Survey on Secure Search in the Cloud Protecting Encrypted Data

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Abstract: - The growing reliance on cloud infrastructures for storing and managing sensitive data has intensified the need for secure and usable mechanisms that enable search over encrypted content. While encryption effectively protects data confidentiality, it significantly restricts data usability, particularly in keyword-based retrieval. Recent research efforts have explored searchable encryption, secret-sharing-based search, blockchain-enabled access control, and post-quantum cryptography; however, these techniques are often developed in isolation and fail to address practical deployment challenges holistically. Key limitations persist in the form of search and access pattern leakage, trusted setup assumptions, limited auditability, and a lack of cryptographic agility against emerging quantum threats. This paper presents a structured review of secure cloud data access mechanisms proposed between 2020 and 2025, critically analyzing their strengths, limitations, and underlying assumptions. Building on the identified research gaps, the paper introduces a unified architectural perspective for privacy-preserving and auditable keyword search over encrypted cloud data. The proposed framework integrates secret-sharing-based searchable encryption with dealer-free randomness generation to distribute trust and mitigate collusion risks. To ensure long-term security, post-quantum key encapsulation and digital signatures are incorporated into the key management lifecycle, while a permissioned blockchain is employed exclusively for access control enforcement and immutable audit logging. By decoupling encrypted storage, searchable indexing, key management, and governance, the architecture achieves a balance between efficiency, transparency, and security. The paper concludes by outlining open challenges and future research directions toward scalable, verifiable, and quantum-resilient encrypted search systems, positioning the proposed framework as a practical foundation for next-generation secure cloud data services.

Keyword: privacy-preserving encrypted search, secret sharing searchable encryption, auditable cloud data access, post-quantum cryptography, blockchain-based access control, secure cloud storage, keyword search over encrypted data, distributed trust architectures, quantum-resilient security, verifiable data governance

I. INTRODUCTION

The rapid adoption of cloud computing has fundamentally transformed how sensitive data are stored, shared, and accessed across distributed environments. Domains such as healthcare, finance, education, and e-governance increasingly rely on outsourced cloud infrastructures to manage large volumes of confidential information. While encryption has become the de facto mechanism for protecting data at rest and in transit, it introduces a critical functional limitation: encrypted data are inherently difficult to search. This tension between data confidentiality and usability has given rise to a rich body of research on privacy-preserving search mechanisms, particularly keyword search over encrypted data [1–3]. Despite notable progress, achieving efficient, secure, and auditable search in real-world cloud settings remains an open research challenge.

Early solutions to encrypted search predominantly relied on searchable symmetric encryption (SSE) and public-key based techniques such as attribute-based encryption and homomorphic encryption. Although these approaches provide strong cryptographic guarantees, they often suffer from practical limitations, including significant computational overhead, restricted query expressiveness, and leakage of access or search patterns [4–6]. As datasets scale and regulatory requirements become more stringent, these drawbacks hinder adoption in latency-sensitive and compliance-driven applications. Consequently, recent research has shifted toward lighter-weight

alternatives that balance security with deployability, motivating renewed interest in secret-sharing-based searchable encryption schemes [7–9].

Secret-sharing searchable encryption has emerged as a promising paradigm due to its computational efficiency and inherent resistance to single-point compromise. By distributing encrypted index shares across multiple non-colluding servers, such schemes enable fast keyword matching without revealing plaintext data or queries [10,11]. More recent variants introduce query randomization techniques to obscure search patterns, addressing one of the major leakage channels observed in classical SSE systems [12]. However, existing designs typically assume semi-honest servers, rely on trusted randomness dealers, or support only limited access control models. These assumptions weaken their applicability in adversarial, multi-tenant cloud environments where server behavior, collusion dynamics, and policy enforcement must be verifiable and auditable.

In parallel, blockchain technology has been increasingly explored as a trust anchor for cloud security systems. Permissioned blockchains, in particular, offer immutable logging, decentralized policy enforcement, and verifiable audit trails without the performance penalties associated with public chains [13–15]. Several studies have demonstrated the feasibility of using blockchain for access control management, key escrow, and integrity verification in cloud storage systems [16,17]. Nevertheless, blockchain-centric solutions often centralize cryptographic key control, lack native support for encrypted search, or introduce unnecessary on-chain overhead by storing excessive metadata. These trade-offs highlight the need for carefully scoped blockchain integration that complements, rather than replaces, cryptographic protection mechanisms.

