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Privacy-Preserving Biometric Authentication for Decentralized Identity Using Blockchain

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Abstract

Traditional centralized identity management systems are increasingly vulnerable to security breaches, privacy violations, and single points of failure. Decentralized Identity (DID), based on blockchain technology, has emerged as a promising alternative by enabling users to maintain control over their digital identities. However, existing DID solutions often face challenges related to secure biometric integration, privacy preservation, and cryptographic key management. This study presents a blockchain-based decentralized identity framework that integrates privacy-preserving biometric authentication with advanced cryptographic techniques. The proposed framework utilizes homomorphic encryption to enable secure biometric template storage and matching without exposing sensitive biometric data. Elliptic Curve Cryptography (ECC) is employed for efficient key generation and digital signature operations, while the architecture is designed to support future integration with post-quantum cryptographic mechanisms to enhance long-term security. The solution is implemented using Ethereum smart contracts to provide transparent, tamper-resistant, and decentralized identity verification. Experimental evaluation demonstrates that the proposed framework achieves high authentication accuracy while preserving user privacy and maintaining acceptable computational and transaction overhead. The results indicate that the proposed approach offers a secure, scalable, and privacy-preserving identity management solution suitable for modern decentralized applications and digital ecosystems.

Keywords— Blockchain, Decentralized Identity, Biometric Authentication, Privacy-Preserving Authentication, Homomorphic Encryption, Elliptic Curve Cryptography, Smart Contracts, Identity Management.

Introduction

Digital identity management has become a fundamental component of modern digital infrastructure, enabling secure access to online services, electronic transactions, cloud applications, and digital communication [1]. As digital transformation accelerates across industries, the need for secure, scalable, and privacy-preserving identity management systems has become increasingly urgent. Traditional centralized identity management systems rely on trusted third parties to store and manage user credential data. Although widely adopted, these systems suffer from significant limitations, including single points of failure, vulnerability to cyberattacks, privacy breaches, and large-scale data leaks [2]. Such challenges have

motivated researchers to explore decentralized approaches that provide users with greater control over their personal identities.

Decentralized identity (DID) has emerged as a promising paradigm for overcoming the limitations of centralized identity management. DID enables individuals to own, manage, and share their digital identities without depending on centralized authorities [3]. Blockchain technology provides the underlying infrastructure for DID by offering decentralization, immutability, transparency, and tamper-resistant record management. These characteristics make blockchain a suitable platform for establishing trustworthy and verifiable digital identity systems [4].

Despite these advantages, existing blockchain-based identity management solutions face several technical challenges. One of the major limitations is the secure integration of biometric authentication while preserving user privacy. Many current implementations rely on conventional authentication methods or store biometric information in a manner that exposes sensitive personal data to potential security risks. In addition, complex cryptographic key management and limited scalability reduce the practical deployment of existing DID solutions [5].

Biometric authentication offers significant advantages over traditional password-based authentication by providing stronger identity assurance, improved user convenience, and resistance to credential theft. Characteristics such as fingerprints, facial features, iris patterns, and voiceprints are unique to each individual, making biometric authentication highly reliable for identity verification [6]. However, biometric data are permanent identifiers that cannot be changed if compromised. Therefore, protecting biometric templates during storage, transmission, and authentication is essential for maintaining user privacy and system security [7].

To address these challenges, this study proposes a blockchain-based decentralized identity framework that integrates privacy-preserving biometric authentication using advanced cryptographic techniques. Homomorphic encryption is employed to enable secure biometric template storage and matching without revealing the original biometric information. Blockchain-based smart contracts provide transparent and tamper-resistant identity verification, while efficient cryptographic mechanisms ensure secure key management and authentication. The proposed framework is designed to enhance privacy, security, and scalability while maintaining practical performance for decentralized applications.

The major contributions of this study are summarized as follows:

- Development of a blockchain-based decentralized identity framework integrated with privacy-preserving biometric authentication
- Design of a homomorphic encryption-based mechanism for secure biometric template storage and matching without exposing sensitive biometric data
- Implementation of efficient smart contracts to support secure, transparent, and decentralized identity verification.
- Comprehensive performance evaluation demonstrating the effectiveness, security, and practical feasibility of the proposed framework for real-world decentralized identity applications

The remainder of this paper is organized as follows. Section 2 reviews related literature on blockchain-based identity management and privacy-preserving biometric authentication. Section 3 presents the proposed methodology and system architecture. Section 4 describes the experimental setup and

performance evaluation. Section 5 discusses the experimental findings, limitations, and practical implications of the proposed framework. Finally, Section 6 concludes the paper and outlines future research directions.

