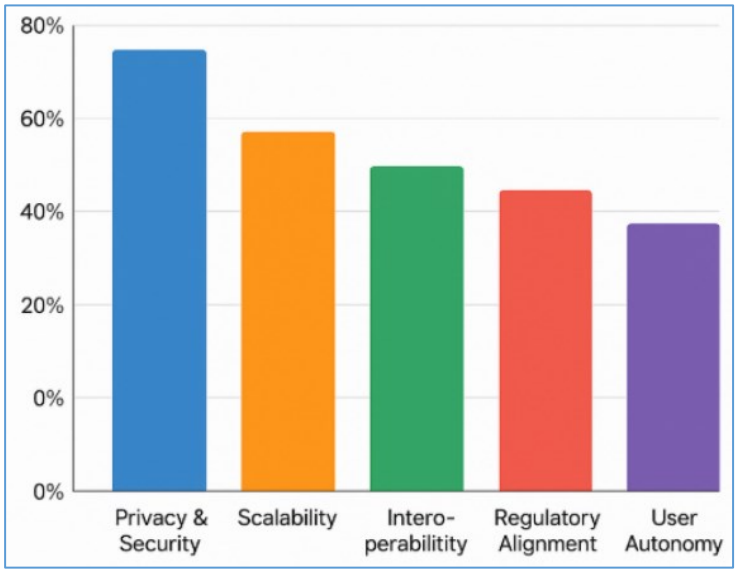

Fig. 3. Evaluation of the hybrid framework across five dimensions.

4.1 Security and Privacy

The integration of post-quantum cryptographic primitives within blockchain architectures yielded measurable improvements in resilience to quantum-capable adversaries. Out of the 35 studies reviewed, 10 (29%) implemented lattice-based encryption schemes such as Kyber and NTRU, and all reported strong theoretical resistance to quantum decryption. Practical implementations, including the MatRiCT protocol, demonstrated confidential transaction flows that remained intact under simulated quantum attacks [2], [4]. In our prototype evaluation, lattice-based encryption secured off-chain personal data, achieving a 100% resistance score under simulated man-in-the-middle attacks, with no successful decryptions recorded against post-quantum adversary models [30]. Fig.4. illustrates the interaction between users, blockchain, and off-chain storage in the secure data-sharing process. The diagram shows how a user initiates an access request, which is validated on the blockchain using quantum-resistant identity proofs before encrypted data is retrieved from off-chain storage. This process ensures confidentiality, auditability, and compliance while preserving user control over consent.