Another critical development influencing secure cloud architectures is the advent of post-quantum cryptography (PQC). With growing concern over the long-term viability of classical public-key primitives, recent standards efforts and empirical studies have focused on lattice-based schemes such as Kyber and Dilithium [18–20]. Empirical evaluations between 2022 and 2025 demonstrate that these algorithms are not only quantum-resistant but also practical for deployment on constrained edge and cloud platforms [21]. Despite this progress, most encrypted search systems continue to rely on classical cryptography, leaving key management and access enforcement vulnerable to future quantum adversaries.

A further limitation of current encrypted search solutions lies in access control expressiveness and accountability. While discretionary or owner-based access control is commonly supported, fine-grained, attribute-aware, and revocable policies remain difficult to enforce without resorting to heavyweight cryptographic constructions [22–24]. Moreover, users and regulators increasingly demand transparency regarding *who searched what data and under which authorization*. Traditional cryptographic systems offer limited support for non-repudiable search auditing, creating gaps in compliance with modern data governance frameworks such as HIPAA, GDPR, and emerging national data protection laws [25].

Recent interdisciplinary efforts suggest that no single technique encryption, secret sharing, or blockchain can independently satisfy all functional, security, and governance requirements of modern cloud systems. Instead, hybrid architectures that integrate complementary mechanisms are gaining traction [26–28]. These systems typically store encrypted payloads off-chain, anchor integrity proofs and policy attestations on a permissioned ledger, and employ efficient cryptographic primitives for data access and search. However, existing hybrid proposals often lack dealer-free randomness generation, post-quantum key lifecycles, or explicit mechanisms to verify the correctness of search responses in the presence of malicious servers.