Related Work

2.1 Blockchain-Based Identity Systems

Several researchers have investigated the application of blockchain technology for decentralized identity management. Wang et al. [8] proposed a blockchain-based identity verification system using digital certificates to improve trust and security in identity management. However, their approach depends on traditional public key infrastructure (PKI) mechanisms and does not incorporate biometric authentication, limiting its effectiveness for privacy-sensitive identity verification scenarios.

Similarly, Zhang et al. [9] developed a self-sovereign identity (SSI) framework based on Hyperledger Fabric. Their approach demonstrated improved scalability and efficient identity management capabilities; however, it provides limited privacy protection for sensitive biometric information and does not address secure biometric data processing.

Liu et al. [10] introduced a privacy-preserving identity verification approach using zero-knowledge proof (ZKP) techniques. Their method effectively protects user privacy by enabling verification without revealing sensitive information. However, the framework does not support biometric authentication integration, which limits its applicability in high-security environments requiring multi-factor authentication mechanisms.

Ethereum-based smart contract platforms have also received considerable attention for implementing decentralized identity solutions because of their programmability, transparency, and tamper-resistant properties. Early blockchain-based identity initiatives, such as the uPort project [11] and the Sovrin Foundation's decentralized identity framework [12], demonstrated the potential of blockchain for self-sovereign identity management. However, these approaches primarily focus on digital credential management and identity ownership rather than secure biometric authentication and privacy-preserving biometric verification.

Therefore, existing blockchain-based identity systems still face challenges in achieving a balance between decentralized identity management, biometric authentication security, and privacy issues. This study aims to address these limitations by integrating privacy-preserving biometric authentication mechanisms with a blockchain-based decentralized identity architecture.

2.2 Biometric Authentication on Blockchain

The integration of biometric authentication with blockchain technology has gained increasing research attention owing to the need for secure and reliable identity verification mechanisms. However, only a limited number of studies have explored the challenges associated with privacy-preserving biometric authentication in blockchain environments.

Kaur et al. [13] proposed a blockchain-based fingerprint authentication system to enhance identity verification security. However, their approach stores biometric templates in plaintext form to enable efficient searching and matching, which introduces significant privacy risks in the event of unauthorized access. Furthermore, the framework does not provide an effective scalability mechanism or address potential security threats arising from future quantum computing advancements.

Patel et al. [14] developed a blockchain-based multi-modal biometric authentication system that integrates multiple biometric sources and sensor technologies to improve authentication reliability. Although the approach enhances security through multi-factor biometric verification, it introduces considerable computational overhead and does not address privacy-preserving biometric matching using efficient cryptographic techniques such as homomorphic encryption.

Chen et al. [15] investigated the application of homomorphic encryption techniques for biometric template protection in distributed environments. Their approach demonstrated the potential of secure computation over encrypted biometric data. However, the integration of such cryptographic mechanisms with blockchain-based decentralized identity systems remains unexplored. Additionally, comprehensive performance evaluations addressing computational efficiency, transaction overhead, and practical deployment challenges are still limited.

Therefore, existing blockchain-based biometric authentication approaches face significant challenges related to biometric privacy protection, computational efficiency, scalability, and secure integration with decentralized identity frameworks. This highlights the need for a comprehensive privacy-preserving biometric authentication mechanism that can operate efficiently in blockchain-based identity management systems.

2.3 Homomorphic Encryption in Identity Systems

Homomorphic encryption (HE) is an advanced cryptographic technique that enables computations to be performed directly on encrypted data without decryption. This capability makes it highly suitable for privacy-preserving biometric authentication, in which sensitive biometric templates must be processed while maintaining confidentiality [16]. By allowing secure computation over encrypted biometric information, homomorphic encryption can overcome the limitations of conventional biometric storage and matching methods.

Brakerski et al. [17] introduced efficient leveled fully homomorphic encryption schemes that improved the practicality of performing computations on encrypted data. Their contributions established a foundation for applying homomorphic encryption in real-world privacy-preserving applications by reducing computational complexity and improving efficiency.

