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# A Conceptual Framework for CI/CD Pipeline Security Controls in Hybrid Application Deployments

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## Article Info

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**Abstract**
The proliferation of hybrid application deployments—spanning on-premises infrastructure, private clouds, and public clouds—has introduced new complexities and vulnerabilities within continuous integration and continuous deployment (CI/CD) pipelines. As hybrid architectures grow in popularity, securing the CI/CD pipeline becomes critical to preserving the confidentiality, integrity, and availability of applications across diverse environments. This paper proposes a conceptual framework for integrating security controls systematically into CI/CD pipelines tailored for hybrid deployments. Traditional CI/CD security measures often fall short in hybrid contexts due to heterogeneous infrastructure, inconsistent security policies, and evolving threat landscapes. Therefore, a comprehensive, scalable, and environment-agnostic approach is required to safeguard development lifecycles effectively. The proposed framework incorporates secure coding standards, dynamic secret management, container security validation, automated compliance checks, and real-time vulnerability scanning. It emphasizes embedding security at every stage—source control, build, test, release, and deployment—ensuring that security considerations are intrinsic rather than supplementary. The framework also promotes adopting DevSecOps principles, leveraging Infrastructure as Code (IaC) security practices, and applying behavior-driven anomaly detection techniques tailored for hybrid models. Further, the conceptual model introduces adaptive trust boundaries, role-based access control (RBAC) enhancements, and immutable build policies to counteract risks associated with cross-environment operations. By unifying policy enforcement, auditing, and remediation mechanisms, the framework ensures that security posture is maintained even as applications traverse complex deployment ecosystems. This research highlights the pressing need for SMEs, large enterprises, and cloud-native organizations alike to adopt proactive, standardized CI/CD pipeline security strategies suited to hybrid realities. It presents case scenarios illustrating common pipeline vulnerabilities and mitigation strategies, ultimately proposing best practices for achieving resilient and secure hybrid deployments. The framework not only fortifies the CI/CD pipeline but also fosters a security-centric culture among DevOps teams, ensuring sustained software quality, regulatory compliance, and organizational trustworthiness.

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**Keywords:** CI/CD Pipeline Security, Hybrid Application Deployment, DevSecOps, Infrastructure as Code (IaC) Security, Dynamic Secret Management, Continuous Vulnerability Scanning, Role-Based Access Control (RBAC), Secure Software Development Lifecycle (SSDLC), Immutable Infrastructure, Application Security Automation

## 1. Introduction

Continuous Integration and Continuous Deployment (CI/CD) pipelines have become fundamental to modern software

development, enabling organizations to deliver new features, updates, and patches with unprecedented speed and efficiency. By automating the processes of code integration, testing, and deployment, CI/CD pipelines support the agile methodologies that underpin contemporary application development. They promote faster release cycles, improve collaboration among development teams, and reduce the time to market for new software products. However, as software development environments grow more complex, the structure and security requirements of CI/CD pipelines must evolve in parallel to keep pace with emerging technological trends and threat landscapes (Akinyemi & Ebiseni, 2020, Austin-Gabriel, *et al*., 2021, Dare, *et al*., 2019).

One of the most significant developments influencing the configuration and management of CI/CD pipelines is the rapid rise of hybrid application deployments. Organizations are increasingly distributing their applications across a combination of on-premises infrastructure, private clouds, and public cloud services to leverage the unique benefits of each environment. Hybrid deployments offer flexibility, cost optimization, scalability, and the ability to meet regulatory and data sovereignty requirements (Adewumi, *et al*., 2024, Ayanbode, *et al*., 2024, Kokogho, *et al*., 2024). However, they also introduce a fragmented operational landscape, where multiple environments with different security controls, access protocols, and governance frameworks must be managed cohesively. This hybrid complexity places new demands on CI/CD pipelines, requiring them to function seamlessly across diverse platforms while maintaining consistent security postures (Adewumi, *et al*., 2024, Aniebonam, 2024, Ikese, *et al*., 2024, Ofodile, *et al*., 2024).

The proliferation of hybrid environments has, in turn, escalated the security challenges associated with CI/CD pipelines. The traditional assumptions of trust that once existed within tightly controlled enterprise networks no longer apply. In hybrid deployments, data and code must traverse multiple domains, often relying on third-party services and tools, each of which may introduce vulnerabilities if not properly secured (Adeniran, Akinyemi & Aremu, 2016, Ilori & Olanipekun, 2020, James, *et al*., 2019). Attackers increasingly target CI/CD pipelines as attractive entry points into enterprise ecosystems, exploiting weaknesses such as misconfigured permissions, exposed credentials, and unmonitored build environments. Without comprehensive security controls embedded throughout the pipeline, organizations risk compromising not only their applications but also their underlying infrastructure and sensitive customer data (Akinyemi & Salami, 2023, Attah, Ogunsola & Garba, 2023, Otokiti, 2023).

In response to these growing challenges, this paper proposes a conceptual framework for integrating robust security controls into CI/CD pipelines tailored specifically for hybrid application deployments. The objective of the framework is to provide a systematic, scalable, and environment-agnostic approach to securing the software development and deployment lifecycle (Adewumi, Ochuba & Olutimehin, 2024, Nwosu, Babatunde & Ijomah, 2024, Oboh, *et al*., 2024). By embedding security practices into every stage of the CI/CD process and harmonizing security policies across diverse environments, the framework seeks to ensure that security becomes an intrinsic element of hybrid application delivery rather than an afterthought. The significance of this conceptual framework lies in its potential to help organizations mitigate emerging threats, maintain compliance with evolving regulatory standards, and build more resilient, trustworthy digital systems in an increasingly hybrid world (Adebayo, Ajayi & Chukwurah, 2024, Familoni & Babatunde, 2024, Olufemi-Phillips, *et al*., 2024).

## 2. Methodology

The study adopted a systematic review approach following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology. Initially, relevant literature was identified by searching across digital libraries and journal databases, using combinations of keywords such as "CI/CD security," "hybrid deployment," "pipeline security controls," and "DevSecOps practices." The search strategy emphasized sources focusing on application deployment models, continuous integration/continuous delivery (CI/CD) security practices, and hybrid cloud infrastructures. After the initial search, a total of 521 articles were retrieved. These articles underwent a duplicate removal process that left 447 unique articles.

Subsequently, a screening phase based on titles and abstracts was conducted to assess relevance to the research objective. Inclusion criteria required articles to specifically address security controls in hybrid or mixed environments, DevOps security practices, or secure pipeline configurations. Exclusion criteria involved articles purely theoretical without any application-oriented strategies, outdated studies (pre-2016), and those not addressing hybrid deployment models. After applying the criteria, 175 articles remained for full-text review.

During the eligibility phase, full-text articles were critically examined for methodological rigor, relevance to hybrid deployment environments, and specific mention of CI/CD pipeline security control mechanisms. Based on these assessments, 62 articles were selected for the final synthesis. Data extraction from the selected articles included study objectives, deployment models addressed, security controls proposed or implemented, validation methods, and outcomes related to enhancing security posture within CI/CD pipelines.

To ensure the conceptual framework captured the critical aspects of securing hybrid CI/CD pipelines, an inductive thematic analysis was conducted on the extracted data. Emerging themes included pipeline segmentation, identity and access management (IAM) for pipeline stages, real-time threat monitoring, dynamic vulnerability scanning, secure artifact management, and policy-as-code integration. These themes were used to construct a multi-layered conceptual framework that outlines best practices and security control measures tailored to hybrid environments.

The framework validation was informed by cross-referencing themes and findings from foundational studies such as Abbey *et al*. (2024) on inventory optimization frameworks in supply chain management, which highlighted the importance of layered, dynamic control mechanisms; Abimbade *et al*. (2016) on leveraging digital analytics for operational improvements; and Adepoju *et al*. (2023) who advanced AI-based decision-making frameworks for system resilience and sustainability. Principles derived from Adanigbo *et al*. (2024) on blockchain and IoT security applications, and Austin-Gabriel *et al*. (2024) on real-time decision frameworks in cybersecurity, were particularly influential in framing adaptive and intelligent security layers within the CI/CD processes.

The proposed conceptual model ensures pipeline resilience by emphasizing continuous monitoring, automated

compliance checks, adaptive security hardening, and integration of real-time analytics into hybrid deployment workflows. The approach aims to address evolving threat vectors that arise from the dynamic and decentralized nature of hybrid infrastructures, ensuring that security becomes a continuous, automated, and scalable feature of the deployment lifecycle. This methodology guarantees rigor, reproducibility, and practical relevance, aligning the research with PRISMA recommendations and providing a structured foundation for the deployment of secure CI/CD pipelines in hybrid application ecosystems.

