Golden Sun-Rise
International Journal of Multidisciplinary on Science and Management
ISSN: 3048-5037/ Volume 1 Issue 1 December 2024 / Page No: 35-44
Paper Id: IJMSM-V1I1P106 / Doi:10.71141/30485037/V1I1P106

Original Article

Privacy Preservation in the Cloud: A Comprehensive Review of Encryption and Anonymization Methods

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Received: 02 January 2024 Revised: 17 January 2024 Accepted: 29 January 2024 Published: 07 February 2024

Abstract - *Cloud computing offers scalable, pay-per-use services without requiring large infrastructure expenditures, it has completely changed how individuals and organizations access and manage massive computer resources. However, because cloud environments are open, shared, and dispersed, they present significant privacy and security concerns, including vulnerabilities in multi-tenant systems, data breaches, and unauthorized access. To safeguard sensitive data while maintaining its usefulness, this study examines privacy-preserving strategies, including homomorphic encryption, attribute-based encryption, and methods for data anonymization such as character masking, randomization, and k-anonymity. It also examines emerging solutions, such as searchable encryption and hybrid models that combine cryptographic and non-cryptographic approaches, to enhance data confidentiality and access control. The study highlights the limitations of current methods, such as computational overhead in encryption and re-identification risks in anonymization. It proposes future research directions, including AI-driven threat detection, quantum-resistant algorithms, and blockchain-based trust models. These advancements aim to address evolving security threats and ensure trustworthy, user-centric cloud computing ecosystems.*

Keywords - *Cloud Computing, Data Privacy, Data Security, Homomorphic Encryption, Attribute-Based Encryption, Data Anonymization, Character Masking, Access Control, Searchable Encryption, Privacy-Preserving Techniques, Blockchain, Quantum Computing.*

I. INTRODUCTION

Cloud computing has revolutionized how people and businesses access and utilize powerful computer resources. It enables the on-demand provisioning of computational power, storage, and networking capabilities, offering significant flexibility and cost efficiency through a pay-per-use model [1]. Users can leverage these resources without investing in dedicated infrastructure, accessing them virtually as though they reside on local machines. This paradigm is supported by virtualization, where software-defined virtual machines (VMs) host operating systems and applications, mimicking physical machines while being entirely abstract. Despite its numerous advantages, Cloud computing poses significant privacy and data security issues. Cloud environments host vast quantities of user data, ranging from personal information to sensitive enterprise content. If improperly secured, such data is vulnerable to breaches, unauthorized access, and malicious exploitation. One fundamental risk lies in this method, which works especially well for public cloud installations, as it processes data without disclosing personally identifiable information.

To mitigate such threats, various privacy-preserving mechanisms have been proposed. Chief among these are cryptographic techniques, such as encryption, which encode data to prevent unauthorized access [2]. While encryption is effective, it introduces considerable computational overhead and complex key management requirements, and may hinder functionalities such as querying and computation over encrypted data. Therefore, while widely used, encryption alone may not suffice for all cloud service scenarios. An alternative or complementary strategy is anonymization, which alters data while maintaining its analytical value to prevent the identification of specific people or sensitive characteristics. In public cloud installations, this method works especially well, as it enables data processing without disclosing personally identifiable information. For example, anonymized datasets can be hosted and analyzed in the cloud, with the original identities securely mapped only in trusted local environments [3]. Recent studies have also explored non-cryptographic methods such as data splitting and distribution across multiple servers, which reduce dependency on encryption while still providing a high level of data protection. These approaches aim to preserve the cost-saving and performance benefits of cloud computing without sacrificing data privacy.

Although various techniques for preserving privacy in the cloud have been introduced, ranging from encryption and access control to anonymization and data masking, a comprehensive survey that encompasses both cryptographic and non-cryptographic solutions is lacking [4]. The purpose of this study is to address this gap by conducting a comprehensive examination of the most recent privacy-preserving techniques specifically designed for cloud environments. It analyzes the effectiveness, limitations, and practical implications of existing solutions. It provides guidelines for Modern cloud computing infrastructures that have changing requirements, therefore improving privacy methods to meet those needs.

A. Structure of the Paper

This paper is organized as follows: Section II provides an overview of privacy preservation techniques. Section III addresses the risks to cloud security and privacy. Information stored in storage. The literature and case studies are reviewed in Section IV. Included are findings and suggestions for more research in Section V, Conclusions.