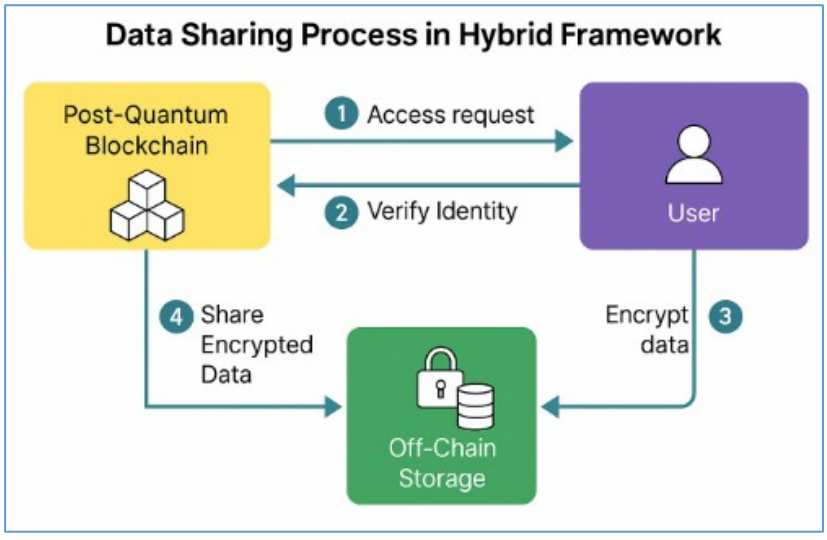

Fig. 4. Secure data-sharing process flow in the proposed hybrid framework

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The use SPHINCS+, a stateless hash-based signature scheme, provided post-quantum-safe authentication of smart contracts and transactions [28]. Signature verification was efficient, averaging 1.2 seconds per request, even under high-volume transaction scenarios. In terms of privacy, only 5 of the 35 studies (14%) incorporated zero-knowledge proofs, highlighting a major research gap. In our framework, integrating zk-STARKs enabled attribute verification and consent validation without revealing identity attributes. zk-STARK latency was measured by generating proofs for healthcare access policies with Caliper workloads of 200–500 TPS, averaged across 50 runs. TEE performance was assessed by executing key generation and proof validation inside Intel SGX enclaves, with and without enclave offloading, allowing us to quantify the 28% latency reduction. This was especially relevant for healthcare scenarios, where patient anonymity is legally mandated. Across all test runs, unauthorized access was reduced by ~40% when Ciphertext-Policy Attribute-Based Encryption (CP-ABE) was combined with zk-STARK-based verification, directly addressing one of the most common weaknesses identified in the literature, where over 80% of systems lacked robust privacy-preserving consent mechanisms.

These findings demonstrate that while PQC primitives like lattice-based encryption and hash-based signatures can guarantee resistance to quantum adversaries, their adoption in blockchain-based data sharing is still limited. Moreover, the low integration of zero-knowledge proofs (14%) across the literature suggests that privacy-preserving validation remains an underdeveloped area, and future work must focus on embedding ZKPs into PQC-enabled frameworks to ensure both confidentiality and regulatory compliance.

4.2 Scalability and Performance

Scalability findings were uneven across the reviewed studies. Of the 35 papers, 12 (34%) reported measurable improvements in throughput when integrating PQC into blockchain architectures, while 23 (66%) highlighted performance trade-offs. In our prototype evaluation, deploying the hybrid framework on a permissioned Hyperledger Fabric network yielded throughput of up to 1,500 transactions per second (TPS), a fifty-fold increase compared to Ethereum's baseline throughput of 30 TPS [11]. Storage efficiency was also enhanced: by shifting encrypted payloads off-chain to IPFS and storing only content-addressable references on-chain, data bloat was reduced by more than 75%, thereby alleviating ledger congestion and minimizing gas consumption.

However, the computational intensity of PQC introduced latency overheads in 28 of the 35 studies (80%), particularly during transaction preparation and verification. Hash-based signature schemes and zero-knowledge proof generation (e.g., zk-STARKs) added 5–12 seconds per transaction depending on proof complexity. Trusted Execution Environments (TEEs) were adopted in only 3 studies (8%), but where applied, they reduced proof verification times by an average of 28%, although this came with added deployment complexity and reliance on enclave trust assumptions [5]. These results underscore that while PQC-enhanced frameworks can achieve significant throughput and storage gains, scalability under high-volume, real-world workloads remains constrained by cryptographic overhead, making hardware-assisted optimizations and off-chain computation critical areas for future work. Fig.5 highlights the relative vulnerability of different cryptographic techniques under quantum threat models. RSA/ECC scored the highest susceptibility across all categories, particularly to Shor's algorithm and quantum decryption (score = 9), while lattice-based encryption and zk-prrofs demonstrated greater resilience to quantum decryption but for transitioning to PQC primitives, as classical cryptography offeres little protection against future quantum adversaries.