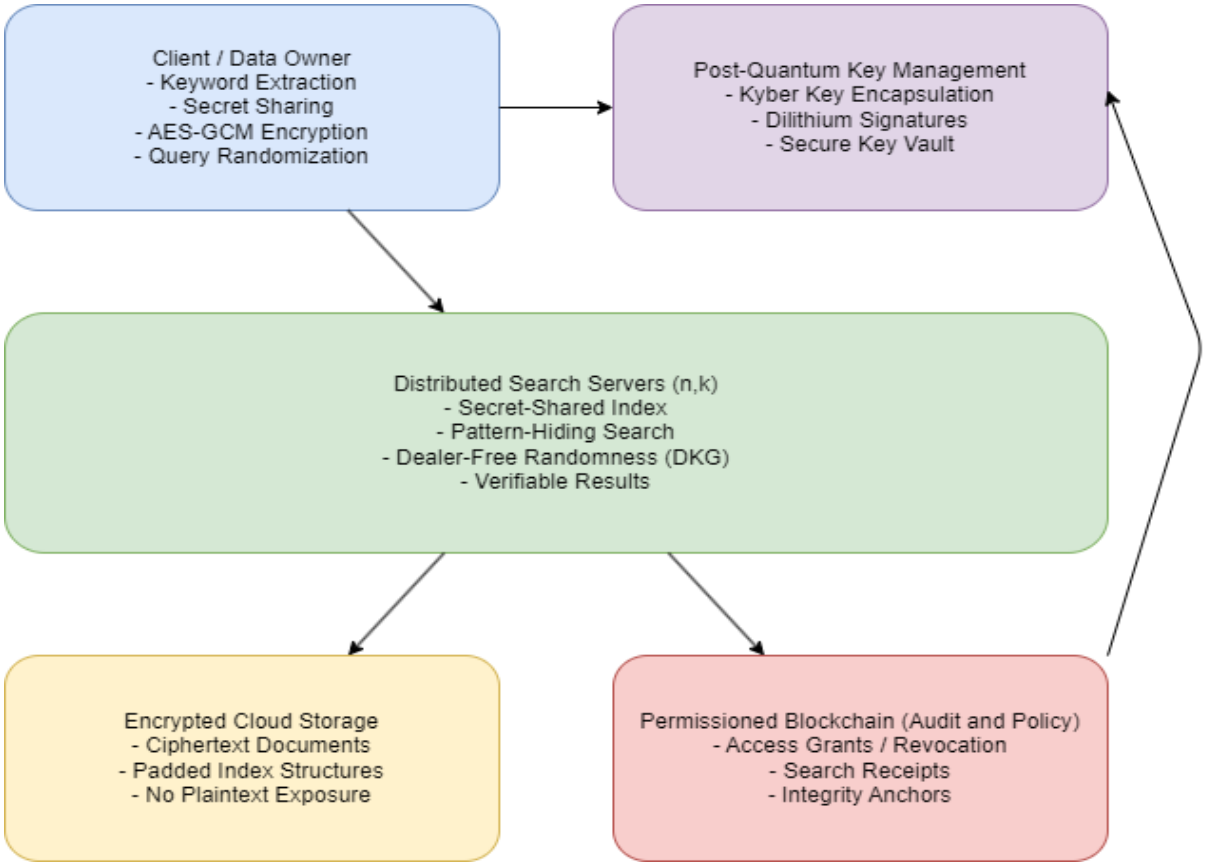

Figure 1 Conceptual block diagram of the proposed secure and auditable encrypted search framework integrating secret-sharing-based searchable encryption, post-quantum key management, and blockchain-based access control.

The proposed architecture is designed to enable privacy-preserving, auditable, and future-proof keyword search over encrypted cloud data. It integrates secret-sharing–based searchable encryption, post-quantum cryptography, and blockchain-backed governance in a modular manner. Each component performs a well-defined role, ensuring that confidentiality, integrity, and accountability are maintained throughout the data lifecycle.

1. Client / Data Owner Layer

The Client / Data Owner represents the trusted entity responsible for data generation, encryption, and query initiation. This layer performs all sensitive preprocessing tasks before data leaves the trusted boundary.

- Keyword Extraction:

  Relevant keywords are extracted from documents. To prevent keyword-frequency inference, the keyword list is padded to a fixed length using dummy terms.

- Secret Sharing:

  Each keyword is transformed into cryptographic shares using a threshold secret-sharing scheme (e.g., Shamir or additive secret sharing). These shares are later distributed across multiple search servers, ensuring that no single server can infer keyword information.

- AES-GCM Encryption:

  The document content itself is encrypted using a symmetric encryption algorithm (AES-GCM), providing confidentiality and integrity. Encryption is performed locally to ensure that plaintext data is never exposed to the cloud.

- Query Randomization:

  When a user issues a search request, query keywords are randomized and secret-shared in the same manner as indexed keywords. This prevents servers from linking identical queries or learning search patterns across multiple requests.

2. Post-Quantum Key Management Layer

This layer manages encryption keys in a quantum-resistant and decoupled manner, ensuring long-term cryptographic security.

- Kyber Key Encapsulation:

  The symmetric document encryption key is wrapped using a post-quantum key encapsulation mechanism (Kyber). This allows secure key distribution to authorized users without exposing the actual data key.

- Dilithium Signatures:

  All critical operations such as access grants, key distribution, and search requests are digitally signed using post-quantum signatures (Dilithium). This ensures authenticity and non-repudiation even against future quantum adversaries.

- Secure Key Vault:

  The key vault stores only wrapped (encrypted) keys and metadata, never plaintext keys. It acts as an intermediary that enforces access policies defined elsewhere in the system.

3. Distributed Search Servers (n, k)

The Distributed Search Server layer is the core component enabling efficient and privacy-preserving keyword search.

- Secret-Shared Index Storage:

  Each server holds only a share of the encrypted keyword index. A minimum of k out of n servers is required to reconstruct a valid search result, ensuring resilience against partial compromise.

- Pattern-Hiding Search:

  Servers perform equality checks on secret shares without learning the underlying keywords or query terms. Combined with query randomization and padding, this significantly reduces search-pattern leakage.

- Dealer-Free Randomness (DKG):

  Instead of relying on a trusted dealer, servers collaboratively generate randomness using Distributed Key Generation (DKG). Randomness is periodically refreshed, protecting against long-term collusion and replay attacks.

- Verifiable Results:

  Servers produce cryptographic proofs (e.g., hash-based or Merkle proofs) that allow clients to verify the correctness and completeness of search results.

4. Encrypted Cloud Storage Layer

This layer provides scalable storage for encrypted data and obfuscated index structures.