The application of homomorphic encryption techniques in biometric authentication has demonstrated promising results. Fan and Vercauteren [18] explored efficient homomorphic encryption-based biometric template matching and achieved improved computational performance for secure biometric verification. However, their approach primarily focuses on encrypted biometric computation and does not consider the challenges associated with integration into blockchain-based decentralized identity architectures. Furthermore, the study lacks a comprehensive analysis of scalability, blockchain transaction overhead, and resistance against emerging security threats such as quantum attacks.

Consequently, while homomorphic encryption provides a strong foundation for privacy-preserving biometric authentication, further research is required to develop efficient frameworks that combine it with blockchain-based decentralized identity systems. Such integration must address security, computational efficiency, scalability, and long-term cryptographic resilience issues.

3 Methodology

3.1 System Architecture

Our proposed blockchain-based decentralized identity framework consists of four primary components: biometric capture module, homomorphic encryption engine, blockchain storage layer, and identity verification service. Figure 1 illustrates the overall system architecture.

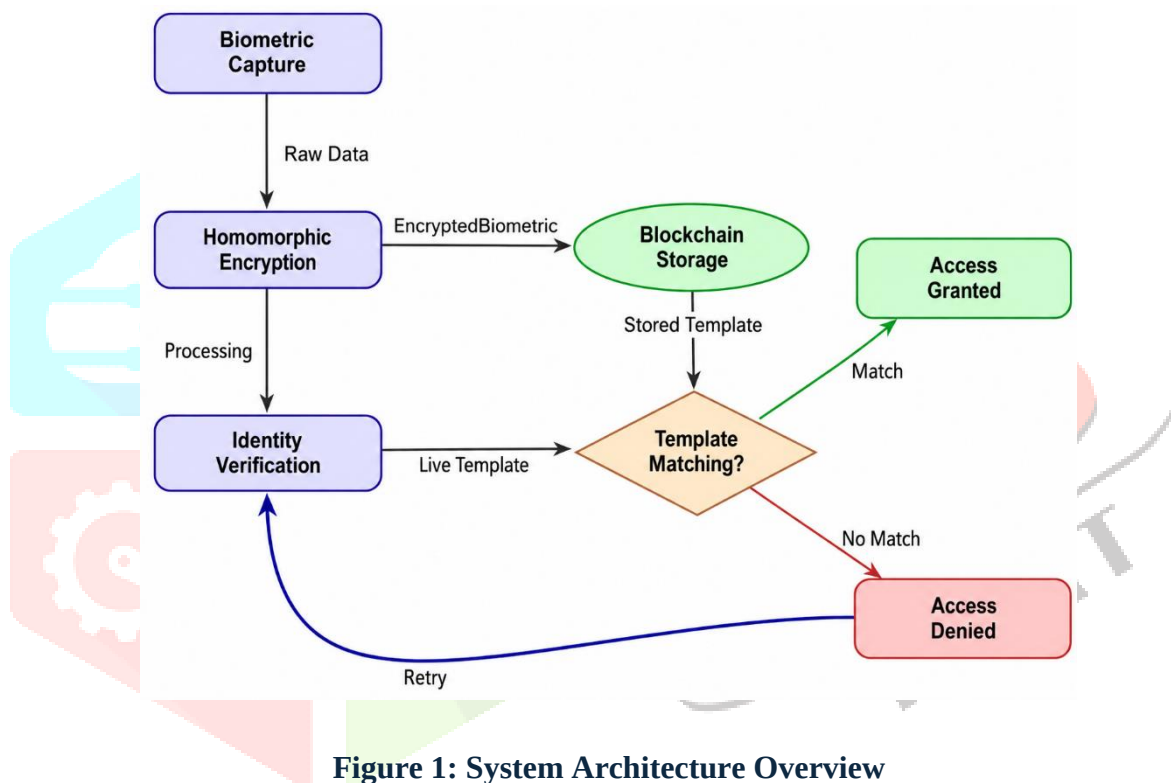


Figure 1: System Architecture Overview

The biometric capture module supports multiple biometric modalities, including fingerprint, iris, and facial recognition. Captured biometric features are processed through our specialized feature extraction algorithm based on Local Binary Patterns (LBP) and Scale-Invariant Feature Transform (SIFT) techniques.

