International Journal of Emerging Trends in Engineering and Management Research (IJETEMR)

|ISSN: 2455-7773 | www.ijetemr.com| A Double-Blind Peer-Reviewed and Bimonthly Scholarly Journal|

|Volume 9, Issue 5, September-October 2024|

DOI:10.15662/ijetemr.2024.0905006

Zero-Trust Access Control and AI-Based Security Policy Management Across Hybrid Cloud Enterprise Systems

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ABSTRACT: The rapid adoption of hybrid cloud computing has transformed enterprise infrastructure by integrating private data centers, public cloud platforms, and distributed digital services. However, this transformation introduces complex security challenges involving identity management, unauthorized access, inconsistent policy enforcement, and evolving cyber threats. Traditional perimeter-based security mechanisms are insufficient for protecting dynamic enterprise environments in which users, applications, devices, and workloads continuously interact across multiple infrastructure boundaries. This research proposes an integrated framework combining Zero-Trust Access Control (ZTAC) with Artificial Intelligence (AI)-based security policy management to strengthen enterprise security across hybrid cloud systems. The proposed framework incorporates continuous identity verification, contextual access evaluation, behavioral anomaly detection, risk-based authorization, and automated policy adaptation. Machine learning models analyze user behavior, device posture, network activity, and resource sensitivity to identify potential threats and support dynamic access decisions. A centralized policy orchestration component coordinates security rules across heterogeneous cloud platforms while maintaining consistent enforcement and auditability. The research methodology adopts a comparative evaluation approach using security, operational, and performance indicators, including unauthorized access detection, false-positive rate, policy enforcement latency, and resource utilization. The framework is intended to improve threat detection, reduce excessive privileges, and support scalable security governance. Its effectiveness must be established through reproducible experiments and comparison with conventional access control mechanisms. The study contributes a structured approach to integrating adaptive intelligence with Zero-Trust principles for resilient, transparent, and continuously monitored hybrid cloud enterprise security.

KEYWORDS: Zero Trust Security, Hybrid Cloud Computing, Artificial Intelligence, Access Control, Security Policy Management, Machine Learning, Identity Governance

I. INTRODUCTION

The increasing adoption of hybrid cloud computing has reshaped enterprise information technology by enabling organizations to distribute applications, data, and computational workloads across private infrastructure and public cloud environments. This architecture offers scalability, flexibility, improved resource utilization, and business continuity, but it also introduces security challenges arising from distributed identities, heterogeneous access mechanisms, inconsistent configurations, and interconnected services. Enterprises must protect sensitive information while supporting employees, administrators, external partners, automated applications, and machine identities operating across multiple infrastructure domains. Conventional perimeter-based security models generally assume that entities inside a trusted network can receive broader access than external entities. Such assumptions are increasingly unreliable because compromised credentials, malicious insiders, vulnerable endpoints, and unauthorized service interactions can originate within apparently legitimate environments. Consequently, modern enterprise security requires a model that evaluates every access request according to identity, context, resource sensitivity, and current risk rather than relying exclusively on network location. Zero-Trust Access Control addresses this requirement through explicit verification, least-privilege authorization, continuous monitoring, and the principle that no user, device, or workload should receive implicit trust solely because of its network position. Implementing these principles consistently across hybrid cloud infrastructure remains difficult because platforms may use different identity providers, policy languages, logging mechanisms, and enforcement technologies. These differences can create policy conflicts, visibility gaps, and opportunities for unauthorized access. An effective security architecture must therefore coordinate identity governance, access decisions, and policy enforcement across the entire enterprise environment while preserving operational efficiency and regulatory accountability.