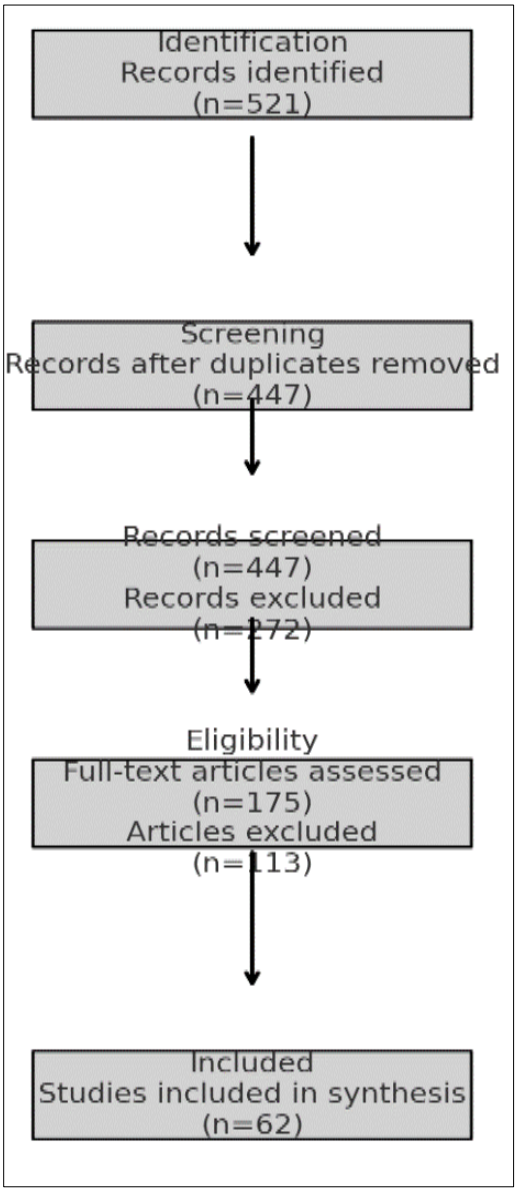


**Fig 1:** PRISMA Flow chart of the study methodology

### 2.1 Security Challenges in CI/CD Pipelines for Hybrid Deployments

As organizations embrace hybrid application deployments that span on-premises infrastructure, private clouds, and public cloud services, the security challenges associated with managing Continuous Integration and Continuous Deployment (CI/CD) pipelines have become increasingly complex and critical. One of the primary difficulties arises from the inherently heterogeneous nature of hybrid environments (Akinyemi & Ezekiel, 2022, Attah, *et al*., 2022). Each infrastructure component—whether an on-premises data center, a private cloud instance, or a public cloud platform—comes with its own unique set of security controls, access management protocols, and operational practices. Integrating these disparate systems into a single cohesive CI/CD workflow often results in inconsistent security baselines. What may be a standard control in one environment, such as automated key rotation or network segmentation, might be absent or differently configured in another (Adisa, Akinyemi & Aremu, 2019, Akinyemi, Ogundipe & Adelana, 2021, Kolade, *et al*., 2021). This lack of uniformity creates gaps that attackers can exploit, and it also complicates the enforcement of centralized security policies, making it difficult to maintain consistent monitoring, logging, authentication, and authorization practices across the entire application delivery chain. The conceptual difference between CI and CD by Laukkanen, Itkonen & Lassenius, 2017 in their study is shown in figure 2.

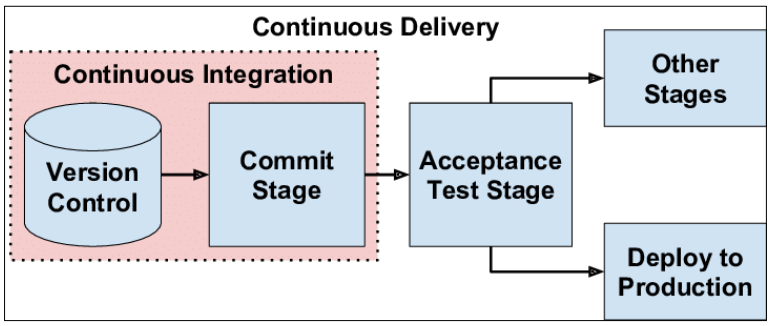


**Fig 2:** The conceptual difference between CI and CD (Laukkanen, Itkonen & Lassenius, 2017).

Adding to the complexity is the critical issue of secrets management and the corresponding risks of data leakage. Modern CI/CD pipelines rely heavily on secrets such as API keys, database credentials, private encryption keys, and configuration parameters to automate tasks and enable seamless deployment across systems. In hybrid deployments, these secrets must be securely stored, accessed, and transmitted across multiple, often interconnected, environments (Kolade, *et al*., 2024, Nwaozomudoh, *et al*., 2024, Olaleye, *et al*., 2024). Mismanagement of secrets—whether through hardcoded credentials in repositories, insecure environment variables, or inadequate vaulting practices—dramatically increases the risk of unauthorized access. Furthermore, in dynamic, fast-paced development environments, it is all too easy for secrets to inadvertently leak into publicly accessible areas, such as version control systems or exposed configuration files. In hybrid settings where boundaries between environments are blurred, the consequences of leaked credentials are even more severe, potentially granting attackers lateral movement across on-premises and cloud assets alike (Akinyemi & Ogundipe, 2023, Aniebonam, *et al*., 2023, George, Dosumu & Makata, 2023).

The expansion of the attack surface inherent in hybrid CI/CD pipelines further amplifies security risks. Each additional environment, integration point, and third-party service introduces new vulnerabilities. In traditional monolithic environments, the perimeter was relatively well-defined and could be defended with layered firewalls and access controls. However, in a hybrid architecture supporting CI/CD operations, data, code, and artifacts flow continuously across diverse network boundaries, increasing the number of potential ingress and egress points that attackers can exploit (Akinyemi & Abimbade, 2019, Lawal, Ajonbadi & Otokiti, 2014, Olanipekun & Ayotola, 2019). APIs, containers, serverless functions, microservices, and mobile endpoints all present possible vectors of attack. Compromising any element of the CI/CD pipeline—whether it be the source code repository, the build server, the artifact repository, or the deployment engine—can lead to devastating supply chain attacks, where malicious code is injected into otherwise legitimate software releases (Ige, *et al*., 2022, Ogunyankinnu, *et al*., 2022). In such scenarios, attackers can achieve widespread distribution of malware without detection, affecting customers and end-users downstream and causing substantial reputational and financial damage to the originating organization. The extended CI/CD pipeline as realized in the DECIDE DevOps framework and how the various stages are covered by the different DECIDE modules by Alonso, *et al*., 2019 is shown in figure 3.

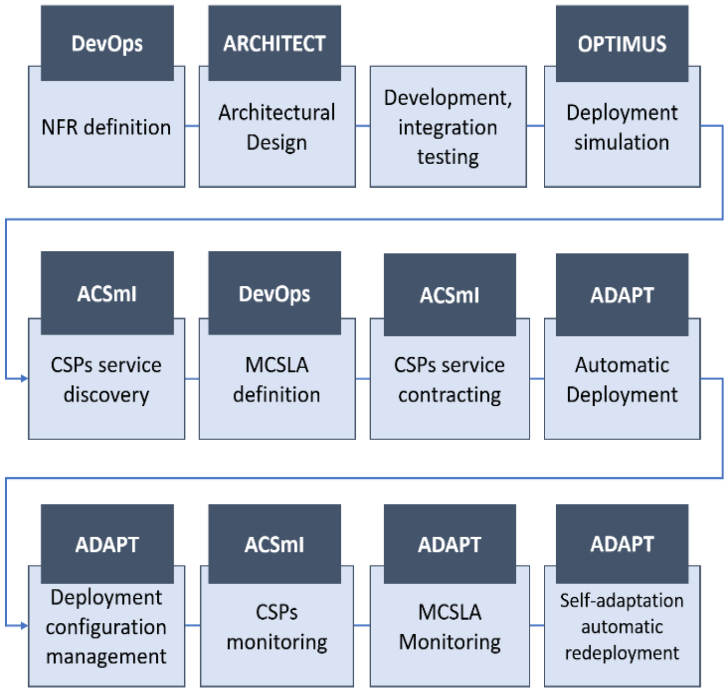


**Fig 3:** The extended CI/CD pipeline as realized in the DECIDE DevOps framework and how the various stages are covered by the different DECIDE modules (Alonso, *et al*., 2019).