II. PRIVACY PRESERVATION TECHNIQUES OVERVIEW

Privacy Preservation Techniques in Cloud Computing involve safeguarding sensitive data using methods like encryption and anonymization. Encryption ensures data confidentiality by converting data into unreadable formats, while anonymization removes personally identifiable information (PII) to protect user identity. Advanced techniques include homomorphic encryption for computing on encrypted data and differential privacy for statistical analysis with added noise. Hybrid models often combine both approaches for stronger protection. These methods help balance security, usability, and performance in cloud environments.

A. Data Anonymization Methods

Data anonymization permanently obscures data while protecting privacy. Techniques for anonymization have been developed in the fields of privacy preservation and statistical disclosure control. Data publishing is the process of providing sensitive information to an unaffiliated third party, ensuring it remains analytically valuable for future applications without disclosing information that could be used to identify specific individuals [4][5]. An approach that shows promise for protecting privacy is data anonymization. To ensure data anonymity and preserve data privacy, the anonymization procedure is applied to the data before transferring it to a third party, such as a medical researcher, as illustrated in Figure 1.

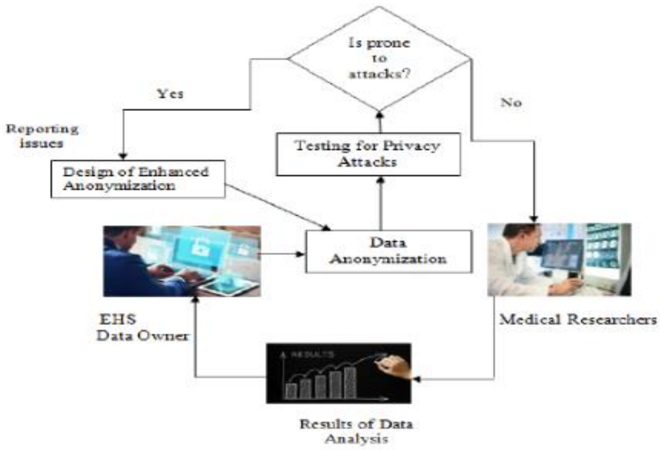

Figure 1. Data Anonymization Process Basic Architecture

a) k-Anonymity

k-Anonymity could serve as a formal protection paradigm. If an attempt is made to detect the data using a region unit, the goal is to make each record in an illustrated variety (k) records ambiguous. An arrangement of data is k-anonymised if there are always k-1 elective records that fit a given set of attributes for any record having that arrangement. They can be any of the following types of qualities. Example: If a dataset contains a person's age, gender, and zip code, the dataset would be anonymized by ensuring that for each combination of these attributes, there are at least k individuals with the same values. Use Cases: k-Anonymity is widely used in datasets with multiple quasi-identifiers(attributes that can indirectly identify an individual, like age, gender, or zip code)and is especially relevant in healthcare and census data [6].

b) Randomization Technique:

A probability distribution is typically used to add noise to the data, a technique known as Randomization. Randomization is used in sentiment analysis, surveys, and more. It is not necessary to be aware of other records in the data to use randomization. It is applicable during the pre-processing and data gathering phases. Randomization eliminates the need to optimize for anonymization. Unfortunately, as our experiment outlined below demonstrates, randomization cannot be applied to large datasets due to time complexity and data utility.

Executed a MapReduce Job on 10,000 entries supplied into the Hadoop Distributed File System from an employee database [7]. Conducted experiments to categorise the staff according to their age and wage levels. To implement randomization, they randomly added 5,000 records to our database, increasing the total to 20,000 records. After executing the MapReduce operation, they made the following observations.