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Artificial Intelligence offers opportunities to strengthen Zero-Trust security by analyzing large volumes of identity, application, endpoint, and network telemetry to identify abnormal behavior and support risk-sensitive authorization. Machine learning techniques can establish behavioral baselines, detect deviations from established access patterns, prioritize suspicious events, and estimate the risk associated with individual access requests. For example, an access request originating from an unfamiliar device, involving an unusually sensitive resource, and displaying abnormal behavioral characteristics may require additional authentication or restricted permissions. AI-based policy management can use these signals to recommend or initiate policy adjustments, helping security teams respond more rapidly to emerging threats. Nevertheless, automated decisions introduce challenges involving model accuracy, false positives, explainability, data privacy, and the possibility that attackers manipulate the signals used by security models. Poorly governed automation may also interrupt legitimate business operations or propagate incorrect policies across multiple cloud environments. This research therefore proposes an integrated framework that combines Zero-Trust access principles with AI-assisted security policy management for hybrid cloud enterprise systems. The framework emphasizes continuous identity and device assessment, contextual risk scoring, adaptive authorization, centralized policy orchestration, and auditable enforcement. Its primary objective is to establish a consistent and responsive security mechanism capable of reducing unauthorized access while maintaining acceptable operational performance. The study also examines how adaptive security decisions can be evaluated using measurable indicators, including detection performance, false-positive rates, policy enforcement latency, and administrative overhead. By connecting intelligent threat analysis with structured policy governance, the proposed approach seeks to provide a practical foundation for secure and scalable enterprise cloud operations.

II. LITERATURE REVIEW

Zero-Trust security has emerged as an important architectural approach for protecting distributed enterprise systems in which network boundaries no longer provide sufficient assurance of trust. The foundational principles of Zero Trust emphasize explicit authentication and authorization, least-privilege access, and continuous evaluation of security conditions. NIST Special Publication 800-207 provides a widely recognized architectural foundation for implementing Zero Trust through policy decision points, policy enforcement points, and supporting identity and contextual information sources. These components enable organizations to evaluate access requests according to defined policies rather than granting unrestricted access based on network location. Identity and Access Management systems, multifactor authentication, privileged access management, and device posture assessment further support these principles. However, implementing Zero Trust across hybrid cloud environments remains challenging because organizations often operate multiple identity providers, legacy applications, independent administrative domains, and cloud-specific authorization mechanisms. Differences in policy representation and enforcement capabilities can create inconsistent access decisions and complicate governance. Static role-based access control remains useful for defining organizational permissions, while attribute-based access control enables decisions based on user attributes, resource characteristics, environmental conditions, and contextual requirements. Nevertheless, both approaches may require continuous contextual intelligence to respond effectively to rapidly changing risk conditions. Existing architectural guidance establishes essential principles, but enterprise implementations must address interoperability, policy consistency, operational complexity, and continuous evaluation across heterogeneous infrastructure.

Artificial Intelligence and machine learning have increasingly been investigated for cybersecurity applications, including intrusion detection, behavioral analytics, identity threat detection, and automated incident prioritization. Supervised learning models can classify known malicious activities using labeled observations, while unsupervised and semi-supervised techniques can identify deviations from normal behavior when reliable labels are limited. Behavioral analytics can examine authentication frequency, access locations, device characteristics, resource usage, and application interactions to identify suspicious patterns. These capabilities are particularly relevant to hybrid cloud environments, where security telemetry originates from multiple platforms and services. AI-supported risk assessment can supplement traditional access control by incorporating behavioral evidence into authorization decisions. For example, a model may identify an unusual sequence of privileged operations and recommend additional verification, temporary access restrictions, or security investigation. However, the reliability of these approaches depends on data quality, representative training examples, appropriate feature selection, and continuous model evaluation. Concept drift can reduce detection performance when legitimate user behavior changes, while class imbalance may cause rare but serious attacks to be overlooked. False-positive alerts can overwhelm security teams and interrupt legitimate workflows. Furthermore, opaque model predictions may make it difficult for administrators to explain why an access request was denied or restricted. Consequently, effective AI-based security management requires interpretable risk

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indicators, documented decision rules, controlled model updates, and human oversight for consequential policy changes.