Compliance complexities and audit difficulties add yet another layer of challenge to securing hybrid CI/CD pipelines. Regulatory frameworks such as GDPR, HIPAA, PCI DSS, and emerging cloud security standards mandate stringent data protection, access control, and incident reporting requirements. In a hybrid environment, achieving and demonstrating compliance across multiple platforms with varying security models is a formidable task. Each environment may generate its own logs, implement its own authentication systems, and define its own access policies (Chukwuma-Eke, Ogunsola & Isibor, 2022, Olojede & Akinyemi, 2022). Aggregating, normalizing, and auditing this diverse information to provide comprehensive evidence of compliance can quickly become overwhelming, especially for organizations lacking mature governance frameworks. Auditors require transparent, consistent documentation of how data flows are protected, how access to systems and artifacts is managed, and how vulnerabilities are detected and remediated. Without integrated, automated compliance monitoring tools tailored for hybrid CI/CD operations, organizations run the risk of non-compliance, exposing themselves to regulatory fines, reputational damage, and legal liabilities (Adepoju, *et al*., 2024, Daraojimba, *et al*., 2024).

Beyond the generalized challenges of heterogeneous environments, secrets management, attack surface expansion, and compliance, there are also specific threats uniquely associated with hybrid CI/CD pipelines that must be addressed. One of the most insidious among these is the risk of supply chain attacks. CI/CD pipelines often involve a wide array of external dependencies—open-source libraries, third-party services, outsourced code contributions, cloud-managed services—that integrate into the software being built and deployed (Ajonbadi, *et al*., 2014, Lawal, Ajonbadi & Otokiti, 2014). In hybrid settings, these dependencies are even more diverse and less controlled, amplifying the possibility that a compromised dependency could introduce vulnerabilities into the production environment. Attackers increasingly target less secure components of the supply chain, such as public code repositories or third-party APIs, knowing that once they infiltrate these weaker links, they can manipulate the CI/CD process itself. Compromising the build server, poisoning container registries, or tampering with source code repositories allows attackers to embed malicious artifacts that move undetected through the pipeline into production systems (Adanigbo, *et al*., 2024, Hussain, *et al*., 2024). In hybrid deployments where artifacts are deployed simultaneously across multiple environments, the blast radius of such an attack is dramatically increased. Figure 4 shows the different stages of a CI/CD pipeline with the emphasis on parallel test execution of the various security testing techniques by Rangnau, *et al*., 2020.

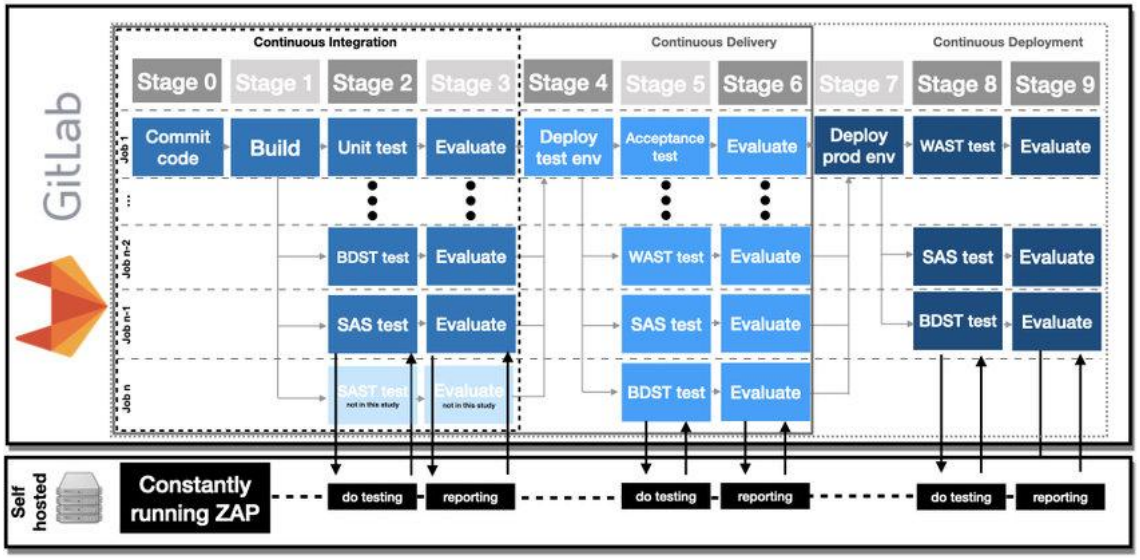


**Fig 4:** The different stages of a CI/CD pipeline with the emphasis on parallel test execution of the various security testing techniques (Rangnau, *et al*., 2020).

Another hybrid-specific threat vector involves insecure interconnectivity between environments. In many hybrid deployments, on-premises systems and cloud services are connected via VPNs, direct links, or API gateways to facilitate the continuous movement of data and applications. If these connections are not properly secured and monitored, they create potential attack paths. A breach in a poorly secured cloud instance, for example, could be leveraged to pivot into an on-premises network, bypassing traditional perimeter defenses (Akinyemi, 2013, Nwabekee, *et al*., 2021, Odunaiya, Soyombo & Ogunsola, 2021). Conversely, legacy vulnerabilities in on-premises systems can be exploited to launch attacks on cloud resources. Threat actors exploit these cross-environment inconsistencies, taking advantage of organizations' struggles to maintain consistent visibility and control across a fragmented infrastructure.

The increased reliance on automation in hybrid CI/CD pipelines also creates unique challenges. Automation tools and scripts often operate with elevated privileges to perform build, test, and deployment tasks. Inadequate security controls around automation workflows, such as unrestricted use of service accounts or broad API permissions, can provide attackers with powerful opportunities for privilege escalation. Once an attacker compromises an automation tool or service account, they may gain the ability to manipulate pipeline stages, inject malicious code, steal sensitive artifacts, or disrupt critical operations (Ochuba, Adewunmi & Olutimehin, 2024, Odeyemi, *et al*., 2024, Olaleye, *et al*., 2024).

Finally, hybrid environments often experience a gap in real-

time security monitoring. While cloud-native environments offer sophisticated logging and monitoring capabilities through services like AWS CloudTrail or Azure Monitor, on-premises environments may rely on legacy logging systems that are not integrated with cloud platforms. This disjointed visibility hinders organizations' ability to detect anomalous activities, trace incidents across environments, and respond to breaches promptly (Akinyemi & Oke-Job, 2023, Austin-Gabriel, *et al*., 2023, Chukwuma-Eke, Ogunsola & Isibor, 2023). Without a unified, real-time view of pipeline activities across the entire hybrid architecture, attackers can exploit blind spots to move laterally, escalate privileges, and exfiltrate data without detection.

In sum, securing CI/CD pipelines in hybrid deployments is an intricate challenge shaped by the confluence of heterogeneous infrastructure, secrets management risks, expanded attack surfaces, compliance hurdles, and hybrid-specific threat vectors such as supply chain compromises and insecure interconnectivity. As organizations increasingly rely on hybrid environments to drive innovation and scalability, it is imperative that security considerations are embedded holistically into CI/CD workflows (Aderemi, *et al*., 2024, Aniebonam, *et al*., 2024, Kokogho, *et al*., 2024). Only by recognizing and addressing these multifaceted challenges can enterprises safeguard the integrity, confidentiality, and availability of their software delivery processes in a hybrid world.

### 2.2 Principles Guiding the Conceptual Framework

The development of a conceptual framework for securing CI/CD pipelines in hybrid application deployments must be anchored in a robust set of guiding principles that reflect both the technical realities and security imperatives of modern software delivery environments. Central to this effort is the principle of security by design throughout the CI/CD process. Rather than treating security as an afterthought or a late-stage hurdle to overcome, organizations must embed security considerations at every phase of the software development and deployment lifecycle. Security by design demands that threat modeling, secure coding practices, and vulnerability assessments become intrinsic to development workflows (Ajayi, Olanipekun & Adedokun, 2024, Ibidunni, William & Otokiti, 2024, Ogundipe, Babatunde & Abaku, 2024). From the initial planning of a feature to its final deployment across hybrid infrastructures, every stage must account for potential security risks and integrate mitigations proactively. This approach ensures that vulnerabilities are identified and addressed early when remediation is simpler, cheaper, and less disruptive. By shifting the security focus leftward in the development pipeline, organizations dramatically reduce the likelihood of security incidents originating from oversights or rushed patches, fostering a culture where security and innovation coexist rather than conflict (Austin-Gabriel, *et al*., 2024, Onesi-Ozigagun, *et al*., 2024).