- As the amount of data increased, a greater number of mappers and reducers were utilized.
- The results were noticeably different both before and after the randomization process.
- Despite randomization, certain outlier records are still susceptible to attacks from adversaries.
- Especially when it comes to attribute disclosure, randomization might not be the best choice for privacy preservation because people do not value data utility more highly than privacy [8].

c) Character Masking

The process of changing a data value's characters by adding a constant symbol, such "*" or "x," is called character masking. Certain elements in the attribute are concealed, while others are left open. Character masking can be either constant or changeable, depending on the kind of property. Swap out the relevant characters with a predetermined symbol when concealing a portion of the data value. This is a string of characters, and it is adequate to achieve the necessary degree of anonymity when part of the data value is hidden. The results of character masking in column F of the sample dataset are displayed in Table I [9]

Table 1. Character Masking on Attribute Postal Code (F)

Postal code
600***
621***
627***
651***

B. Common Encryption Algorithms Used in Cloud Storage

If symmetric encryption is used, both the sender and the recipient may encrypt and decrypt communications using the same key. Cloud computing uses symmetric algorithms, such as the Advanced Encryption Standard (AES) and the Data Encryption Standard (DES). Asymmetric encryption uses separate but related public and private keys. The encryption process uses the public key, while the decryption process uses the private key. With a private key, only the verified receiver can decipher the message. In cloud computing, asymmetric algorithms such as the Homomorphic encryption algorithm or the Classification Attribute-Based Encryption model are used. Hybrid encryption, on the other hand, combines symmetric and asymmetric encryption for maximum security [10].

a) Homomorphic Encryption

Only the client has access to the secret key, which is utilized by Homomorphic Encryption systems to execute actions on encrypted data without decryption. Decrypting an operation's output is identical to performing the same computation on the raw data. The goal of homomorphic encryption is to encrypt a collection of ciphertexts in such a way that the decrypted result is identical to the result of an operation on the plaintexts [11].

C. *Types Of Homomorphic Encryption(HE)*

A homomorphism is a mapping from one set to another that keeps the relationships between members of the original set in the new set. Homomorphic encryption refers to an operation on a set of ciphertexts that produces decryption results that are identical to those of an operation on the plaintexts. Three distinct types of HE schemes may be neatly classified according to the maximum number of operations that are permissible on the encrypted data:

- **Partially Homomorphic Encryption (PHE):** In PHE, there is a single operation type that may be executed an infinite number of times.
- **Somewhat Homomorphic Encryption (SWHE):** This permits a limited number of times for certain types of operations. Schemes for SWHE enable students to multiply and add. However, before the first FHE scheme, SWHE methods were developed; however, the ciphertext sizes increase with each homomorphic operation, resulting in a limitation on the maximum number of permissible operations.
- **Fully Homomorphic Encryption (FHE):** FHE allows for the execution of an unlimited number of operations an infinite number of times. In 2009, Craig Gentry created the first practical and workable Fully Homomorphic Encryption (FHE) method. This method is capable of computing any function on encrypted data by evaluating an infinite number of additions and multiplications. In addition to describing the technique, it provides a robust foundation for obtaining FHE and is based on mathematical ideal lattices [12].

a) *Classification of Attribute-Based Encryption Model*

Attribute-based encryption is a type of public key encryption referred to as one-to-many public key encryption. Decryption of the ciphertext is restricted to users whose characteristics match the encryptor's specified access policy. An idea with roots in identity-based encryption. Encryption is the process of changing data from its original format into an incomprehensible code. The process of returning encrypted data to its original format is known as decryption. Only after the data has been encrypted can the authorized party decode it. Consequently, encryption makes sure that the information is safe and private. There is a plethora of encryption methods out there, each with its own set of benefits. An established method for cloud computing is attribute-based encryption. Some attribute-based encryption methods have drawbacks that require examination. Most of the time, only the characteristics are encrypted, rather than the entire dataset, using attribute-based encryption. Cryptography in ABE is simple, secure, and cost-effective compared to other methods. Because the qualities, rather than the data itself, are included in the encrypted data, the ABE is secure. No data is ever compromised in the event of an attack. Attribute-based encryption has the disadvantage of being expensive to decrypt data. The program is made secure by using attribute-based encryption. The ABE outperforms competing encryption algorithms in terms of performance. Therefore, going forward, all cloud apps will use attribute-based encryption. Critical and real-time applications are being relocated to the cloud for use in next-generation computing. Figure 2 illustrates the various forms of ABE and their corresponding classifications [13].