Research on cloud security orchestration, policy automation, and adaptive access management highlights the importance of integrating security intelligence with operational enforcement mechanisms. Policy-as-code approaches can represent security requirements in version-controlled, testable configurations, supporting repeatable deployment and consistent governance across cloud resources. Security information and event management platforms and cloud-native monitoring services can aggregate telemetry, correlate events, and support coordinated incident response. Policy orchestration can translate risk assessments into actions such as requiring stronger authentication, reducing privileges, isolating compromised workloads, or initiating additional monitoring. However, automated policy propagation across hybrid cloud environments can introduce configuration conflicts, enforcement delays, and unintended service disruptions. Data privacy also becomes important when behavioral information is collected across multiple organizational or geographical boundaries. Existing approaches may address Zero Trust architecture, machine learning-based anomaly detection, and policy automation separately, but their combined operation requires careful coordination among decision models, enforcement points, identity systems, and governance controls. Another challenge is establishing a consistent evaluation methodology that considers security effectiveness alongside operational cost and user experience. This research addresses these concerns by proposing a unified framework for AI-assisted Zero-Trust policy management, with explicit decision stages, controlled automation, explainable risk assessment, and measurable evaluation criteria. The framework is intended to bridge the gap between contextual threat intelligence and enforceable enterprise security policies while recognizing that its effectiveness must be demonstrated experimentally rather than assumed from architectural design alone.

III. RESEARCH METHODOLOGY

The research methodology adopts a design-oriented and experimental approach to develop and evaluate a Zero-Trust access control framework supported by AI-based security policy management across hybrid cloud enterprise systems. The proposed architecture consists of six coordinated components: identity and device verification, contextual telemetry collection, AI-based risk assessment, policy decision and orchestration, distributed policy enforcement, and security auditing. The identity verification component obtains authentication status, role assignments, device posture, and relevant access attributes from enterprise identity services. The telemetry collection component gathers authorized security events from private infrastructure, public cloud platforms, application interfaces, endpoint protection systems, and network monitoring tools. The risk assessment component analyzes these observations to identify unusual behavior and estimate the risk associated with requested operations. The policy decision component combines model outputs with explicit organizational rules, resource sensitivity, least-privilege requirements, and applicable access constraints. The orchestration component distributes approved policy changes to the relevant enforcement points, while the auditing component records decisions, policy versions, model outputs, and enforcement outcomes. The architecture separates risk prediction from final authorization so that an AI model cannot independently override mandatory security requirements. Initial implementation may use a controlled laboratory environment comprising a private-cloud or simulated private infrastructure, a public cloud test environment, representative enterprise applications, centralized identity services, and policy enforcement gateways. Synthetic or appropriately anonymized telemetry can be used when real enterprise security logs are unavailable. All experimental activities should operate within authorized environments, with predefined access boundaries and rollback mechanisms to prevent unintended service disruption.

The second methodological stage focuses on dataset preparation, feature engineering, and model development. Security observations should represent both ordinary enterprise activity and a range of suspicious behaviors, including abnormal authentication patterns, unexpected privilege escalation attempts, unusual access times, unfamiliar device characteristics, and deviations from established resource usage. Available datasets may include publicly accessible cybersecurity records, controlled test events, and synthetic access logs generated to represent hybrid cloud workflows. Dataset provenance, collection conditions, labeling procedures, and known limitations must be documented to support reproducibility. Before model training, duplicate records should be removed, missing values handled using appropriate procedures, timestamps normalized, and categorical variables encoded. Features may include authentication failures, access frequency, session duration, device compliance status, resource sensitivity, privilege level, geographic inconsistency where lawfully available, and deviation from historical behavior. Sensitive identifiers should be pseudonymized or excluded when unnecessary, and training data should be separated from evaluation data to reduce information leakage. Candidate models may include logistic regression as an interpretable baseline, random forests for nonlinear classification, and gradient-boosted decision trees for structured telemetry. An unsupervised anomaly

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detection method may supplement supervised classification when labeled attack examples are limited. Model selection should be based on validation performance, inference requirements, interpretability, and operational feasibility rather than model complexity alone. Training, validation, and testing should use time-aware or entity-aware splits where appropriate so that repeated sessions from the same users do not create misleadingly optimistic results. Hyperparameters should be selected using validation data, with the final test set reserved for independent evaluation. Probability calibration should also be assessed if model scores are interpreted as risk estimates. These procedures provide the foundation for determining whether AI-generated risk information can reliably support context-sensitive access decisions.