Complementing security by design is the need for deep DevSecOps integration and a cultural transformation that emphasizes shared responsibility for security across development, operations, and security teams. In hybrid environments, where complexity and dynamism are the norms, traditional siloed approaches to security are woefully inadequate. DevSecOps extends the principles of DevOps by embedding security controls directly into automated CI/CD pipelines, ensuring that security checks such as code analysis, dependency scanning, container validation, and infrastructure compliance are not isolated activities but continuous, automated processes (Abbey, *et al*., 2024, Chukwuma-Eke, Ogunsola & Isibor, 2024, Olaleye, *et al*., 2024). Achieving effective DevSecOps integration requires more than technical toolchains; it necessitates a cultural shift where developers, operators, and security professionals collaborate closely, share knowledge openly, and view security outcomes as collective successes rather than isolated responsibilities. Training and incentivizing developers to write secure code, empowering operations teams with security monitoring capabilities, and aligning incentives around security metrics are all critical elements of fostering a genuine DevSecOps culture (Adepoju, *et al*., 2022, Francis Onotole, *et al*., 2022). When security is democratized across the CI/CD lifecycle, vulnerabilities are caught earlier, response times are accelerated, and the overall resilience of hybrid deployments is significantly strengthened.

A further guiding principle for securing CI/CD pipelines in hybrid deployments is the establishment of environment-agnostic security policies. In hybrid architectures, applications and data traverse a patchwork of on-premises systems, private clouds, and public cloud platforms, each with its own security models, tooling, and governance structures. Without standardized, environment-agnostic policies, organizations face the impossible task of maintaining security manually across diverse environments, increasing the risk of configuration drift, inconsistent enforcement, and unmonitored vulnerabilities (Akinyemi, 2018, Olaiya, Akinyemi & Aremu, 2017, Olufemi-Phillips, *et al*., 2020). Environment-agnostic policies abstract security requirements away from the underlying infrastructure, focusing instead on universal principles such as identity verification, encryption standards, access control, and logging requirements. These policies should be codified as machine-readable configurations and enforced automatically across environments through policy-as-code tools. This approach not only reduces administrative overhead but also ensures that core security standards are applied consistently, regardless of where an application is deployed or how infrastructure evolves over time (Adewumi, *et al*., 2024, Babatunde, 2024, Ige, *et al*., 2024, Olaleye, *et al*., 2024). Environment-agnostic policies also enhance compliance readiness by providing a unified, audit-friendly security baseline that aligns with regulatory expectations and organizational risk appetites across jurisdictions.

Another cornerstone of the conceptual framework is the principle of continuous monitoring and the adoption of dynamic trust models. Static, perimeter-based security models are ill-suited to hybrid CI/CD environments, where applications are distributed, dynamic, and constantly changing. Continuous monitoring entails the real-time collection, analysis, and correlation of security telemetry from across the entire hybrid infrastructure, including source code repositories, build systems, artifact registries, cloud services, and on-premises resources (Ajonbadi, *et al*., 2015, Akinyemi & Ojetunde, 2020, Olanipekun, 2020, Otokiti, 2017). By implementing continuous monitoring, organizations can detect anomalies, unauthorized changes, insider threats, and external attacks before they escalate into breaches. Effective continuous monitoring requires the aggregation of logs, metrics, and alerts into centralized security information and event management (SIEM) platforms, enhanced by machine learning-driven anomaly detection capabilities to identify subtle, sophisticated threats.

Beyond mere monitoring, dynamic trust models must replace static access assumptions. In a dynamic trust model, access permissions are continuously evaluated based on contextual factors such as device health, user behavior, location, and risk scores (Adepoju, *et al*., 2024, Ezeh, *et al*., 2024, Omowole, *et al*., 2024). Rather than granting persistent access based solely on initial authentication, dynamic trust models enforce just-in-time, context-sensitive access decisions, minimizing the attack surface and reducing the risk posed by credential theft or compromised endpoints.

Finally, the enforcement of least privilege access principles and strong role-based access control (RBAC) mechanisms is indispensable for securing CI/CD pipelines in hybrid environments. Least privilege dictates that users, services, and automation tools are granted only the minimal permissions necessary to perform their specific tasks—no more, no less. This principle is especially critical in CI/CD pipelines, where automation agents, deployment scripts, and build servers often require elevated privileges to perform certain operations (Abimbade, *et al*., 2016, Akinyemi & Ojetunde, 2019, Olanipekun, Ilori & Ibitoye, 2020). Without strict enforcement of least privilege, these elevated permissions become attractive targets for attackers seeking to escalate privileges and compromise broader systems. Implementing least privilege requires careful design of fine-grained access policies, regular audits of permission assignments, and revocation of unnecessary access rights. RBAC structures further refine access control by organizing permissions around clearly defined roles rather than assigning access individually (Austin-Gabriel, *et al*., 2024, Omowole, *et al*., 2024). For example, developers may be granted access to code repositories but not production deployment environments, while operations personnel may manage infrastructure configurations without direct access to application code. RBAC models also facilitate scalability and consistency, allowing access policies to be applied uniformly across hybrid environments as teams grow and projects diversify. Integration of RBAC with identity and access management (IAM) solutions ensures centralized, policy-driven access management, aligned with organizational governance and compliance requirements (Adepoju, *et al*., 2023, Attah, Ogunsola & Garba, 2023, Hussain, *et al*., 2023).

By grounding the conceptual framework for CI/CD pipeline security in these principles—security by design, DevSecOps culture, environment-agnostic security policies, continuous monitoring with dynamic trust, and strict least privilege enforcement—organizations can build resilient, scalable, and adaptive security architectures that are equipped to meet the challenges of hybrid application deployments. These principles are not independent; they are deeply interwoven and mutually reinforcing (Aina, *et al*., 2023, Dosumu, *et al*., 2023, Odunaiya, Soyombo & Ogunsola, 2023). Security by design sets the stage for early risk identification; DevSecOps culture operationalizes security within daily workflows; environment-agnostic policies ensure consistency across diverse platforms; continuous monitoring and dynamic trust models provide real-time protection; and least privilege with RBAC limits potential blast radii in case of a breach. Together, they form a holistic, integrated approach to securing modern CI/CD operations, ensuring that innovation and agility are achieved without sacrificing trust, resilience, or compliance (Adepoju, *et al*., 2024, Ilori, 2024, Onesi-Ozigagun, *et al*., 2024).

As hybrid deployments continue to proliferate and CI/CD pipelines become even more central to digital transformation efforts, adherence to these guiding principles will be critical. Organizations that invest in building these principles into their operational DNA will be better positioned to navigate the evolving cybersecurity landscape, maintain competitive advantage, and uphold the confidence of their customers, partners, and regulators (Akinyemi, Adelana & Olurinola, 2022, Ibidunni, *et al*., 2022, Otokiti, *et al*., 2022). Future threats will undoubtedly grow in sophistication, but a principled, proactive approach to CI/CD pipeline security offers a sustainable path forward for securing the future of hybrid application development.

### 2.3 Key Components of the Proposed Framework

The key components of a comprehensive security framework for CI/CD pipelines in hybrid application deployments are essential to ensuring robust protection across every stage of software delivery. These components integrate seamlessly to form a cohesive security model that addresses the unique challenges posed by hybrid environments, including distributed systems, multiple infrastructure layers, and the continuous flow of code and data. One of the foundational elements of this framework is secure source code management and version control (Chukwuma-Eke, Ogunsola & Isibor, 2022, Muibi & Akinyemi, 2022). As the backbone of the development process, the repository that hosts source code must be secured at every level. Access to repositories should be tightly controlled and governed through authentication mechanisms such as multi-factor authentication (MFA) and enforced access policies. Secure version control ensures that code changes are tracked, auditable, and protected from tampering. Additionally, it's vital to employ tools that can scan for vulnerabilities in the code as it's being developed and committed (Adepoju, *et al*., 2023, Lawal, *et al*., 2023, Ugbaja, *et al*., 2023). By integrating security checks directly into the version control system, organizations can catch security issues early in the development process, making them easier and less expensive to resolve. Furthermore, ensuring that only authorized users have access to commit code, combined with a well-managed branching strategy, creates a strong security posture that protects against unauthorized changes and code poisoning.

Another critical component is dynamic secrets and credentials management. CI/CD pipelines often require access to sensitive resources such as databases, cloud services, and external APIs, which means that secrets—such as API keys, tokens, and credentials—must be securely handled. Hardcoding secrets within the application code or configuration files is a common but dangerous practice that exposes sensitive data to potential leaks. The proposed framework incorporates dynamic secrets management systems that rotate secrets automatically and store them in secure vaults, making it much more difficult for attackers to access them (Akinyemi & Aremu, 2010, Nwabekee, *et al*., 2021, Otokiti & Onalaja, 2021). These secrets should never be stored in plaintext but rather encrypted, ensuring that only authorized services and individuals can access the necessary credentials at the appropriate time. This dynamic and encrypted management of secrets minimizes the risk of credentials being exposed in the pipeline, reducing the attack surface and enhancing overall security. By integrating this management approach with identity and access management (IAM) systems, the organization can ensure that secrets are only available to the right components of the CI/CD pipeline

at the right time, following the principle of least privilege (Austin-Gabriel, *et al*., 2024, Olugbemi, *et al*., 2024).