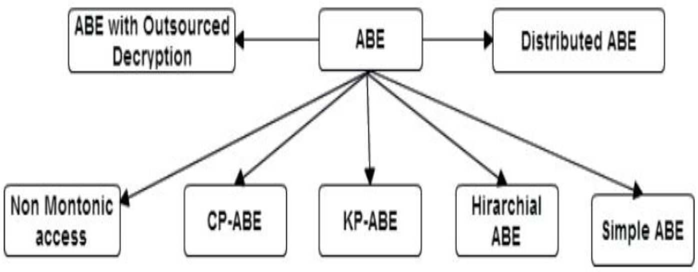

Figure 2. Classification of Attribute-Based Encryption

D. *Importance of Data Privacy and Security in the Cloud*

Data security is a problem that affects all technology. Nevertheless, when used in an unregulated setting such as cloud computing, it presents a major challenge. There are security concerns associated with any IT system, but cloud computing introduces additional ones that must be considered separately. Generally, these dangers are prevalent in shared, dispersed, and open settings. Isolating pre-existing issues from those introduced by Cloud Computing is crucial for effective risk analysis. This paper addresses only problems associated with data and the Cloud.

Data stored on the service provider's infrastructure is more susceptible to security breaches than data saved on conventional infrastructure for three primary reasons: (1) data is accessible over the internet; (2) data from multiple users shares the same physical infrastructure; and (3) data is transferred to the cloud from other locations [14].

E. Data Confidentiality

Ensuring data congruence is crucial for clients who wish to store sensitive or confidential data in the cloud. Making the cloud more dependable and trustworthy is one method to address issues with access control and authentication in cloud computing that impact data integrity:

- **Homomorphic Encryption:** Encryption is frequently used to guarantee data secrecy. One type of suggested encryption scheme is homomorphic encryption. Furthermore, the entire process does not have to decrypt the data, guaranteeing consistency between the encryption results of the clear operation and the outputs of the algebraic operation on the ciphertext. The incompatibility between data and data activities in the cloud can be resolved using this method.
- **Encrypted Search and Database:** The use of restricted homomorphic encryption algorithms in cloud systems is being examined by researchers, as homomorphic encryption is considered to be hazardous. Encrypted search, a popular privacy-preserving multi-keyword ranked search method, was introduced to search encrypted cloud data and rate the search results without endangering user privacy.
- **Hybrid Technique:** A hybrid approach that combines key sharing and authentication methods is recommended for data confidentiality and integrity. The use of robust authentication and key-sharing methods can enhance the security of user-cloud service provider interactions. Cloud service providers and consumers can safely distribute keys by using the RSA public key algorithm [15].

III. SECURITY AND PRIVACY THREATS IN CLOUD DATA STORAGE

- **Access control in cloud computing:** Access control is a crucial technique to ensure that only authorized users can access specific data and resources in the cloud. It enforces security policies by verifying identities and assigning permissions based on roles, attributes, or policies. Effective access control prevents unauthorized access, protects sensitive information, and supports data privacy, integrity, and regulatory compliance in multi-user cloud environments.
- **ABE in cloud computing:** One encryption method that works well with cloud computing is ABE, which may also provide privacy protection when exchanging data. Numerous ABEs have been proposed by academics for various participating companies in cloud computing systems to secure users' privacy-sensitive data. ABE enables the encryption of cloud storage data and provides fine-grained access control. Attribute encryption is extremely relevant to secure cloud-based data sharing systems due to its four fundamental characteristics: fine-grained access control, scalability, flexibility in defining access policies, and resistance to collusion attacks.
- **Searchable encryption:** A cloud service's data frequently takes the form of ciphertext. A crucial question is how to protect a cloud service's privacy and security without compromising its functionality. Searchable encryption (SE) technology is a highly suitable approach for protecting cloud private data as a crucial network security technique, as it enables keyword-based retrieval of ciphertexts. A balance between usability and security in cloud environments can be achieved through searchable encryption, which combines symmetric and asymmetric encryption with secure indexing strategies, access control policies, and cryptographic protocols to enhance data confidentiality and facilitate efficient query operations.
- **Combination technologies in cloud privacy:** investigated and assessed the research on search encryption, attribute encryption, and access restriction as methods of protecting cloud computing privacy. Because cloud computing is a dynamic and complex environment with high information aggregation and research advancements, better privacy security protection is obtained by integrating numerous related technologies, including access control, trust, and ABE [16].