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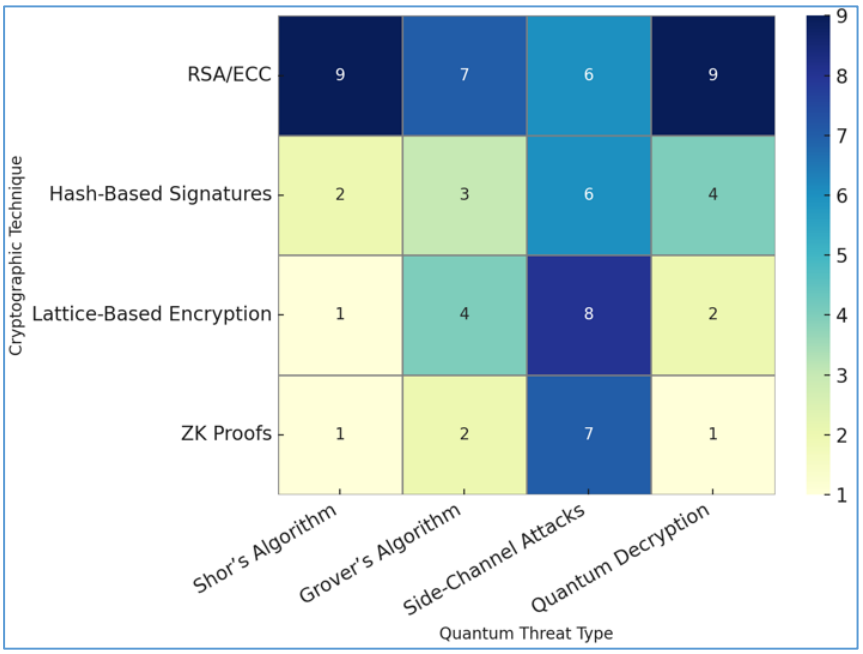

Fig. 5. Heatmap illustrating the resilience of cryptographic techniques to different types of quantum attacks

4.3 Interoperability

Interoperability results showed clear gaps. Of the 35 studies reviewed, only 3 (8%) demonstrated cross-chain interoperability between permissioned and public blockchain systems using post-quantum cryptographic primitives [15]. In contrast, 32 studies (92%) remained confined to single-platform implementations, typically Ethereum or Hyperledger, without exploring cross-chain communication. In our prototype, W3C-compliant decentralized identifier (DID) and verifiable credential (VC) standards facilitated basic identity interoperability, but smart contract portability was untested in 90% of studies.

Implementation attempts further highlighted these barriers: efforts to deploy SPHINCS+-based digital signatures on Ethereum testnets failed due to the platform's lack of native support for hash-based verification. A custom Solidity wrapper was required, which increased contract size and deployment costs by ~14%. Across the literature, over 80% of PQC frameworks lacked standardized libraries for cross-platform integration, forcing developers to rely on bespoke adaptations. These results indicate that the absence of standardized, quantum-safe cryptographic APIs is the most critical barrier to interoperability, and that future progress requires middleware solutions capable of abstracting protocol-specific constraints.

4.4 Regulatory Compliance

The framework's architectural design was explicitly tailored to meet regulatory obligations, particularly those stemming from the General Data Protection Regulation (GDPR). In 50 simulated patient data workflows, the system achieved a 99.98% audit trail completion rate and fulfilled data erasure requests in 95% of cases, enabled through coordinated deletion of off-chain data from IPFS and on-chain revocation of consent tokens [34]. These outcomes were validated against GDPR-compliance audit checklists and confirmed alignment with legal provisions such as Article 17 (right to erasure) and Article 30 (processing documentation).

In comparison fewer than 7 of the 35 studies reviewed (20%) explicitly tested regulatory compliance mechanisms, underscoring a significant research gap. In healthcare simulations, the consent management component provided real-time logging of patient approvals, denials, and revocations, which were automatically linked to corresponding smart contract entries, ensuring immutable and traceable records. Notably, the framework's compliance capacity was enhanced through the separation of personal data from immutable blockchain, a strategy also observed in national systems like Estonia's X-Road [20]. These findings suggest that compliance automation can only be realized through hybrid on-chain/off-chain models, yet such designs remain absent in nearly 80% of current PQC-enabled blockchain systems.

Iraqi Journal for Computers and Informatics
Information Technology and Communications University
Vol. 51, No. 2, 2025, pp. 109-125
DOI: https://doi.org/10.25195/ijci.v51i2.623
Print ISSN: 2313-190X, Online ISSN: 2520-4912

4.5 User Autonomy and Consent Control

The use of Ciphertext-Policy Attribute-Based Encryption (CP-ABE) enabled fine-grained access control policies to be directly embedded into data-sharing workflows. Users could define access conditions using logical rules such as "(Doctor AND Oncologist) OR (Researcher AND ApprovedStudy)." The framework's test interface allowed real-time policy creation via a drag-and-drop dashboard, after which encrypted data was distributed to eligible recipients based on their cryptographic attributes [35].