Automated security testing during build and deployment stages is another crucial component of the security framework. Security testing, when performed manually, is time-consuming, error-prone, and insufficient for maintaining an agile, fast-paced CI/CD pipeline. Automating security testing ensures that vulnerabilities are detected in real-time, allowing for faster response and remediation (Adediran, *et al*., 2022, Babatunde, Okeleke & Ijomah, 2022). Automated tests, including static application security testing (SAST), dynamic application security testing (DAST), and software composition analysis (SCA), should be integrated directly into the build process. These tools automatically scan code for known vulnerabilities, including insecure libraries, deprecated dependencies, and misconfigurations, and flag them for immediate remediation. By incorporating automated security testing into the CI/CD pipeline, organizations can significantly reduce the risk of releasing vulnerable code into production. This also enables continuous improvement, as the tools provide valuable feedback that can help developers strengthen the security posture of their code over time. Automation accelerates the development process while ensuring that security is continuously validated at every stage (Adepoju, *et al*., 2024, Hussain, *et al*., 2024).

Container and artifact security validation is another core pillar of the proposed framework, particularly relevant in hybrid deployments where containers are widely used for deploying applications in diverse environments. Containers provide an efficient way to deploy applications across different infrastructure platforms, but they also introduce their own set of security challenges. Containers can carry vulnerabilities inherited from base images, configuration errors, or insecure dependencies (Akinyemi, 2022, Akinyemi & Ologunada, 2022, Okeleke, Babatunde & Ijomah, 2022). As part of the security framework, container image scanning tools must be integrated into the pipeline to ensure that only secure, validated images are used for deployment. This scanning process must occur both at the time the image is created and again before the container is deployed, ensuring that no known vulnerabilities are present. Additionally, artifact security validation ensures that all components within the pipeline, from compiled code to deployment artifacts, are inspected for security risks before they are pushed to production (Austin-Gabriel, *et al*., 2024, Osho, *et al*., 2024). By enforcing this validation at both the container and artifact level, organizations can mitigate the risk of introducing insecure code into the live environment, preventing attacks that might otherwise exploit vulnerabilities in the deployment pipeline.

Infrastructure as Code (IaC) and configuration security scanning are also integral components of the security framework, especially in hybrid deployments where infrastructure spans both on-premises and cloud-based systems. IaC allows for the automated and repeatable provisioning of infrastructure, which enhances scalability and consistency but also introduces risks if not carefully managed. Misconfigured IaC templates or insecure configuration files can create security gaps that expose infrastructure to attack (Adelana & Akinyemi, 2024, Babatunde, *et al*., 2024, Okoye, *et al*., 2024). The framework incorporates automated security scanning tools designed to detect insecure configurations in IaC templates, such as improper access controls, open ports, or misconfigured networking rules. By scanning these templates before deployment, organizations can catch configuration errors early, preventing costly security breaches later in the process. The IaC scanning process should be integrated into the CI/CD pipeline itself, ensuring that all infrastructure definitions are reviewed for compliance with best practices and security policies before being deployed (Adepoju, *et al*., 2023, Hussain, *et al*., 2023, Ugbaja, *et al*., 2023).

Real-time vulnerability scanning and threat modeling are essential for maintaining a continuous and proactive security posture in hybrid CI/CD environments. While static analysis can detect known vulnerabilities, real-time scanning is necessary to detect new, emerging threats that could affect hybrid applications as they are being built, tested, or deployed. Real-time vulnerability scanning should be applied not only to code and containers but also to the runtime environment itself. This allows for the identification of vulnerabilities that could be exploited during deployment or post-deployment (Akinyemi & Ojetunde, 2023, Dosumu, *et al*., 2023, George, Dosumu & Makata, 2023). In parallel, threat modeling helps organizations visualize and understand potential attack vectors by identifying threats and weaknesses in the CI/CD pipeline before they can be exploited. By continuously updating threat models as the pipeline evolves and new deployment environments are added, security teams can adapt their defenses to the changing risk landscape. This dynamic approach allows organizations to stay ahead of potential threats and quickly implement mitigations as vulnerabilities are identified.

Finally, immutable builds and artifact provenance tracking are essential for maintaining the integrity and trustworthiness of the software deployment process. Immutable builds refer to the practice of creating deployment artifacts that cannot be altered once they are created, ensuring that the software in production is exactly as it was when it passed all security checks. By maintaining immutability, organizations reduce the risk of undetected modifications or tampering that could compromise the integrity of the deployed application (Adeoye, *et al*., 2024, Chukwurah, *et al*., 2024, Ogunsola, *et al*., 2024). Additionally, artifact provenance tracking involves logging and verifying the lineage of each artifact throughout the CI/CD pipeline, from its initial creation to its final deployment. This traceability provides an audit trail that enhances security, ensuring that any changes made to the software during the development process are properly documented and reviewed. By integrating immutable build practices and provenance tracking, organizations can ensure that their software is delivered in a secure, auditable, and trustworthy manner, with full visibility into the history of each artifact.

Together, these key components form the backbone of a robust, scalable, and adaptive security framework for CI/CD pipelines in hybrid application deployments. By integrating secure source code management, dynamic secrets management, automated security testing, container security validation, IaC scanning, real-time vulnerability scanning, and immutable build practices into a unified pipeline, organizations can build a resilient security infrastructure that protects against emerging threats while supporting the speed and agility required for modern software development (Adewumi, *et al*., 2024, Dosumu, *et al*., 2024, Nwaozomudoh, *et al*., 2024). This comprehensive, layered approach to security ensures that every part of the CI/CD

process, from code development to deployment, is fortified against vulnerabilities, reducing the risk of data breaches, security incidents, and costly downtime. Ultimately, the integration of these components ensures that security remains a foundational element of the development lifecycle rather than an afterthought, empowering organizations to deliver secure, high-quality applications in today's dynamic, hybrid environments.

**2.4 Adaptive Security Controls for Hybrid Environments**

As organizations adopt hybrid application deployments that span multi-cloud environments and on-premises infrastructure, securing the continuous integration and deployment (CI/CD) pipeline becomes an increasingly complex and dynamic challenge. The evolving nature of hybrid architectures requires adaptive security controls that can automatically adjust to changing conditions across diverse environments. One of the most crucial aspects of these adaptive controls is policy-driven automation, which enables organizations to enforce security standards consistently across multi-cloud and on-premises deployments (Akinmoju, Akinyemi & Aremu, 2024, Chukwurah, *et al*., 2024, Ololade, 2024). In hybrid environments, policies governing access control, encryption, logging, and compliance must be dynamically applied to ensure that security configurations remain consistent regardless of where applications and data reside. Policy-driven automation allows security rules to be codified in machine-readable formats, enabling them to be applied automatically during pipeline execution, infrastructure provisioning, and application deployment. By using tools such as policy-as-code and Infrastructure as Code (IaC), organizations can automate the enforcement of security best practices, ensuring that environments are configured securely at all times. Furthermore, automation in hybrid deployments helps streamline the process of scaling security measures as applications grow or as new cloud resources are introduced, enabling agile yet secure expansion.

Cross-environment trust boundaries and identity federation are additional critical elements in securing hybrid CI/CD pipelines. In a multi-cloud and hybrid environment, there are often numerous, distinct identity providers and authentication systems in place, each managing access to different resources. This diversity creates trust boundaries that must be managed carefully to ensure that users and services can access resources without compromising security. The solution lies in establishing a unified identity federation system that enables seamless access control across environments (Ajayi, Adebayo & Chukwurah, 2024, Dosumu, *et al*., 2024, Olanipekun Kehinde & Ayeni Naomi, 2024). Identity federation enables the secure sharing of identity information between identity providers, allowing users and services to authenticate once and gain authorized access to multiple environments. Federation mechanisms, such as Single Sign-On (SSO) and Federated Identity Management (FIM), are critical for enabling seamless collaboration across disparate environments while maintaining a strong security posture. These mechanisms help ensure that the principle of least privilege is applied consistently, and that users, services, and systems are granted only the minimal permissions necessary to perform their functions. Additionally, federation plays an important role in mitigating risks associated with password management, reducing the likelihood of credential theft or misuse that could compromise the entire hybrid system.