A. Data Breaches

Multi-tenant virtualized environments contain a significant amount of potentially sensitive data and are therefore of considerable interest to hackers. Any vulnerability in a single virtual machine may cause vulnerability in other, separate virtual machines on the same host and lead to disclosure of sensitive data to a third party:

a) Unauthorized Access

Data is stored securely because access control ensures that only authorized people have access. It consists of authentication, authorisation, and accounting. To define roles and rules effectively and provide sophisticated access control systems, several research initiatives have been undertaken. The Role-Based Multi-Tenancy Access Control (RBMTAC) paradigm, for instance, is designed to effectively control a user's access authorization, offering data separation and independent applications. The user's identity and relevant duties are ascertained through identity management [17]. The authors allowed the data owner to select unreliable cloud servers to do the majority of the compute activities required for fine-grained data access control without revealing the underlying data's contents. Also, they use data attributes to create and implement access rules. There are other recommendations for physical methods to ensure access control to the virtual machines or hypervisors. For example, the administrator needs a hardware token to launch the hypervisor.

b) Scalable Service

To their knowledge, very few of the research articles that are currently available take into account the privacy-preservation issues that arise when services are recommended in a dispersed cloud context. This article explains the research relevance of the privacy-preserving service recommendation problem and formalises it [18].

c) Ethical Concerns in Cloud Computing

To mitigate the ethical dilemma in the system, ethics is employed. This may be achieved by cloud rule makers and client-side T&C agreement negotiators taking into account as many scenarios as possible and providing explicit advice to indicate which ones exist. The cloud provider will likely notify you if someone attempts to access your data, regardless of whether they are successful, according to the agreed-upon level of protection, for instance. If someone else has already viewed a portion of your data, the provider may alert you to the possibility of data theft even though there may not be concrete proof that the data has been accessed. It remains admirable to educate clients about ethics, even if the contract does not expressly address this. [19].

d) Challenges of Encryption in Cloud Computing

A variety of encryption methods and approaches are employed to enhance cloud computing security, providing users with the assurance to store their data securely in the cloud. In the present study, they reviewed several data encryption techniques. Bi-directional DNA encryption was described by Amit et al. as a method to enhance the security of cloud computing. Nevertheless, no algorithm now in use concentrates on cloud computing users who do not speak English, in addition to those who utilise the ASCII character set. However, the security of cloud computing may be improved by using this method with Unicode letters. This study explained the various stages of transforming data into a different format to encrypt it with greater complexity [20].

e) Anonymization Approach for Privacy Preserving in Cloud Computing

Suggested a novel method for ensuring the anonymity of cloud computing services. The data is anonymised using this algorithm before being sent to service providers. According to the authors, this approach to user privacy protection is safer and more adaptable than cryptography methods. However, each cloud service provider uses a different anonymisation technique. Therefore, in cloud computing systems that are networked, the clouds may work together to quickly re-identify the original data. Moreover, the writers do not assess or validate the effectiveness of their approach.

IV. LITERATURE REVIEW

This section presents earlier studies on Techniques for anonymisation and encryption to protect privacy in cloud computing settings. Table II provides a structured comparison of previous research, focusing on symmetric and asymmetric encryption, homomorphic encryption, and anonymization methods such differential privacy and k-anonymity, as well as how they apply and the security issues they present in cloud-based systems. Rao, Xie and Zhao (2020) proposed a cloud-based data sharing system that protects privacy for numerous groups. By utilizing group signatures, broadcast encryption, and encryption based on ciphertext-policy attributes, this approach creates a versatile access control framework that facilitates anonymous data exchange within and across groups. Additionally, our method facilitates effective user revocation. Extensive studies and trials demonstrate the scheme's security and effectiveness [21].

Wu et al. (2020) suggested a private random decision tree-based architecture for data mining in ECC that protects privacy. The architecture offers an effective data utility in addition to a robust privacy guarantee. First, for private random DT in ECC, offer a paradigm based on differential privacy. Explain the particular algorithms and the related work that each participant needs to finish after that. Subsequently, examine the primary determinants of privacy and utility, and execute additional improvements to boost utility [22]. Kumar and Bhatia (2020) note that the main issue that worsens as the number of users increases is protecting privacy. This paper thoroughly examines the existing methods for cloud storage security in the context of cloud computing. This article provides an overview of cloud computing and its associated security issues. The necessary security requirements, such as data integrity, availability, and confidentiality. Security vulnerabilities in recent cloud security techniques are evaluated. The method's possible future use is evaluated, along with the challenges associated with cloud security [23].