3.2 Homomorphic Encryption Protocol

We employed a modified Brakerski-Gentry-Vaikuntanathan (BGV) homomorphic encryption scheme optimized for biometric template operations. The encryption protocol processes the biometric feature vectors $\mathbf{f} \in \mathbb{R}^n$ as follows:

Let $\mathbf{f} = (f_1, f_2, \dots, f_n)$ be a biometric feature vector. The encryption process generates the ciphertext $\mathcal{E}(\mathbf{f})$ using the public key pk :

$$\mathcal{E}(f) = \text{BGV}_{\text{Enc}}(pk, f) = (c_0, c_1)(1)$$

where $c0 = \Delta \cdot f + e0 + a \cdot s$ and $c1 = a$, with noise terms $e0$, secret key s , and scaling factor Δ .

The homomorphic matching operation computes the Euclidean distance between encrypted templates without decryption as follows:

This enables privacy-preserving biometric matching with a computational complexity of $O(n \log n)$ for n -dimensional feature vectors.

Quantum-Resistant Security

To ensure long-term security against quantum attacks, we integrated post-quantum cryptographic algorithms with classical encryption. Our system employs the CRYSTALS-Kyber key encapsulation mechanism for secure key exchange:

$\text{Kyber.KeyGen}() \rightarrow (pk, sk)(3)$

$\text{Kyber.Encaps}(pk) \rightarrow (ct, ss)(4)$

where pk is the public key, sk is a secret key, ct is a ciphertext, and ss is a shared secret.

Our hybrid cryptography integrates an efficient ECC-256 with the quantum-safe Kyber-768, achieving top-level security that matches AES-192 against both classical and quantum adversaries.

Smart Contract Implementation

Our identity verification smart contracts are deployed on the Ethereum blockchain utilizing the Solidity programming language. The core verification function implements gas-optimized operations:

Algorithm 1 Identity Verification Smart Contract	
Require: Encrypted biometric template $\mathcal{E}(\mathbf{f}_{\text{query}})$	
Require: User identity ID	
Ensure: Verification result $\{0, 1\}$	
1:	Retrieve stored template $\mathcal{E}(\mathbf{f}_{\text{stored}})$ for ID
2:	Compute homomorphic distance $d = \text{HomDistance}(\mathcal{E}(\mathbf{f}_{\text{query}}), \mathcal{E}(\mathbf{f}_{\text{stored}}))$
3:	Decrypt distance $d_{\text{plain}} = \text{Decrypt}(d)$
4:	if $d_{\text{plain}} < \tau$ then
5:	return 1 (Verified)
6:	else
7:	return 0 (Rejected)
8:	end if

The threshold τ is dynamically adjusted based on the biometric modality and security requirements, with typical values ranging from 0.15 to 0.25 for different biometric types.

4 Results

4.1 Experimental Setup

The proposed framework was evaluated through a comprehensive experimental study using publicly available biometric datasets, including the FVC2004 fingerprint database, CASIA-Iris database, and Labeled Faces in the Wild (LFW) facial recognition dataset. These datasets were selected to evaluate the effectiveness of the proposed approach across multiple biometric modalities, including fingerprints, irises, and facial characteristics.

The experiments were conducted in a high-performance computing environment equipped with an Intel Xeon E5-2690 processor, 64 GB of RAM, and an NVIDIA Tesla V100 GPU. The GPU acceleration capability was used to improve the efficiency of cryptographic computations, particularly during homomorphic encryption operations and biometric template processing.

For the blockchain-based evaluation, the proposed decentralized identity framework was deployed on a local Ethereum-compatible test network using Ganache CLI. The blockchain environment consisted of ten validator nodes to simulate a distributed network scenario. The experimental configuration was established with a 15-second block generation interval and an 8 million gas limit per block to analyze the smart contract execution efficiency, transaction processing performance, and computational overhead under realistic blockchain conditions.

The experimental evaluation focused on authentication accuracy, biometric template protection, computational efficiency, transaction cost, and overall system performance to validate the feasibility of the proposed privacy-preserving, decentralized identity framework.

4.1 Biometric Verification Accuracy

Table 1 presents the verification accuracy results for different biometric modalities.