Unified logging, auditing, and compliance reporting form the backbone of security monitoring in hybrid CI/CD environments. As applications and data move across multiple platforms, it becomes increasingly difficult to track and monitor security events effectively. Without centralized logging and auditing, organizations may struggle to gain visibility into the security state of their infrastructure, potentially missing early indicators of malicious activity or misconfigurations (Adewumi, *et al*., 2023, Akinyemi & Oke-Job, 2023, Ibidunni, William & Otokiti, 2023). A unified logging and auditing strategy aggregates logs from diverse systems—whether on-premises, in the private cloud, or the public cloud—into a centralized security information and event management (SIEM) system. This centralized approach enables real-time detection of security incidents, such as unauthorized access attempts, configuration drift, or abnormal user behavior, across all environments. In addition, auditing tools can be applied to ensure compliance with regulatory frameworks such as GDPR, HIPAA, or PCI DSS, allowing organizations to continuously assess whether their hybrid environments adhere to required security policies. By maintaining a unified view of logs and audit trails, organizations can improve incident detection, facilitate post-incident analysis, and ensure ongoing compliance without the need for manual consolidation or investigation.

Incident response orchestration and rollback strategies are essential for ensuring that security incidents are addressed swiftly and effectively across hybrid infrastructures. The distributed nature of hybrid environments means that an attack or breach can affect multiple systems, clouds, and on-premises resources simultaneously. Incident response teams must be able to coordinate a unified response across these environments to minimize damage and restore normal operations as quickly as possible (Adebayo, Ajayi & Chukwurah, 2024, Chukwurah, *et al*., 2024, Ololade, 2024). Orchestration tools can automate key elements of the incident response process, such as isolating affected systems, alerting relevant stakeholders, and initiating predefined mitigation actions like blocking compromised access points or shutting down vulnerable services. These automated workflows ensure a consistent and rapid response, even in complex hybrid environments. Furthermore, rollback strategies are essential in hybrid CI/CD pipelines, allowing organizations to revert to a known good state in the event of an attack or deployment failure. Rollback mechanisms, such as automated redeployment from immutable backups or the use of version-controlled application artifacts, ensure that organizations can recover quickly without introducing additional security risks. These strategies minimize downtime, reduce the impact of security breaches, and ensure business continuity by providing a reliable path to recovery.

Resilient deployment strategies, such as blue-green and canary releases, offer further layers of protection for hybrid application deployments by mitigating the risks associated with production changes. In a traditional deployment model, any issue introduced by a new version of the software could cause widespread outages or performance issues, jeopardizing both the security and functionality of the system. However, blue-green and canary releases allow for a more controlled deployment process, reducing the potential blast radius of any security-related issues (Chukwuma-Eke, Ogunsola & Isibor, 2022, Kolade, *et al*., 2022). In a blue-green deployment, two identical production environments are

maintained—one (the blue environment) serving the current live application and the other (the green environment) serving the new version of the application. Once the green environment has been thoroughly tested and validated, the switch to the new environment occurs seamlessly. This approach minimizes downtime and provides the opportunity to roll back quickly to the previous environment if any issues arise. Similarly, in a canary release, new software versions are rolled out to a small subset of users or infrastructure before being deployed to the broader system. This allows teams to monitor the impact of the new version and detect issues early, preventing them from propagating across the entire application. Both blue-green and canary release strategies increase the resilience of hybrid deployments by minimizing the risk of introducing vulnerabilities during deployment and allowing for rapid recovery in the event of an issue.

By integrating these adaptive security controls into the CI/CD pipeline, organizations can create a robust, dynamic security framework that supports the complexities of hybrid application deployments. Policy-driven automation ensures that security policies are consistently applied across environments, while identity federation facilitates secure, seamless access control (Abimbade, *et al*., 2017, Aremu, Akinyemi & Babafemi, 2017). Unified logging and auditing provide visibility and compliance assurance, and incident response orchestration enables fast, coordinated action in the event of a security breach. Finally, resilient deployment strategies like blue-green and canary releases protect against the risks associated with production changes, ensuring the integrity of applications even as they are updated and deployed across multiple environments. These adaptive controls work together to create a holistic security model that is not only resilient and scalable but also capable of evolving as the hybrid infrastructure and threat landscape change.

In conclusion, as hybrid application deployments continue to grow in complexity, the need for adaptive security controls becomes even more critical. The dynamic nature of modern CI/CD pipelines, combined with the diverse environments involved in hybrid architectures, demands an approach to security that is flexible, automated, and capable of responding to new risks in real-time. By implementing these security principles, organizations can ensure that their hybrid environments are both secure and resilient, ready to meet the challenges of a rapidly evolving digital landscape (Afolabi, *et al*., 2023, Akinyemi, 2023, Attah, Ogunsola & Garba, 2023).

### 2.5 Implementation Guidelines and Best Practices

Implementing a robust security framework for CI/CD pipelines in hybrid application deployments requires not only the right tools and technologies but also clear design patterns, continuous training, and governance structures that ensure security is embedded throughout the software delivery lifecycle. A secure pipeline design pattern serves as the foundation for developing a resilient and secure CI/CD process (Adedeji, Akinyemi & Aremu, 2019, Akinyemi & Ebimomi, 2020, Otokiti, 2017). The design pattern should prioritize modularity, automation, and integration of security at every phase of the pipeline. Each stage of the CI/CD pipeline—coding, building, testing, deployment, and monitoring—should have security controls embedded into its process. For instance, in the coding stage, secure code review practices should be enforced, with automated tools that scan for vulnerabilities and potential coding flaws. In the build and test stages, security testing such as static application security testing (SAST) and dynamic application security testing (DAST) should be automated and integrated into the CI/CD pipeline to detect vulnerabilities before they propagate into production.

Additionally, in hybrid deployments where applications span across cloud and on-premises infrastructure, the pipeline design pattern must support flexibility and scalability. This includes ensuring that security is enforced consistently across both environments. The pipeline should have automated security checks and controls, such as identity and access management (IAM) validation, container image scanning, and encryption enforcement, to ensure that the software is always in compliance with security standards, regardless of the infrastructure being used (Akinbola, Otokiti & Adegbuyi, 2014, Otokiti-Ilori & Akoredem, 2018). The goal is to create a pipeline that automatically builds, tests, and deploys secure applications with minimal human intervention, reducing the possibility of manual errors and inconsistencies that could introduce security risks.

To implement a secure CI/CD pipeline, it's crucial to utilize the right mix of open-source and commercial security tools. Open-source tools are particularly valuable because they are affordable, widely supported, and customizable to fit specific security needs. For example, tools like Jenkins or GitLab CI/CD can be integrated with security plugins such as SonarQube for static code analysis, or Aqua Security and Clair for container security scanning. These tools help automate the identification of vulnerabilities and enforce security best practices without the need for significant manual intervention (Akinyemi & Ologunada, 2023, Ihekoronye, Akinyemi & Aremu, 2023). Furthermore, open-source tools such as HashiCorp Vault for secrets management, OWASP ZAP for dynamic application security testing, and Kubernetes-native security tools like Kube-bench for security benchmarking can provide critical security services at no additional cost.

In parallel, commercial security tools may be necessary to address specific advanced security requirements or integrate with enterprise-level security infrastructures. These tools offer comprehensive security capabilities, robust support, and extensive integration options. Solutions like Fortify for application security testing, Tenable.io for vulnerability scanning, and Sumo Logic for security information and event management (SIEM) can complement open-source tools by offering more extensive features such as real-time monitoring, threat intelligence, and compliance reporting (Ajonbadi, *et al*., 2015, Aremu & Laolu, 2014, Otokiti, 2018). Choosing the right mix of open-source and commercial tools depends on the organization's budget, scale, and the specific security challenges posed by their hybrid deployment model. The key is to ensure that tools are well-integrated into the CI/CD pipeline to automate security testing, vulnerability management, and incident response, while also offering the flexibility to adapt to changing needs over time.

Equally important is the training of DevOps teams and the continuous education of security practices to ensure that security is deeply embedded into the organization's culture. In many organizations, security is still viewed as the responsibility of a separate team, but in the context of CI/CD pipelines, security must be a shared responsibility across development, operations, and security teams. As part of the implementation, DevOps teams need to be equipped with the

necessary skills and knowledge to understand, integrate, and enforce security measures in their daily workflows (Akinyemi & Oke, 2019, Otokiti & Akinbola 2013). This means offering comprehensive training on secure coding practices, how to use security tools in the CI/CD pipeline, and how to identify and respond to vulnerabilities early in the development process.