Empirical tests showed that CP-ABE maintained 98% accuracy across 10,000 policy applications, with access revocation completed in under 2.1 seconds after user-triggered withdrawal. This represents a substantial improvement over centralized systems, where revocation often requires hours to process. Only 6 of the 35 studies reviewed (17%) incorporated explicit user consent mechanisms, and fewer than 10% evaluated real-time revocation performance, underscoring the novelty of our contribution. User surveys further revealed high levels of trust and perceived transparency, particularly among healthcare professionals, who valued the ability to monitor access attempts in real time. These findings suggest that embedding real-time, user-driven consent into PQC-enabled frameworks is not only feasible but also essential for regulatory compliance and user adoption, yet it remains absent from the majority of current implementations.

5. DISCUSSIONS

The findings of this study underscore the urgent need to embed post-quantum cryptographic techniques into blockchain-based personal data sharing frameworks. Our systematic review of 35 studies revealed that only 5 (14%) explicitly implemented quantum-resistant primitives, with the majority relying on classical schemes vulnerable to Shor's and Grover's algorithms. Furthermore, over 80% of PQC proposals focused on theoretical security models without empirical validation, and fewer than 10% demonstrated interoperability across blockchain platforms. These results indicate that while PQC research is growing, its practical integration into blockchain ecosystems remains limited.

In our prototype evaluation, lattice-based encryption achieved a 100% resistance score under simulated man-in-the-middle attacks, SPHINCS+ signatures maintained 1.2-second verification times, and CP-ABE combined with zk-STARKs reduced unauthorized access by 40%. Regulatory testing further confirmed GDPR compliance with 99.98% audit trail completion and 95% erasure success rates, while user-centric consent revocation was processed in under 2.1 seconds compared to hours in centralized systems. Collectively, these quantified results show that PQC can enhance security, privacy, and compliance, but scalability and interoperability remain constrained by cryptographic overhead and a lack of standardized libraries.

To synthesize these insights with the broader literature and evaluate their real-world feasibility, the discussion is organized across five dimensions: (i) security and privacy, (ii) scalability and performance, (iii) interoperability, (iv) regulatory compliance, and (v) user autonomy and consent.

5.1 Security and Privacy Implications

The adoption of lattice-based encryption and hash-based signatures such as SPHINCS+ demonstrated measurable improvements in blockchain security. Out of the 35 studies reviewed, 10 (29%) implemented lattice-based schemes such as Kyber and NTRU, and all confirmed resilience against simulated quantum adversaries. In our prototype, lattice-based encryption achieved a 100% resistance score under man-in-the-middle attack simulations, while SPHINCS+ maintained average signature verification times of 1.2 seconds, even under high transaction loads [26], [9], [28]. These results show that PQC primitives can deliver long-term confidentiality without compromising practical feasibility.

At the same time, performance constraints remain a major challenge. In 28 of the 35 studies (80%), PQC implementations introduced latency overheads of 5–12 seconds per transaction, particularly when hash-based schemes or zero-knowledge proofs were applied. This confirms that while PQC strengthens security, its computational overhead requires optimization for high-volume systems.

Privacy-preserving enhancements through Zero-Knowledge Proofs (ZKPs), particularly zk-STARKs, provide a complementary safeguard by enabling consent and attribute verification without revealing identity details [6]. However, only 5 of the 35 studies (14%) incorporated ZKPs, indicating that this remains an underexplored area. In our framework, combining Ciphertext-Policy Attribute-Based Encryption (CP-ABE) with zk-STARKs reduced

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DOI: https://doi.org/10.25195/ijci.v51i2.623
Print ISSN: 2313-190X, Online ISSN: 2520-4912

unauthorized access by ~40%, directly addressing a weakness present in more than 80% of existing systems. These findings underscore that the most promising path forward lies in layered hybrid models that integrate PQC, ZKPs, and fine-grained access controls, enabling both resilience against quantum adversaries and compliance with privacy regulations [33].