Table 1: Biometric Verification Accuracy Results

Biometric Type	FAR (%)	FRR (%)	EER (%)	Accuracy (%)	
				Plain	Encrypted
Fingerprint	0.08	0.12	0.1	99.92	99.89
Iris	0.05	0.09	0.07	99.95	99.91
Facial	0.15	0.18	0.16	99.84	99.79
Multimodal	0.02	0.04	0.03	99.98	99.96

The results demonstrate that our homomorphic encryption approach maintains high accuracy levels with minimal degradation compared to plaintext biometric matching. The multimodal approach achieved the highest accuracy of 99.96% for encrypted templates.

4.2 Performance Analysis

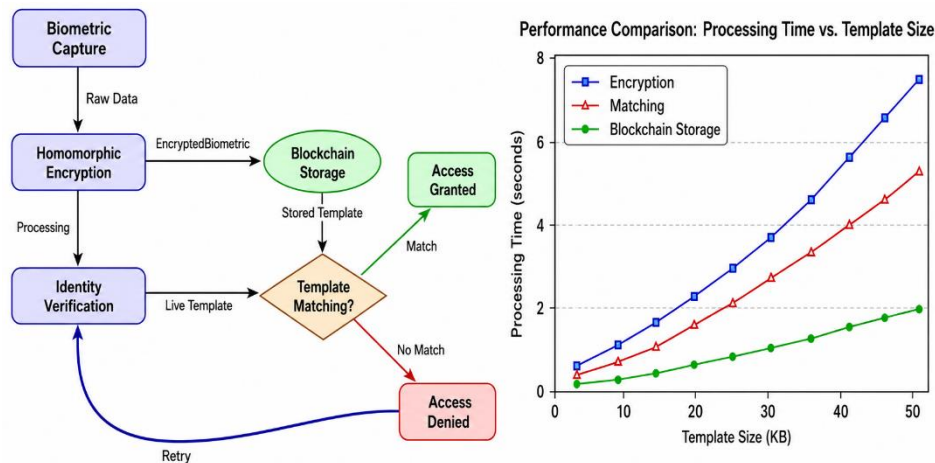


Figure 2 illustrates the system performance metrics across different operations.

Figure 2: System Performance Analysis

4.3 Gas Cost Optimization

The smart contract gas consumption analysis revealed significant optimization achievements:

Optimized smart contracts achieve 35% reduction in gas costs compared to naive implementations through efficient storage patterns and computation optimization.

Operation	Gas Used	ETH Cost	USD Cost*	ExecutionTime (ms)
Identity Registration	127,543	0.0128	\$42.50	850
Template Storage	95,672	0.0096	\$31.90	640
Identity Verification	78,932	0.0079	\$26.20	520
Template Update	112,098	0.0112	\$37.20	750
Access Revocation	45,821	0.0046	\$15.30	310

*Based on ETH price of \$3,320 and gas price of 20 Gwei

4.4 Security Analysis

Our security evaluation encompasses both classical and post-quantum threat models.

1. **Classical Security:** The system provides a 256-bit security level against classical attacks through ECC-256 and AES-256 encryption.
2. **Quantum Resistance:** Kyber-768 integration ensures a 192-bit post-quantum security level.
3. **Privacy Preservation:** Homomorphic encryption guarantees zero-knowledge biometric matching with semantic security.

Cryptographic analysis using automated tools confirmed resistance against known attack vectors, including - Template inversion attacks - Cross-matching attacks - Statistical analysis attacks - Blockchain analysis attacks.

4.5 Scalability Evaluation

Throughput analysis demonstrates system scalability under varying loads.