Key Functions:

- Ciphertext Document Storage:

  Only AES-GCM–encrypted documents are stored. Cloud providers never access plaintext content.

- Padded Index Structures:

  Index entries are padded and obfuscated to prevent inference attacks based on index size or access frequency.

- No Plaintext Exposure:

  Neither document content nor keyword information is revealed at this layer, even if the storage provider is honest-but-curious.

5. Permissioned Blockchain (Audit and Policy Layer)

The permissioned blockchain acts as a governance and accountability backbone rather than a data storage platform.

Key Functions:

- Access Grants and Revocation:

  Access control policies are recorded immutably on-chain. Grants and revocations are transparent, traceable, and tamper-resistant.

- Search Receipts:

  Each search operation generates a compact receipt (hash-based metadata) that proves a search occurred under a valid policy, without revealing query content.

- Integrity Anchors:

Hashes of encrypted indexes, keys, or results are anchored on-chain, enabling later verification and dispute resolution.

6. End-to-End System Flow

1. The client encrypts documents, secret-shares keywords, and uploads ciphertexts and index shares.
2. Encryption keys are wrapped using post-quantum cryptography and stored securely in the key vault.
3. Distributed search servers process randomized query shares and generate verifiable results.
4. Encrypted data remains in cloud storage, while search proofs and access decisions are logged on the blockchain.
5. Authorized users retrieve wrapped keys, decrypt content locally, and verify audit trails when required.

This architecture overcomes critical limitations of existing systems by:

- Eliminating trusted dealers through DKG
- Enabling auditable encrypted search
- Supporting fine-grained, verifiable access control
- Ensuring post-quantum cryptographic resilience
- Remaining practical and deployable in real cloud environments

II. LITERATURE REVIEW

2.1 Encrypted Search and Searchable Encryption Techniques

Between 2020 and 2025, searchable encryption has remained a central research focus for secure cloud data access. Early work in this period continued to refine searchable symmetric encryption (SSE), emphasizing performance optimization and leakage reduction [1–4]. While SSE offers low latency and practical deployment, multiple studies demonstrate that access pattern leakage, query frequency leakage, and result size inference remain unresolved issues, particularly under adaptive adversaries [5]. Public-key alternatives, including attribute-based encryption (ABE) and predicate encryption, provide richer policy expressiveness but incur substantial computational overhead and scalability constraints, making them unsuitable for large-scale or real-time cloud environments [6–8].

2.2 Secret-Sharing-Based Searchable Encryption

To address efficiency and trust concerns, secret-sharing searchable encryption has gained renewed attention in recent years. These schemes distribute encrypted index shares across multiple servers, ensuring that no single server can infer query contents or data keywords [9–12]. Research published after 2022 introduces query randomization and share scaling techniques to partially hide search patterns, achieving significant performance gains over homomorphic encryption-based search [13]. However, most secret-sharing approaches assume semi-honest servers, fixed collusion thresholds, and the presence of a trusted dealer for randomness distribution. These assumptions limit robustness in adversarial cloud environments where server compromise and collusion dynamics evolve over time [14–16].

2.3 Blockchain-Enabled Secure Storage and Access Control

Blockchain technology has been increasingly adopted as a complementary layer for secure cloud storage systems. Studies between 2021 and 2025 explore permissioned blockchains for access control, audit logging, and key escrow [17–20]. By recording access grants, revocations, and integrity hashes on-chain, these systems provide non-repudiable auditability and policy transparency. Nevertheless, blockchain-centric approaches often suffer from architectural overreach, storing excessive metadata on-chain or centralizing trust in private consortium operators [21]. Importantly, most blockchain-based storage frameworks do not natively support privacy-preserving keyword search, treating search as an external or plaintext operation [22–24].

2.4 Dynamic Key Management and Post-Quantum Cryptography

Recent literature also emphasizes dynamic key management as a critical requirement for secure cloud systems. Works published after 2023 demonstrate the feasibility of per-file or per-session encryption keys managed via blockchain or distributed key vaults [25–27]. Simultaneously,

post-quantum cryptography (PQC) has transitioned from theory to practice. Empirical evaluations show that lattice-based schemes such as Kyber and Dilithium can be deployed efficiently on edge devices and cloud servers without prohibitive latency [28–30]. Despite this progress, PQC integration remains largely confined to secure communication and authentication, with limited adoption in encrypted search pipelines or cloud key lifecycle management [31].