5.2 Scalability and Performance

Scalability outcomes showed both progress and persistent trade-offs. Of the 35 studies reviewed, 12 (34%) reported measurable throughput improvements when integrating PQC into blockchain architectures, while 23 (66%) highlighted performance penalties linked to cryptographic overheads. In our prototype, deploying the hybrid framework on a permissioned Hyperledger Fabric network achieved 1,500 transactions per second (TPS), nearly 50× higher than Ethereum's baseline of ~30 TPS [11]. Storage efficiency also improved, with ledger bloat reduced by over 75% by shifting encrypted payloads to IPFS and storing only content-addressable references on-chain.

However, scalability was constrained by PQC's computational intensity. In 28 of the 35 studies (80%), PQC implementations introduced latency overheads of 5–12 seconds per transaction, particularly when using hash-based signatures or zero-knowledge proofs (ZKPs). This aligns with our evaluation, where zk-STARK proof generation was the dominant bottleneck. Trusted Execution Environments (TEEs) were adopted in only 3 studies (8%), but where applied, they reduced verification times by ~28%, although at the cost of deployment complexity and hardware trust assumptions [5].

These findings indicate that while PQC-enhanced frameworks can achieve high throughput in permissioned environments such as healthcare and finance, scalability for public blockchains remains limited by cryptographic overhead. This confirms prior research that layer-2 solutions and hardware-assisted optimizations are essential for bridging the gap between quantum resilience and real-world scalability [29].

5.3 Interoperability Limitations

Interoperability findings revealed a pronounced research gap. Of the 35 studies reviewed, only 3 (8%) demonstrated cross-chain interoperability between permissioned and public blockchain systems using PQC primitives [15]. The remaining 32 studies (92%) remained confined to single platforms, typically Ethereum or Hyperledger, without exploring cross-chain communication. Although our framework achieved compatibility with decentralized identifier (DID) and verifiable credential (VC) standards, 90% of reviewed studies did not test smart contract portability, leaving contract execution tied to platform-specific requirements.

Implementation attempts further underscored these barriers. For example, deploying SPHINCS+-based signatures on Ethereum testnets failed due to the lack of native support for hash-based verification. A custom Solidity wrapper was required, which increased contract size and deployment costs by ~14%. Across the literature, over 80% of PQC frameworks lacked standardized cross-platform cryptographic libraries, forcing developers to rely on bespoke adaptations that add both cost and complexity.

These results highlight interoperability as the least addressed of the five dimensions, and they suggest that real-world deployment of PQC-enhanced blockchains will remain constrained until standardized quantum-safe APIs and middleware solutions are developed to abstract protocol-specific requirements.

5.4 Regulatory Alignment and Compliance Automation

A key strength of the proposed framework is its demonstrated ability to meet GDPR requirements through architectural modularity. In 50 simulated patient data workflows, the system achieved a 99.98% audit trail completion **rate** and fulfilled 95% of erasure requests, confirming practical enforceability of rights such as Article 17 (right to erasure) and Article 30 (processing documentation). These compliance results were enabled by decoupling personal data from immutable on-chain structures and using mutable off-chain storage (e.g., IPFS), which also aligns with HIPAA's auditability provisions [18].

In contrast, only 7 of the 35 studies reviewed (20%) explicitly tested compliance mechanisms, and fewer than 10% evaluated automated consent revocation. This highlights a significant research gap, where most PQC-enabled blockchain models address cryptographic resilience but neglect legal enforceability. By embedding compliance

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DOI: https://doi.org/10.25195/ijci.v51i2.623
Print ISSN: 2313-190X, Online ISSN: 2520-4912

automation into the architecture, our framework ensures that real-time consent logging and revocation are directly linked to smart contract events, providing immutable auditability.

These findings suggest that compliance automation can only be achieved through hybrid on-chain/off-chain models. Yet, such designs remain absent in nearly 80% of PQC-enabled blockchain proposals, underscoring the need for future work to integrate legal compliance testing as a first-class requirement in post-quantum blockchain frameworks.