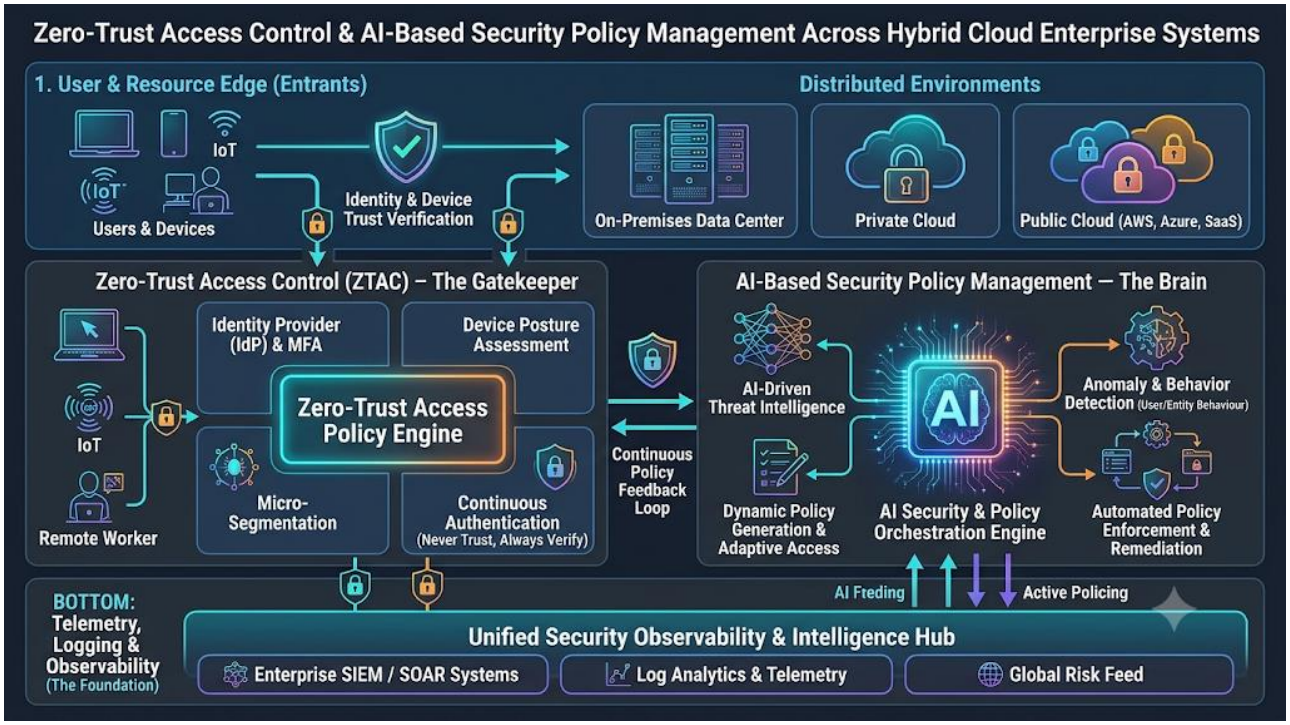


Figure 1: Architecture for Zero-Trust Access Control (ZTAC) and AI-Driven Security Policy Management Across Hybrid Cloud Enterprise Systems.