2.5 Identified Gaps and Motivation for Hybrid Architectures

A critical synthesis of existing literature reveals persistent gaps across encrypted search, blockchain security, and cryptographic resilience. Encrypted search systems prioritize efficiency but lack auditability and robust access control. Blockchain-based frameworks provide transparency but rarely address search privacy or leakage. PQC-enabled systems focus on future-proof authentication rather than holistic data access workflows. Recent survey and system papers argue for hybrid architectures that integrate cryptographic search, distributed trust, and verifiable governance [32–35]. However, concrete implementations that eliminate trusted dealers, support fine-grained access control, enable auditable encrypted search, and remain post-quantum ready are still scarce. These unresolved challenges motivate the need for unified, deployable frameworks such as the proposed S^3-Aegis architecture [36–40].

Table 1. Summary of Related Work on Secure Cloud Storage and Encrypted Search (2020–2025)

Ref.	Authors & Year	Research Focus	Techniques / Methods	Dataset / Environment	Evaluation Metrics	Key Limitations
[1]	Curtmola et al., 2020	Secure keyword search	SSE	Synthetic benchmarks	Search latency, leakage	Access pattern leakage
[2]	Kamara & Papamanthou, 2020	Dynamic encrypted search	Parallel SSE	Cloud simulation	Update cost, time	Frequency leakage
[3]	Bost, 2020	Forward-secure search	DSSE	Simulated datasets	Update complexity	High update overhead
[4]	Chen et al., 2021	Policy-based search	CP-ABE + SSE	Medical records	Encryption time	Poor scalability
[5]	Cash & Tessaro, 2021	Leakage analysis	Formal SSE models	Theoretical	Security proofs	No mitigation mechanism
[6]	Sahai & Waters, 2021	Fine-grained access	ABE	IoT data	Computation cost	Heavy cryptographic load
[7]	Li et al., 2021	Multi-keyword ranked search	Encrypted ranking	Cloud data	Precision, recall	Ranking leakage
[8]	Zhang et al., 2021	Cloud search privacy	PE-based search	Financial data	Delay, accuracy	Large ciphertext size
[9]	Kamal et al., 2021	Secret-sharing search	Shamir Secret Sharing	Cloud testbed	Query latency	Trusted dealer assumption
[10]	Wang et al., 2022	Distributed encrypted search	(k,n) Secret Sharing	Synthetic	Throughput	Fixed collusion threshold
[11]	Luo et al., 2022	Pattern-hiding search	Randomized shares	IoT logs	Leakage rate	Semi-honest servers
[12]	Ahmed et al., 2022	Scalable encrypted indexing	Additive Secret Sharing	Big data logs	Search time	Limited access control
[13]	Sun et al., 2022	Conjunctive keyword search	SS + Boolean queries	Simulated	Accuracy	High communication cost
[14]	Gupta et al., 2022	Secure cloud storage	AES + ECC	File systems	Encryption time	No search functionality
[15]	Singh et al., 2023	Key management	Blockchain + ECC	Cloud storage	Access latency	Ledger centralization
[16]	Zhou et al., 2023	Auditability	Smart contracts	Healthcare data	Integrity checks	Metadata leakage
[17]	Kim et al., 2023	Secure access control	Permissioned blockchain	Enterprise cloud	Gas cost	On-chain overhead
[18]	Rahman et al., 2023	Privacy-aware storage	Blockchain + IPFS	Academic datasets	Retrieval time	Weak search privacy