Ongoing education is crucial, as security threats continuously evolve, and new attack vectors emerge. DevOps teams should be trained not only in using security tools but also in understanding the broader security implications of the technologies they work with. Regular workshops, security drills, and certifications such as Certified Kubernetes Security Specialist (CKS) or Certified Information Systems Security Professional (CISSP) can help to keep the teams up-to-date with the latest security standards, frameworks, and attack trends (Attah, Ogunsola & Garba, 2022, Babatunde, Okeleke & Ijomah, 2022). Additionally, it's essential to encourage a culture of continuous improvement in security practices, where the lessons learned from past incidents are shared and improvements are made based on evolving threats.

Governance and policy templates are also key components of implementing a secure CI/CD pipeline, especially in hybrid environments where security requirements must be consistently applied across a combination of cloud and on-premises infrastructure. Governance frameworks for hybrid CI/CD pipelines should define clear security policies, procedures, and guidelines for managing the entire pipeline, from code inception to production deployment. Policies should cover access control, data protection, incident response, and the enforcement of security best practices across both cloud and on-premises resources (Abimbade, *et al*., 2022, Aremu, *et al*., 2022, Oludare, Adeyemi & Otokiti, 2022). Templates for security policies and governance frameworks should be readily available and customizable to fit the needs of different organizations. These templates help streamline the process of establishing security controls, making it easier for DevOps teams to align with organizational and regulatory security standards.

Governance templates should be integrated into the CI/CD pipeline to ensure that security and compliance checks are automated. For example, security controls like identity management, encryption, and data retention policies can be defined within the governance framework and enforced automatically at each stage of the pipeline. Policy-as-code tools, such as Open Policy Agent (OPA) and HashiCorp Sentinel, can be used to codify these policies and ensure they are consistently applied to the pipeline (Adewumi, *et al*., 2024, Chukwurah, *et al*., 2024, Ikese, *et al*., 2024). This enables teams to automate compliance reporting and audits, reducing the administrative burden of manually checking for compliance and improving the overall security posture of the pipeline.

Furthermore, a governance framework should include incident response plans, specifying the actions to be taken in the event of a security breach or vulnerability being discovered. These plans should define escalation processes, the roles and responsibilities of security and DevOps teams, and recovery procedures for rolling back vulnerable builds or artifacts. Having predefined, automated incident response procedures integrated into the pipeline ensures that the team can quickly contain and mitigate security threats, reducing the risk of exposure or further compromise (Adelana, Akinyemi & Oladimeji, 2024, Ige, *et al*., 2024, Olufemi-Phillips, *et al*., 2024).

In conclusion, implementing a secure CI/CD pipeline in hybrid application deployments requires a combination of thoughtful design, the right tools, continuous education, and strong governance. Secure pipeline design patterns must be implemented to automate security controls, while a balanced mix of open-source and commercial security tools must be chosen to address specific needs. Training and ongoing education are essential to embed security into the culture of DevOps teams, while governance frameworks and policy templates ensure that security measures are consistently applied across hybrid environments (Adebayo, Ajayi & Chukwurah, 2024, Olulaja, Afolabi & Ajayi, 2024, Ugbaja, *et al*., 2024). By following these best practices, organizations can create CI/CD pipelines that are not only efficient and scalable but also resilient against emerging threats, ensuring the continuous delivery of secure software across diverse infrastructures.

### 2.6 Case Studies and Common Threat Scenarios

In real-world scenarios, CI/CD pipeline breaches have become increasingly common, often resulting in significant data loss, business disruption, and reputational damage. These breaches are particularly damaging in hybrid application deployments, where the combination of on-premises and cloud infrastructures introduces complex challenges in managing security consistently across multiple environments. One of the most notable examples of a CI/CD pipeline breach occurred in 2020 when attackers targeted the popular software repository service, Codecov (Adedoja, *et al*., 2017, Aremu, *et al*., 2018, Otokiti, 2012). The attackers exploited a vulnerability in the company's CI/CD pipeline, allowing them to gain access to sensitive environment variables and credentials used in its code testing processes. This breach resulted in the exposure of API keys and other secrets, which were then used to access internal company data and customer environments. The attackers were able to inject a malicious script into the CI/CD pipeline, which was executed on the company's systems and spread to its clients. This case highlights the significant risk posed by insecure secrets management within the CI/CD pipeline, particularly when sensitive keys or tokens are improperly handled or stored.

Another significant breach occurred in 2018, involving the CI/CD pipeline of a widely used cryptocurrency exchange platform. In this incident, attackers exploited weak security practices in the company's code deployment process to insert a backdoor into the application. The attackers had gained access to the CI/CD environment, likely through social engineering or phishing techniques aimed at the development team. Once inside, they were able to alter the deployment artifacts, effectively bypassing code review and security testing stages (Akinyemi & Aremu, 2017, Famaye, Akinyemi & Aremu, 2020, Otokiti-Ilori, 2018). This breach underscores the risks associated with a lack of secure code management and the need for comprehensive automated security testing within the CI/CD pipeline, ensuring that only verified, trusted code is deployed to production environments.

The framework proposed for securing CI/CD pipelines in hybrid application deployments directly addresses the types of vulnerabilities illustrated in these case studies. By integrating secure source code management practices, automated vulnerability scanning, and dynamic secrets

management, the framework offers a proactive approach to mitigating the risks of unauthorized access to sensitive data and malicious code injection. Secure source code management involves not only controlling access to repositories but also incorporating automated tools that analyze commits for potential security flaws (Afolabi, Ajayi & Olulaja, 2024, Folorunso, *et al*., 2024, Olufemi-Phillips, *et al*., 2024). By embedding security testing into the build and deployment phases, vulnerabilities can be detected early, minimizing the risk of flawed or malicious code making its way into production. Additionally, the framework ensures that dynamic secrets management tools are integrated into the pipeline, reducing the likelihood of sensitive information being exposed or misused. This level of control and automation makes it significantly harder for attackers to gain unauthorized access or inject malicious code into the pipeline undetected.

In hybrid deployments, the integration of on-premises and cloud infrastructure creates unique security challenges. The fluid nature of hybrid environments means that applications, data, and services often move between multiple cloud providers and on-premises systems, each with its own security controls, access policies, and network boundaries. One common threat scenario in these environments is the compromise of insecure APIs or misconfigured cloud environments (Nwaimo, *et al*., 2023, Odunaiya, Soyombo & Ogunsola, 2023, Oludare, *et al*., 2023). For instance, a common vulnerability occurs when cloud-native services such as APIs or container registries are configured to have overly permissive access rights, allowing attackers to move laterally across environments. Attackers can exploit these misconfigurations to access sensitive data or inject malicious code into the CI/CD pipeline, compromising the entire deployment lifecycle. This type of vulnerability is often exacerbated by inconsistent security practices between environments and the lack of centralized security management.

The proposed framework mitigates these specific hybrid deployment threats by enforcing strict access controls, continuous monitoring, and automated security checks across all environments. By using identity federation and role-based access control (RBAC) mechanisms, the framework ensures that users and services are granted only the necessary permissions to access specific resources. Additionally, the integration of environment-agnostic security policies ensures that security requirements are uniformly applied, regardless of whether the deployment occurs in a public cloud, a private cloud, or on-premises infrastructure (Ajonbadi, Otokiti & Adebayo, 2016, Otokiti & Akorede, 2018). Continuous monitoring tools that track and alert on abnormal activities, such as unauthorized access attempts or misconfigurations, play a crucial role in identifying potential threats in real-time. Automated security scanning tools also provide an additional layer of protection by continuously scanning code, containers, and infrastructure for vulnerabilities, ensuring that the pipeline remains secure throughout the development lifecycle.

Lessons learned from both successful and failed security implementations in CI/CD pipelines offer valuable insights into best practices for protecting hybrid application deployments. One of the key takeaways from successful implementations is the importance of adopting a "shift-left" approach to security, where security is integrated early into the software development lifecycle rather than tacked on as a final step (Abimbade, *et al*., 2023, Ijomah, Okeleke & Babatunde, 2023, Otokiti, 2023). Successful organizations that have implemented CI/CD security frameworks have prioritized early-stage security testing and continuously assessed the security posture of their pipelines, reducing the likelihood of vulnerabilities being introduced later in the process. Automated code analysis, container security scanning, and continuous integration of security policies have become critical tools for identifying and addressing vulnerabilities before they make it to production.

Another lesson learned is the significance of comprehensive threat modeling and proactive risk management. Successful implementations often include threat modeling as an integral part of the CI/CD pipeline, allowing teams to anticipate potential risks and design security controls accordingly. By identifying and mitigating security risks early, organizations can prevent costly breaches and minimize the potential impact of security incidents (Addy, *et al*., 2024, Babatunde, Okeleke & Ijomah, 2024, Nwaozomudoh, *et al*., 2024). Furthermore, continuous risk assessment, facilitated by real-time vulnerability scanning and auditing, allows organizations to adapt their security measures as new threats emerge, ensuring that their CI/CD pipelines remain resilient to evolving attack techniques.