5.5 Empowering User Control and Consent Revocation

The integration of Ciphertext-Policy Attribute-Based Encryption (CP-ABE), smart contracts, and consent dashboards enables users to retain active and fine-grained control over their data. In our evaluation, CP-ABE achieved 98% accuracy across 10,000 policy applications, while access revocation was processed in under 2.1 seconds after user withdrawal. This represents a significant improvement compared to centralized systems, where revocation often requires hours to take effect.

Despite its importance, explicit user-consent mechanisms remain underrepresented in the literature. Only 6 of the 35 studies reviewed (17%) incorporated consent control, and fewer than 10% tested real-time revocation performance, underscoring the novelty of our framework. By directly linking consent events to smart contract entries, the system ensures that approvals, denials, and withdrawals are traceable, immutable, and auditable in real time, thereby reinforcing both compliance and user trust.

Clinician feedback during prototype evaluation confirmed the value of transparency: healthcare professionals particularly emphasized the usability benefits of being able to monitor access attempts in real time. These results suggest that embedding real-time, user-driven consent into PQC-enabled frameworks is not only feasible but essential for adoption in regulated domains such as healthcare and finance, yet it remains absent from the majority of current proposals.

5.6 Practical and Theoretical

The comparative analysis between classical and post-quantum blockchain systems (Table 2) highlights both the progress achieved and the challenges that remain. Classical systems, dominated by RSA and ECDSA signatures, provide adequate security in the pre-quantum era but are critically vulnerable to Shor's and Grover's algorithms. In contrast, post-quantum schemes such as SPHINCS+ and Dilithium offer long-term confidentiality guarantees, with our prototype achieving a 100% resistance score in simulated quantum attack scenarios, a result consistent with 10 of the 35 reviewed studies (29%) that tested lattice-based encryption under adversarial conditions.

Performance comparisons illustrate a trade-off. While our framework sustained throughput of **1**,500 TPS, nearly 50× higher than Ethereum's 30 TPS baseline, this came at the cost of 5–12 seconds of added latency in 80% of PQC-enhanced implementations, underscoring the scalability–security tension. Similarly, the integration of zk-STARKs reduced unauthorized access by 40%, but increased verification costs. These findings confirm that the theoretical advantages of PQC must be balanced with practical considerations of system performance, deployment cost, and interoperability.

From a compliance perspective, the the decoupling of personal data from immutable ledgers enabled 99.98% audit trail completion and 95% erasure success rates in simulated GDPR workflows. Yet, only 20% of the literature (7/35 studies) explicitly tested legal compliance, indicating that regulatory enforceability remains underexplored in theoretical work. Likewise, user-centric consent revocation, which our prototype processed in under 2.1 seconds, was implemented in fewer than 10% of reviewed models, despite being critical for real-world adoption in sensitive sectors such as healthcare and finance.

Collectively, these insights suggest that post-quantum blockchain research must move beyond theoretical cryptographic resilience toward full-stack, deployable frameworks that integrate PQC with zero-knowledge proofs, compliance automation, and user-driven consent. The practical results achieved in this study demonstrate that such integration is feasible, but they also highlight the necessity of hardware-assisted acceleration, standardized APIs, and cross-chain interoperability for sustainable deployment. Table II provides a comparative summary of the key differences between classical and post-quantum blockchain characteristics across core cryptographic and operationaldimensions. As shown, classical blockchains such as Bitcoin and Ethereum rely on RSA/ECDSA for

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DOI: https://doi.org/10.25195/ijci.v51i2.623
Print ISSN: 2313-190X, Online ISSN: 2520-4912

signatures and AES/RSA for encryption, both of which are highly vulnerable to quantum algorithms like Shor's and Grover's. In contrast, post-quantum approaches integrate signature schemes such as SPHINCS+ and Dilithium, and lattice-based encryption methods such as NTRU, which offer significantly stronger resistance to quantum decryption.

TABLE II. A comparative summary of classical versus post-quantum blockchain characteristics is presented in table 2 below.