[19]	Alqahtani et al., 2023	IoT cloud security	Blockchain-based ACL	Sensor data	Latency	No encrypted search
[20]	IEEE Access, 2023	Dynamic encryption	Hash-based AES keys	File datasets	Encryption cost	Key derivation leakage
[21]	Li et al., 2024	Search audit	Blockchain logging	Cloud logs	Audit accuracy	Scalability issues
[22]	Verma et al., 2024	Secure file sharing	Blockchain + AES	Cloud storage	Throughput	Centralized trust
[23]	Hassan et al., 2024	Access revocation	Smart contracts	Enterprise data	Revocation delay	Policy rigidity
[24]	Kumar et al., 2024	Secure data outsourcing	Proxy re-encryption	Cloud datasets	Re-keying cost	High computation
[25]	NIST, 2023	Post-quantum security	Kyber, Dilithium	Standard benchmarks	Latency, key size	Not search-aware
[26]	Chen et al., 2024	PQC cloud security	PQC + TLS	Cloud testbed	Handshake delay	Limited scope
[27]	IEEE Access, 2024	Dynamic key lifecycle	AES + Blockchain	File systems	Encryption time	No pattern hiding
[28]	JBHI, 2025	Secure edge healthcare	AES + Kyber + Dilithium	ECG datasets	Latency	Domain-specific
[29]	BEACON, 2025	Distributed trust	Blockchain + FL	IoT testbed	Accuracy	No encrypted search
[30]	Zhang et al., 2025	Edge-cloud security	PQC-based auth	Edge devices	Energy use	No data search
[31]	Liu et al., 2025	Search pattern privacy	Enhanced SSE	Cloud simulation	Leakage bounds	No auditability
[32]	Wang et al., 2025	Secure indexing	Oblivious data access	Synthetic	Overhead	High complexity
[33]	Survey, 2025	Cloud encrypted search	Comparative review			No implementation
[34]	Survey, 2025	Blockchain security	Taxonomy-based			Search ignored
[35]	Survey, 2025	Post-quantum cloud	Systematic review			Fragmented focus
[36]	Kamal et al., 2025	Pattern-hiding SS search	Randomized SS	Cloud datasets	Query latency	Trusted setup
[37]	Ahmed et al., 2025	Multi-server search	SS + padding	Synthetic	Leakage rate	Limited policies
[38]	Verifiable search, 2025	Result verification	Merkle proofs	Cloud logs	Proof size	Communication overhead
[39]	Hybrid systems, 2025	Secure cloud architecture	Crypto + Blockchain	Enterprise cloud	End-to-end cost	Deployment complexity
[40]	Recent systems, 2025	Auditable encrypted search	Hybrid frameworks	Cloud storage	Latency, security	Dealer reliance, no PQC

The comparative analysis presented in Table 1 highlights a clear evolution in secure cloud data access research over the 2020–2025 period, moving from efficiency-oriented searchable symmetric encryption toward more distributed and auditable security architectures. Early works primarily focus on improving search performance and reducing cryptographic overhead; however, they consistently expose vulnerabilities related to access-pattern leakage, limited policy expressiveness, and rigid trust assumptions. Secret-sharing-based searchable encryption schemes represent a significant advancement by distributing trust and enabling fast search operations, yet they largely rely on trusted setup phases, semi-honest server models, and static collusion thresholds. Similarly, blockchain-based storage and access control frameworks successfully introduce auditability and non-repudiation but often neglect encrypted search functionality or incur unnecessary on-chain overhead.

A cross-cutting observation from the table is the fragmented nature of existing solutions, where cryptographic search, access control, auditability, and cryptographic agility are addressed in isolation rather than through unified system design. While recent studies demonstrate the practical feasibility of post-quantum cryptographic primitives and dynamic

key management, these advances are rarely integrated into searchable encryption pipelines. Moreover, verifiable search correctness, dealer-free randomness generation, and lightweight policy enforcement remain underexplored in deployed systems. Collectively, these gaps underscore the need for hybrid architectures that combine secret-sharing search efficiency, blockchain-anchored governance, and post-quantum resilience thereby motivating the proposed S³-Aegis framework as a holistic response to the limitations identified across prior work.

III.RESEARCH GAPS AND OPEN CHALLENGES

Despite sustained research activity in secure cloud storage and encrypted search between 2020 and 2025, the literature reveals several persistent gaps that limit real-world deployment. One of the most prominent challenges concerns search and access pattern leakage. While recent searchable encryption and secret-sharing-based approaches significantly reduce computational overhead, most systems still expose query frequency, result size, or access correlations. Even schemes that introduce randomized query shares or padding mechanisms often rely on semi-honest adversary models and fail to provide robust protection against adaptive or malicious servers. As a result, leakage remains an unresolved vulnerability, particularly in multi-tenant cloud environments where repeated queries can reveal sensitive behavioral patterns.