Shekhawat, Sharma, and Koli (2019) explain three methods attribute-based encryption, homomorphic encryption, and order-preserving encryption to ensure data integrity and confidentiality. These methods protect data privacy while preserving the effectiveness and scalability of large datasets for decision-making, and they are most effective when utilized on the cloud [24]. Madan and Goswami (2018) developed the k-anonymization model to protect cloud privacy. The suggested strategy is powered by Dragon Particle Swarm Optimization (Dragon-PSO), a recently created optimization model that blends the Particle Swarm Optimization (PSO) algorithm with the Dragonfly Algorithm (DA). By calculating the fitness function for the proposed Dragon-PSO algorithm, the proposed plan achieves high values for both privacy and utility. Information Loss and Classification Accuracy are the two criteria used to assess the suggested system [25].

Hiremath and Kunte (2017) The objective is to provide a Party Auditor (TPA)-based effective public auditing method for confirming the accuracy of cloud data. AES is used for encryption in the suggested auditing approach, and Data integrity checks employ the Secure Hash Algorithm (SHA-2) to give message digests or verification information. The research demonstrates that the suggested plan is demonstrably safe and that TPA audits files of varying sizes in a consistent amount of time [26].

Table 2. Comparative Analysis of Privacy Preservation in the Cloud

Reference	Focus Area	Key Findings	Challenges	Key Contribution
Rao, Xie and Zhao (2020)	Multi-group data sharing with privacy	Supports intra/cross-group anonymous access using group signature, CP-ABE, and broadcast encryption	Efficient user revocation; complex access policies	Flexible access control with anonymity and revocation in cloud
Wu et al. (2020)	Privacy-preserving data mining	In ECC, it suggests DP-based private random decision trees that strike a compromise between privacy and usefulness	Utility vs. privacy trade-off; performance overhead	Framework for secure data mining with differential privacy
Kumar and Bhatia (2020)	Review of cloud storage security	Reviews key security requirements (integrity, availability, confidentiality); surveys recent cloud methods	Evolving threat landscape and compliance challenges	Highlights trends, methodologies, and open research directions
Shekhawat, Sharma and Koli (2019)	Encryption techniques for privacy	Describes homomorphic, order-preserving, and ABE schemes for cloud and big data	Scalability with big data; computation cost	Efficient encryption-based methods for secure, scalable cloud storage
Madan and Goswami (2018)	k-Anonymity via optimization	Uses Dragon-PSO to enhance privacy with low information loss and good accuracy	Optimization model complexity; balancing utility	Optimization-based anonymization with strong privacy-utility balance
Hiremath and Kunte (2017)	Public auditing in cloud storage	AES and SHA-2-based scheme with constant-time TPA auditing	Secure audit without exposing data; trusted TPA	Lightweight auditing using cryptography with integrity guarantee

V. CONCLUSION AND FUTURE WORK

Cloud computing offers scalable, cost-effective access to vast computing resources, allowing individuals and businesses to utilize services like processing, data storage, and application hosting without having to make large infrastructure investments. However, preserving data security and privacy in cloud settings is a constant battle due to problems such as data breaches, unauthorized access, and vulnerabilities in multi-tenant systems. Methods such as data anonymisation, attribute-based encryption, and homomorphic encryption offer reliable ways to safeguard private data without sacrificing usability. Despite their strengths, cryptographic methods often introduce computational overhead, whereas non-cryptographic approaches, such as anonymization, may face limitations in interconnected cloud systems. Ongoing research and hybrid techniques that combine encryption, access control, and anonymization are required to manage evolving privacy and security threats and ensure the dependability and legitimacy of cloud computing for a variety of applications.

Future advancements in cloud computing are expected to be significant due to new technologies and evolving user demands, particularly in the areas of privacy and security. Research will likely focus on developing more effective cryptographic methods, including fully homomorphic encryption (FHE), to overcome current performance and cost constraints and enable computation on encrypted data with minimal computational overhead. Non-cryptographic methods, such as advanced data anonymization and differential privacy, are expected to evolve to better balance data utility and privacy, particularly in interconnected cloud environments where re-identification risks persist. The integration of AI and ML will enhance real-time threat detection, access control, and automated enforcement of privacy policies, thereby improving security in multi-tenant systems.

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