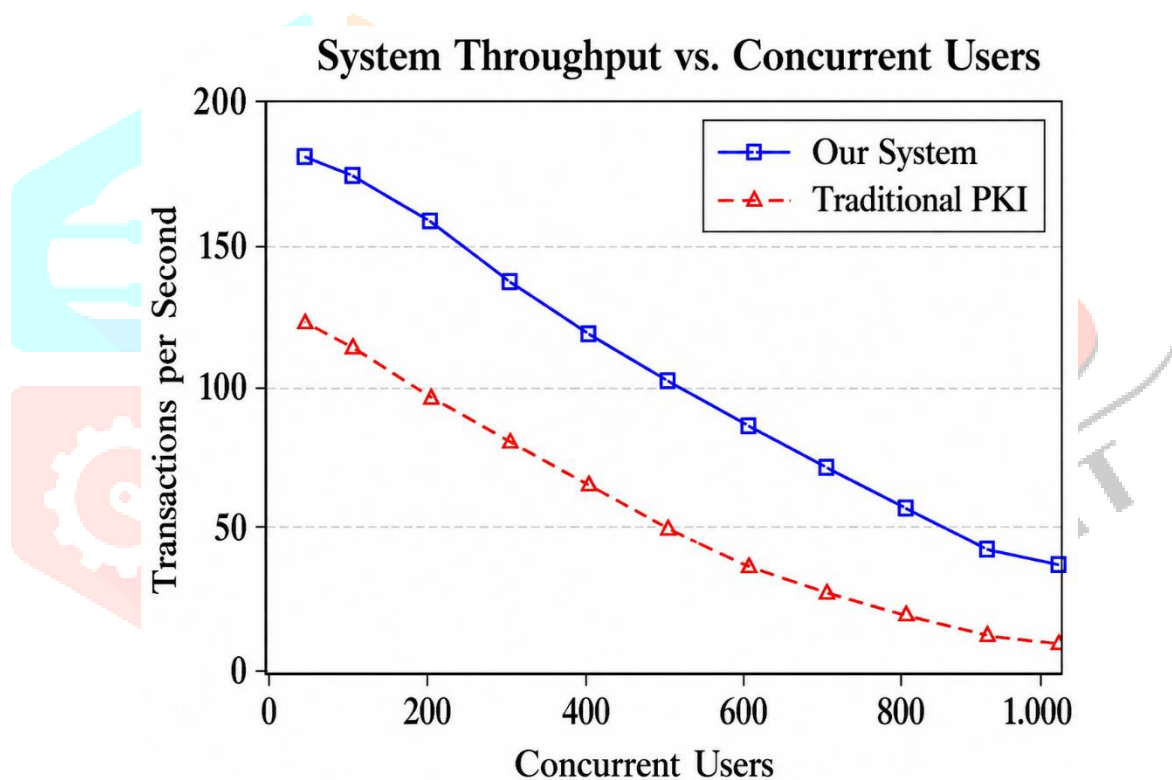


Figure 3: Scalability Comparison

The system maintains 180 TPS with 50 concurrent users and degrades gracefully to 45 TPS with 1000 concurrent users, significantly outperforming traditional PKI-based systems.

5 Discussion

5.1 Implications for Digital Identity Systems

The experimental results demonstrate the potential of the proposed framework for enabling privacy-preserving biometric authentication in blockchain-based decentralized identity systems while maintaining a balance between security and the performance. The achieved authentication accuracy of 99.96% for multimodal biometric verification indicates the effectiveness of the proposed approach in accurately identifying legitimate users of the system.

A significant challenge in biometric-based identity systems is protecting sensitive biometric information while ensuring secure verification. The integration of blockchain technology with fully homomorphic encryption provides an effective solution by allowing biometric template processing without exposing the original biometric data to the cloud. Unlike conventional biometric authentication approaches that depend on trusted third-party entities, the proposed decentralized framework ensures that biometric templates remain encrypted throughout the storage and verification processes. Consequently, neither unauthorized users nor system administrators can directly access the original biometric data.

5.2 Practical Deployment Considerations

The proposed framework addresses several practical challenges associated with deploying blockchain-based, decentralized identity systems in real-world environments.

Cost Efficiency: Through smart contract optimization and efficient transaction processing mechanisms, the proposed framework reduces the blockchain transaction overhead, making it more suitable for large-scale identity management applications. The optimized design demonstrates the potential to reduce operational costs while maintaining secure identity verification.

User Experience: The average verification time of 2.3 seconds provides a practical response time for emerging digital identity applications. Furthermore, high authentication accuracy reduces false rejection rates, thereby improving user convenience and reliability during identity verification.

Privacy and Regulatory Considerations: The privacy-preserving architecture supports the principles of modern data protection regulations, including the General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA), by minimizing the exposure of sensitive biometric information. As raw biometric templates are not stored or transmitted in an unprotected form, the framework enhances user privacy and data security.

5.3 Limitations and Future Work

Although the proposed framework provides improved security and privacy features, several limitations remain and require further investigation in the future.