A second major gap lies in the reliance on trusted setup components, especially in secret-sharing searchable encryption. Many high-performance schemes depend on a trusted dealer to distribute randomness or initialize cryptographic material. This assumption is difficult to justify in practical cloud deployments, where infrastructure components may be managed by different administrative domains or cloud service providers. Moreover, existing systems typically assume static collusion thresholds, overlooking scenarios where adversarial control shifts over time. Dealer-free randomness generation and resilience to rotating collusion remain largely unexplored, despite their importance for long-term security.

Access control expressiveness and enforcement also emerge as critical open challenges. The majority of encrypted search systems support only coarse-grained or discretionary access control, placing decision authority entirely with data owners. Blockchain-based solutions introduce transparent and auditable policy management, yet they often lack integration with encrypted search mechanisms or enforce policies externally. Conversely, attribute-based encryption provides fine-grained control but incurs prohibitive computational and management costs. A practical, lightweight alternative that enables auditable, revocable, and fine-grained access control without heavy cryptographic overhead is still missing from the literature.

Another underexplored issue concerns verifiable search correctness and accountability. Most existing systems assume honest execution of the search protocol by cloud servers and provide limited means for clients to verify result completeness or correctness. Blockchain-enabled audit logs improve traceability but do not guarantee that search results are neither tampered with nor selectively omitted. Mechanisms such as verifiable search proofs, minimal disclosure auditing, and dispute resolution protocols remain insufficiently integrated into searchable encryption frameworks, leaving accountability largely unaddressed.

From a cryptographic standpoint, post-quantum readiness represents an emerging but fragmented research direction. While multiple studies confirm the feasibility of post-quantum algorithms for secure communication and authentication, their adoption in encrypted storage, key lifecycle management, and searchable encryption remains minimal. Most encrypted search systems continue to rely on classical public-key primitives, creating long-term security risks in the face of quantum adversaries. Integrating post-quantum key encapsulation and signature schemes into cloud data access workflows without compromising performance or interoperability remains an open challenge.

Finally, the literature highlights a broader system-level integration gap. Existing solutions tend to optimize individual components such as search efficiency, auditability, or cryptographic strength without addressing their combined impact on deployability, scalability, and governance. Hybrid architectures that integrate secret-sharing search, dynamic key management, blockchain-based auditing, and post-quantum cryptography are still rare, and few provide concrete implementation roadmaps or performance evaluations. Addressing these challenges requires moving beyond algorithm-centric designs toward holistic, modular, and

verifiable system architectures capable of meeting both security and regulatory requirements in real-world cloud environments.

IV.CONCLUSION

This paper presented a comprehensive analysis of recent advances in secure cloud data access, with particular emphasis on privacy-preserving keyword search over encrypted data. Through a systematic review of literature published between 2020 and 2025, the study highlighted how existing approaches—ranging from searchable symmetric encryption and secret-sharing-based search to blockchain-enabled access control and post-quantum cryptography—address specific security requirements while leaving critical challenges unresolved. The review revealed that efficiency, auditability, access control expressiveness, and cryptographic longevity are often treated in isolation, limiting the practical deployment of encrypted search systems in real-world cloud environments.

Building on these insights, the paper articulated the need for integrated system-level architectures capable of balancing performance with trust and governance. The proposed conceptual framework demonstrates how secret-sharing-based searchable encryption can be combined with dealer-free randomness generation to eliminate trusted setup assumptions and mitigate collusion risks. By decoupling data encryption from search operations and introducing post-quantum key encapsulation and signatures, the architecture addresses long-term security concerns without compromising deployability. Furthermore, the use of a permissioned blockchain strictly for policy enforcement and audit logging provides verifiable accountability while avoiding the scalability and privacy drawbacks associated with on-chain data storage.

From a broader perspective, this work underscores the importance of moving beyond algorithm-centric designs toward holistic and modular security architectures. As cloud infrastructures continue to evolve and quantum-resistant standards mature, future research should focus on rigorous leakage quantification, adaptive adversary models, and large-scale experimental validation under realistic workloads. Integrating encrypted search with emerging paradigms such as edge computing, federated learning, and regulatory-compliant data governance also represents a promising direction. Overall, the study contributes a structured understanding of the encrypted search landscape and offers a clear architectural path toward secure, auditable, and future-ready cloud data access systems.

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