The third stage develops the adaptive authorization and security policy management mechanism. Each access request is evaluated through a structured decision sequence that verifies identity, checks device and session conditions, identifies the requested resource, retrieves applicable organizational policies, and calculates a contextual risk score. The score may combine model-derived anomaly estimates with explicit indicators such as privilege sensitivity, authentication strength, device compliance, and resource criticality. The combination method should be documented and calibrated using validation data; mandatory policy violations must remain decisive regardless of a low predicted risk score. Based on the combined assessment, the system can assign requests to predefined response categories, such as normal authorization, additional authentication, restricted access, temporary denial, or security investigation. Thresholds should be established using validation experiments and the relative costs of unauthorized access and legitimate-user disruption. Rather than applying a single threshold universally, the framework may use resource-sensitive thresholds for low-risk services, confidential business data, and privileged administrative operations. Policy orchestration translates approved decisions into platform-compatible rules and distributes them to the appropriate enforcement points. A policy-as-code repository maintains version history, review records, test results, and rollback information. Before deployment, policy changes should pass syntax validation, conflict detection, authorization checks, and simulation or staging tests. High-impact actions, such as disabling critical accounts or isolating essential production services, should require human approval unless explicitly authorized under a carefully defined emergency procedure. Automated actions should have bounded scope, expiration conditions, and recovery mechanisms. The framework should also record the features that influenced a decision, the policy rule applied, the model version used, and the resulting enforcement action. These controls improve transparency and reduce the risk of uncontrolled automation across heterogeneous cloud environments.

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The fourth stage evaluates the proposed framework through controlled experiments and comparative analysis. At least three configurations should be considered: conventional static or role-based access control, Zero-Trust access control using predefined contextual rules, and the proposed AI-assisted Zero-Trust policy management framework. Each configuration should be tested against comparable access scenarios, including legitimate user activity, suspicious authentication sequences, excessive privilege requests, compromised-device simulations, and policy inconsistency cases. Where feasible, experiments should be repeated across different workload volumes and hybrid cloud configurations to examine robustness and scalability. Security effectiveness should be measured using precision, recall, F1-score, false-positive rate, false-negative rate, and unauthorized access prevention rate. Operational performance should be assessed using policy evaluation latency, end-to-end authorization latency, policy propagation time, CPU and memory consumption, and the volume of alerts requiring human review. Governance measures should include policy conflict frequency, audit completeness, rollback success, and the proportion of automated actions that satisfy predefined approval requirements. User impact can be assessed through legitimate access denial rates and the frequency of additional authentication challenges. Results should report sample sizes, experimental conditions, variability, and confidence intervals where appropriate. Statistical comparisons should use suitable tests selected according to the distribution and dependency structure of the observations. Ablation experiments can examine the contribution of behavioral features, device posture, explainability mechanisms, and automated orchestration by removing one component at a time. Sensitivity analysis should determine how alternative risk thresholds affect security and usability. The evaluation must distinguish measured results from expected benefits; no performance improvement should be claimed until supported by collected experimental evidence. Limitations may include incomplete threat coverage, synthetic data, model drift, cloud-provider differences, and the difficulty of reproducing sophisticated adversarial behavior. Finally, the research should document implementation details, datasets or generation procedures, model configurations, policy definitions, and evaluation scripts to facilitate independent replication. The resulting analysis will establish whether AI-assisted Zero-Trust policy management provides measurable advantages over conventional and rule-based alternatives while maintaining transparency, operational resilience, and consistent access governance across hybrid cloud enterprise systems.

IV. RESULTS AND DISCUSSION

The proposed Zero-Trust Access Control and AI-Based Security Policy Management framework for hybrid cloud enterprise systems provides an integrated approach to strengthening identity verification, access authorization, threat detection, and security policy enforcement across distributed infrastructure. The framework combines continuous authentication, contextual access evaluation, machine learning-based risk assessment, and automated policy adaptation to improve security across public cloud, private cloud, and on-premises environments. The evaluation framework considers security effectiveness, unauthorized access prevention, threat detection accuracy, policy enforcement latency, and operational scalability as its principal performance indicators. The expected results indicate that integrating AI-driven analytics with Zero Trust principles can improve the identification of suspicious access patterns compared with static rule-based security mechanisms. By continuously evaluating identity attributes, device posture, network context, behavioral characteristics, and resource sensitivity, the system can determine whether access requests satisfy established security requirements. In contrast to conventional perimeter-based security models, the proposed approach treats every access request as potentially untrusted and requires contextual verification before granting resource access. AI-based anomaly detection further supports the identification of unusual login activities, privilege escalation attempts, suspicious API calls, and deviations from normal user behavior. These capabilities provide a foundation for more adaptive and responsive enterprise security management. However, quantitative improvements must be established through controlled experiments rather than assumed without measured evidence.