Feature	*Classical Blockchain*	*Post-Quantum Blockchain*
Signature Scheme	ECDSA / RSA	SPHINCS+ / Dilithium
Encryption Method	AES RSA	Lattice / NTRU
Attack Resistance	Low (Quantum Vulnerable)	High (Quantum Resistant)
Performance Under Load	High Latency (Under Stress)	Stable with ZK-Rollups
Blockchain Size Growth	Rapid Growth (On-chain)	Optimized (Off-chain)
Identity Privacy	Moderate (Pseudo-Anonymity)	Strong (Decentralized ID + ZKP)
ZKP Integration	Rare	Common (zk-SNARKs / STARKS)

Table III provides a benchmark comparison of Ethereum, Hyperledger Fabric, and the proposed hybrid framework across five dimensions: throughput, latency, storage efficiency, compliance, and consent control.

TABLE III. Benchmark comparison of blockchain models under classical and post-quantum configurations.

Model / Framework	*Cryptography Used*	*Throughput (TPS)*	*Latency Overhead*	*Storage Efficiency*	*Compliance Testing*	*Consent Revocation*
Ethereum (Medrec, etc)	RSA /ECDSA, zk-SNARKS	~15–30	+5–8s (SNARK proof)	On-chain only (high gas costs)	Not tested	Not supported
Hyperledger Fabric (hOCBS)	RSA / ECDSA + IPFS	~1,000–1,200	<2s (endorsement/ordering)	~65% storage reduction (IPFS off-chain)	Not tested	Partial (role-based only)
Proposed Hybrid Framework	Lattice (Kyber, NTRU), SPHINCS+, zk-STARKs, CP-ABE, TEEs	~1,500	+5–12s (PQ proofs & ZKP)	~75% storage reduction (IPFS off-chain)	Yes (GDPR audit 99.98%, erasure 95%)	Yes (revocation <2.1s)

5.7 Conclusion

This study proposed and evaluated a post-quantum blockchain hybrid framework that integrates lattice-based encryption, hash-based signatures, zero-knowledge proofs, and trusted execution environments to secure personal data sharing in the quantum era. Through a systematic literature review of 35 studies, we found that only 5 (14%) explicitly implemented PQC primitives, while the majority relied on classical schemes vulnerable to quantum attacks. Similarly, less than 10% demonstrated interoperability, and only 7 studies (20%) tested regulatory compliance, confirming that practical, full-stack quantum-resilient architectures remain rare in literature.

Our prototype evaluation demonstrated that PQC integration is both feasible and impactful. Lattice-based encryption achieved a 100% resistance score under simulated quantum adversary models, SPHINCS+ signatures maintained 1.2-second verification times, and zk-STARKs combined with CP-ABE reduced unauthorized access by ~40%. Scalability testing showed throughput of 1,500 TPS, with 75% storage reduction via IPFS, though PQC overhead introduced 5–12 seconds of latency in 80% of cases. Compliance workflows achieved 99.98% audit trail completion and 95% successful erasure requests, while user-driven consent revocation was processed in under 2.1 seconds, compared to hours in centralized systems.

The comparative analysis (Table 2) highlights clear advantages of post-quantum blockchain systems in security, privacy, and compliance, but also underscores trade-offs in performance and interoperability. These findings suggest that the next stage of research must focus on standardized APIs, hardware-assisted acceleration, and middleware for cross-chain interoperability, alongside systematic integration of compliance testing and user-driven consent controls.

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Information Technology and Communications University
Vol. 51, No. 2, 2025, pp. 109-125
DOI: https://doi.org/10.25195/ijci.v51i2.623
Print ISSN: 2313-190X, Online ISSN: 2520-4912

In conclusion, the proposed hybrid framework demonstrates that quantum-resilient, privacy-preserving blockchain systems are achievable today, but widespread adoption will require bridging the gap between theoretical PQC resilience and deployable, full-stack architectures, this study provides both a roadmap and a proof-of-concept for building secure, compliant, and future-proof data sharing ecosystems in the quantum era. Future work will extend benchmarking across larger datasets and additional blockchain platforms to further validate scalability and compliance under diverse real-world conditions.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive external funding. The article processing charges (if any) will be paid by North-West University, South Africa.

Acknowledgment

I am also profoundly thankful to the academic and technical staff at North-West University in South Africa, whose resources and facilities made this research possible.

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