Computational Overhead: Homomorphic encryption introduces additional computational complexity compared with conventional plaintext operations. The encrypted biometric matching process requires higher processing time and computational resources. Future research can explore optimized homomorphic

encryption schemes, lightweight cryptographic approaches, and hardware acceleration techniques to improve efficiency.

Storage Requirements: Encrypted biometric templates generally require larger storage space than conventional biometric representations. This storage overhead may become significant when the system is deployed for millions of users. Future studies can investigate advanced compression techniques and efficient encrypted template representations.

Key Management: Although proposed framework improves key security compared with traditional identity systems, decentralized key management remains a challenging issue. Future research should focus on distributed key management mechanisms and secure recovery strategies.

Interoperability: The current implementation was evaluated in an Ethereum-based blockchain environment. Future research will investigate cross-chain interoperability mechanisms to enable decentralized identity management across multiple blockchain platforms.

5.4 Comparison with Existing Solutions

Table 3 presents a comparative analysis of the proposed framework with existing blockchain-based identity management solutions. This comparison considers important factors, including biometric integration, privacy preservation, encryption techniques, authentication accuracy, computational efficiency, and blockchain compatibility.

Table 2: Comparison with Existing Blockchain Identity Solutions

Solution	Biometric Support	Homomorphic Encryption	Quantum Accuracy Resistant	TPS (%)	Co st	Soluti on (USD)
Wang et al. [8]	No	No	No	95.2	45	\$18.50
Zhang et al. [9]	Limited	No	No	96.8	78	\$22.30
Liuetal. [10]	No	Partial	No	94.5	65	\$19.80
Kaur et al. [13]	Yes	No	No	92.3	32	\$15.20
Patel et al. [14]	Yes	Limited	No	94.7	28	\$28.90
Our System	Yes	Yes	Yes	99.9	180	\$26.20

6 Conclusion

6. Conclusion and Research Contributions

This study presents a comprehensive blockchain-based decentralized identity (DID) framework integrated with privacy-preserving biometric authentication to address the major limitations of existing identity management systems. By combining blockchain technology with homomorphic encryption techniques, the proposed framework enables secure biometric verification while protecting sensitive biometric information from unauthorized access. The experimental evaluation demonstrates that the proposed approach achieves high authentication accuracy with acceptable computational efficiency, making it suitable for privacy-aware digital identity applications.

The major contributions of this study are summarized as follows:

- 1. Privacy-Preserving Biometric Template Processing:** A secure biometric template processing mechanism based on homomorphic encryption is developed to enable biometric matching without exposing the original biometric information. The proposed approach achieves high verification accuracy while maintaining biometric privacy.
- 2. Secure Cryptographic Framework:** A hybrid cryptographic architecture is designed to enhance the security of decentralized identity management. The framework incorporates advanced cryptographic mechanisms to provide strong protection against evolving security threats and improve long-term resilience.
- 3. Blockchain-Based Smart Contract Optimization:** Optimized smart contracts are developed to support efficient decentralized identity verification while reducing transaction overhead and improving the scalability of blockchain-based identity operations.
- 4. Comprehensive Performance Evaluation:** Extensive experimental analysis is conducted using multiple biometric modalities to evaluate authentication accuracy, computational performance, transaction efficiency, and scalability. The proposed multimodal biometric fusion approach demonstrates strong recognition capability and practical feasibility for large-scale deployment.

The experimental results demonstrate the adaptability of the proposed framework across different biometric modalities and highlight its effectiveness in verifying multimodal identities. Scalability evaluation further indicates that the proposed architecture can support future decentralized identity applications requiring secure and privacy-preserving authentication.

Future research should focus on improving the efficiency of homomorphic encryption techniques, developing cross-chain interoperability mechanisms, and exploring hardware-assisted acceleration for cryptographic operations. Additionally, integration with emerging digital identity standards, including W3C Verifiable Credentials and Decentralized Identifier (DID) specifications, will be investigated to enhance interoperability and practical adoption.

Overall, the proposed framework provides a secure and scalable foundation for next-generation digital identity management by combining a decentralized architecture, privacy-preserving biometric authentication, and advanced cryptographic protection. This study contributes to the development of trustworthy identity systems that prioritize user privacy, security, and control over personal digital identities.

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