A second important outcome concerns the effectiveness of intelligent security policy management across hybrid cloud environments. Conventional policy administration frequently relies on manually configured access rules, fragmented identity systems, and provider-specific security controls, which can introduce inconsistencies and increase administrative complexity. The proposed framework addresses these limitations through centralized policy coordination, automated policy validation, and context-aware authorization decisions. AI-based risk scoring enables security administrators to prioritize access requests according to their assessed risk levels, while policy orchestration translates approved decisions into enforceable controls across connected environments. For example, a low-risk request from a compliant device may receive narrowly scoped access, whereas an unusual request involving a privileged account, unfamiliar location, or noncompliant endpoint may trigger additional authentication, restricted permissions, or temporary denial. Such decisions should remain constrained by explicit organizational policies and least-privilege requirements. The framework also supports policy synchronization across cloud platforms, reducing the likelihood of

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conflicting permissions and outdated access configurations. Nevertheless, policy consistency depends on reliable identity federation, accurate asset inventories, compatible enforcement interfaces, and regular validation of provider-specific implementations. Incorrect model predictions or incomplete contextual information could otherwise produce unnecessary restrictions or permit inappropriate access.

The third area of discussion concerns operational performance, scalability, and governance. Integrating AI-based access control into hybrid cloud infrastructure introduces additional computational requirements associated with telemetry collection, feature processing, model inference, and policy evaluation. Consequently, the framework must balance security effectiveness with authentication responsiveness and service availability. Lightweight inference models, event-driven processing, caching of appropriate contextual information, and distributed policy enforcement can reduce processing overhead without eliminating continuous verification. Performance evaluation should measure access decision latency, detection precision, recall, false-positive rate, policy synchronization delay, resource consumption, and the proportion of unauthorized attempts successfully blocked. Comparative experiments should include conventional static access control, rule-based Zero Trust enforcement, and the proposed AI-assisted approach under equivalent workloads. Testing should also examine adversarial behavior, concept drift, missing telemetry, and temporary connectivity failures. Explainable AI can help administrators understand the factors contributing to elevated risk scores, while immutable audit records support accountability and compliance reviews. Overall, the framework offers a structured approach to adaptive enterprise security, but its practical value depends on empirical validation, reliable implementation, transparent decision-making, and continuous monitoring of both security outcomes and operational costs.

V. CONCLUSION

The integration of Zero Trust access control and AI-based security policy management represents a promising approach to protecting hybrid cloud enterprise systems against increasingly sophisticated cyber threats. As enterprises distribute applications, identities, workloads, and sensitive information across public cloud services, private infrastructure, and on-premises data centers, traditional perimeter-oriented security mechanisms become insufficient for managing complex access relationships. The proposed framework addresses this challenge by combining continuous identity verification, least-privilege authorization, contextual risk assessment, behavioral anomaly detection, and coordinated policy enforcement. Rather than assuming that authenticated users or devices are automatically trustworthy, the framework evaluates access requests according to identity assurance, device compliance, resource sensitivity, observed behavior, and relevant environmental conditions. This approach supports more granular and dynamic protection of enterprise resources while reducing dependence on static permissions and network location. AI-driven analytics can further strengthen security operations by identifying suspicious patterns, prioritizing high-risk events, and supporting timely policy adjustments. When combined with robust identity governance, multi-factor authentication, encryption, and comprehensive logging, these capabilities establish a more resilient foundation for enterprise cybersecurity. The framework is particularly relevant to organizations operating heterogeneous cloud infrastructures where consistent authorization and centralized security visibility are essential for maintaining confidentiality, integrity, and availability.

The study also highlights that intelligent access control must be implemented with appropriate governance, performance monitoring, and human oversight. AI models can improve contextual risk analysis, but their decisions may be affected by biased training data, incomplete telemetry, adversarial manipulation, and changes in legitimate user behavior. Therefore, automated authorization decisions should operate within clearly defined policy boundaries, with sensitive actions subject to stronger verification and administrator approval where appropriate. Explainability, auditable decision records, policy version control, and reliable rollback mechanisms are essential for maintaining accountability. Similarly, organizations must evaluate the computational overhead and operational complexity introduced by continuous monitoring and automated policy orchestration. The effectiveness of the framework should be demonstrated through reproducible experiments that compare its performance with established security baselines using representative workloads and clearly documented evaluation metrics. Such experiments should report actual detection rates, false-positive rates, access decision latency, scalability, and unauthorized access prevention outcomes rather than relying on assumed improvements. In conclusion, the proposed framework provides a conceptual and methodological foundation for integrating adaptive intelligence with Zero Trust security across hybrid cloud enterprise systems. Its long-term success will depend on careful integration, continuous validation, effective governance, and alignment between automated decisions and organizational security requirements.

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VI. FUTURE WORK

Future research should focus on developing more sophisticated AI models that improve the accuracy, adaptability, and interpretability of Zero Trust access decisions across heterogeneous enterprise cloud environments. One promising direction involves combining supervised learning, unsupervised anomaly detection, and sequential behavioral analysis to identify both known attack patterns and previously unseen threats. Supervised models could classify recognized malicious activities, while unsupervised methods could detect deviations from established identity and workload behavior. Sequential models could evaluate changes in authentication patterns, privilege usage, session duration, and resource access over time. Researchers could also investigate graph-based learning to represent relationships among users, devices, applications, service accounts, APIs, and data resources. Such representations may help identify indirect privilege escalation pathways, compromised identities, and suspicious lateral movement across interconnected cloud environments. Another important research direction is the development of explainable risk assessment mechanisms that communicate why an access request was classified as risky and which contextual factors influenced the decision. This capability would help security administrators validate model recommendations, investigate disputed access decisions, and identify potential sources of bias. Future experiments should compare these techniques using consistent datasets, realistic hybrid cloud workloads, multiple attack scenarios, and reproducible evaluation procedures. Particular attention should be given to generalization across cloud providers, changes in enterprise behavior, and the reliability of model predictions under incomplete or noisy telemetry conditions.

A second major direction involves autonomous policy orchestration, privacy-preserving intelligence sharing, and resilient enforcement across geographically distributed enterprise infrastructure. Future frameworks could incorporate federated learning to enable participating cloud environments to improve threat detection collaboratively without routinely transferring raw security telemetry to a central repository. Research should examine the privacy risks associated with shared model updates, including information leakage, poisoning attacks, and inconsistent data quality. Reinforcement learning may also be investigated for optimizing policy selection under carefully defined constraints, provided that experimental environments, safety boundaries, and rollback procedures prevent exploratory decisions from exposing production resources. Digital twins and cyber ranges could support controlled evaluation of adaptive policies before deployment in operational systems. In addition, future implementations should investigate interoperability standards and policy translation mechanisms that maintain consistent authorization semantics across different identity providers, cloud platforms, container orchestration systems, and enterprise applications. Resilience under degraded network connectivity, identity provider outages, and unavailable AI inference services will remain essential. Secure fallback policies should deny sensitive operations when trust cannot be established while preserving explicitly authorized emergency access procedures. Researchers should also measure the financial and operational implications of these approaches, including infrastructure costs, administrative workload, false-denial consequences, and incident response efficiency. Finally, longitudinal studies across realistic enterprise deployments could assess whether adaptive Zero Trust policies remain effective as infrastructure, users, and threats evolve. These developments would help transform the proposed framework into a more explainable, interoperable, privacy-aware, and operationally reliable security architecture for future hybrid cloud enterprises.

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|ISSN: 2455-7773 | www.ijetemr.com| A Double-Blind Peer-Reviewed and Bimonthly Scholarly Journal|

|Volume 9, Issue 5, September-October 2024|

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