On the other hand, lessons from failed security implementations often highlight the consequences of neglecting key security practices. One common mistake is the failure to implement sufficient security controls around secret management and access controls. In several high-profile breaches, compromised credentials or poorly managed access keys were the entry points for attackers, allowing them to gain unauthorized access to CI/CD pipelines and infrastructure. Failing to enforce least-privilege access, not encrypting sensitive data, or neglecting to rotate secrets regularly leaves pipelines vulnerable to exploitation (Akinyemi & Ebimomi, 2020, Onesi-Ozigagun, *et al*., 2024, Oyewole, *et al*., 2024). Furthermore, a lack of proper monitoring and auditing can allow attackers to remain undetected for long periods, exacerbating the impact of the breach.

In addition to secret management, another lesson from failed implementations is the lack of integration between security tools and the CI/CD pipeline itself. Many organizations continue to rely on manual security checks, which are slow, inconsistent, and prone to human error. The absence of automated security testing, real-time vulnerability scanning, and continuous monitoring significantly increases the risk of vulnerabilities going unnoticed and undetected in the pipeline (Akinyemi & Makinde, 2024, Chukwurah, Adebayo & Ajayi, 2024, Olufemi-Phillips, *et al*., 2024). Successful implementations prioritize automation, integrating security tools seamlessly into the CI/CD pipeline to ensure that security checks are applied consistently at every stage of the development lifecycle.

The concept of supply chain security is another area where lessons have been learned. The risk of supply chain attacks has become more prominent as CI/CD pipelines rely heavily on third-party libraries, APIs, and services. A failure to properly vet and secure these dependencies can lead to malicious code being introduced into the pipeline, as was the case with the SolarWinds breach in 2020. Organizations must take a proactive approach to managing third-party dependencies, using automated dependency scanning tools to identify vulnerabilities in open-source libraries and

commercial software (Adewumi, *et al*., 2024, Balogun, Akinyemi & Aremu, 2024, Ogunsola, *et al*., 2024). Securely managing dependencies within the CI/CD pipeline, along with implementing checks for known vulnerabilities, is essential to preventing supply chain attacks from reaching production.

In conclusion, real-world breaches and threat scenarios underscore the need for a comprehensive and adaptive security framework for CI/CD pipelines, particularly in hybrid environments. The proposed framework mitigates specific threats through a combination of secure code management, dynamic secrets management, automated security testing, and continuous monitoring. Lessons learned from both successful and failed security implementations highlight the importance of integrating security into the development lifecycle, prioritizing proactive risk management, and automating security controls (Austin-Gabriel, *et al*., 2024, Omowole, *et al*., 2024, Shittu, *et al*., 2024). By following these best practices and continuously refining security measures, organizations can significantly reduce the risks associated with CI/CD pipelines and protect their hybrid applications from evolving threats.

### 2.7 Future Research Directions

As the landscape of hybrid application deployments continues to evolve, securing CI/CD pipelines becomes an increasingly complex challenge. The growing adoption of hybrid infrastructures, which span on-premises systems and cloud environments, introduces new vulnerabilities and risk vectors. To address these challenges, future research directions must focus on integrating cutting-edge technologies like artificial intelligence (AI) and machine learning (ML), enhancing threat intelligence capabilities, and adapting compliance standards to the unique needs of hybrid CI/CD pipelines (Adetunmbi & Owolabi, 2021, Arotiba, Akinyemi & Aremu, 2021). These research avenues promise to transform how organizations secure their software development lifecycles, making the process more efficient, proactive, and resilient to modern threats.

One of the most promising areas of research for enhancing CI/CD pipeline security is the integration of AI and machine learning for predictive pipeline security. As the volume and sophistication of cyber threats continue to grow, traditional security measures—often reactive and manual—are no longer sufficient. Predictive security powered by AI and ML has the potential to revolutionize threat detection in CI/CD pipelines by identifying potential vulnerabilities and attack patterns before they manifest into full-fledged incidents (Abimbade, *et al*., 2023, George, Dosumu & Makata, 2023, Lawal, *et al*., 2023). Machine learning models, trained on historical data, can analyze past security events and use this information to predict future risks, providing early warnings about potential breaches or misconfigurations. For instance, AI models could monitor code commits, build processes, and deployment configurations, learning to detect subtle patterns of behavior that indicate emerging threats, such as abnormal API usage or unauthorized access attempts. The incorporation of predictive security tools would significantly improve the security posture of CI/CD pipelines by enabling teams to act on potential risks before they materialize into damaging attacks, thus shifting security from a reactive to a proactive approach.

Moreover, predictive security can help streamline the process of managing vulnerabilities by automating the identification and prioritization of potential threats. As the volume of code changes and infrastructure updates increases, manual vulnerability management becomes increasingly unfeasible. AI-driven tools can automatically categorize vulnerabilities based on their severity, potential impact, and likelihood of exploitation, allowing security teams to focus on addressing the most pressing issues (Akinbola & Otokiti, 2012, Onesi-Ozigagun, *et al*., 2024, Udo, *et al*., 2024). This dynamic and data-driven approach to vulnerability management would not only increase efficiency but also reduce the likelihood of security flaws being overlooked, ensuring that the CI/CD pipeline remains secure throughout the software development lifecycle.

Advanced threat intelligence is another critical research area that has the potential to significantly enhance the security of hybrid DevSecOps environments. Hybrid architectures, which blend on-premises and cloud-based systems, present a complex and dynamic threat landscape that requires sophisticated threat intelligence strategies. While traditional threat intelligence models focus primarily on perimeter security, the evolving nature of hybrid environments necessitates a more integrated, continuous, and context-aware approach (Nwaimo, Adewumi & Ajiga, 2022, Olufemi-Phillips, *et al*., 2024, Onesi-Ozigagun, *et al*., 2024). Future research should explore the integration of real-time threat intelligence into hybrid DevSecOps workflows to provide a comprehensive view of the threat landscape, spanning both cloud and on-premises systems. By incorporating threat feeds and actionable intelligence into CI/CD pipelines, organizations can better understand the evolving tactics and techniques of attackers, enabling them to adapt their defenses accordingly.

In a hybrid environment, the need for real-time, context-aware threat intelligence is critical. As software moves between different environments, each with its own unique set of security controls and vulnerabilities, threat intelligence must be able to adapt to these changing conditions. Research could explore how threat intelligence platforms can be integrated with hybrid cloud and on-premises environments to provide a unified view of security risks across all systems (Akinyemi & Odesanmi, 2024, Ige, *et al*., 2024, Ike, *et al*., 2024). This research could focus on creating automated mechanisms that detect and respond to specific threats in real-time, such as intrusions within cloud service providers or malicious activities on local networks. Additionally, by combining threat intelligence with machine learning algorithms, organizations could create adaptive security systems that dynamically adjust security measures based on emerging threats and evolving attack tactics.

Another important research area in the future of CI/CD pipeline security is the development of evolving standards for hybrid CI/CD security compliance. As more organizations migrate to hybrid architectures, the existing regulatory frameworks and compliance standards—designed primarily for more traditional IT infrastructures—are often insufficient to address the complexities of securing CI/CD pipelines in multi-cloud and on-premises environments (Adelana & Akinyemi, 2021, Esiri, 2021, Odunaiya, Soyombo & Ogunsola, 2021). Future research should focus on the development of new, hybrid-specific compliance standards that take into account the unique security challenges presented by these environments. These standards should provide clear guidelines for securing hybrid CI/CD pipelines while ensuring that organizations can still meet industry-

specific regulatory requirements, such as GDPR, HIPAA, and PCI DSS.

One of the key challenges in securing hybrid CI/CD pipelines is maintaining consistent compliance across different environments, each with its own set of security models and regulatory requirements. Research should explore ways to automate compliance checks and audits across multi-cloud and on-premises systems, integrating compliance monitoring directly into the CI/CD pipeline. This would enable organizations to continuously validate that their pipelines are compliant with relevant security policies and regulatory standards (Akinyemi & Ebimomi, 2021, Chukwuma-Eke, Ogunsola & Isibor, 2021). For example, automated tools could scan code, infrastructure, and deployment artifacts for compliance with security standards before they are deployed to production. Such automation would significantly reduce the manual effort involved in compliance checks, streamline audit processes, and improve the overall security of the pipeline.

As hybrid CI/CD environments become more complex, maintaining compliance across different environments can become increasingly difficult. Future research should explore how cloud service providers, on-premises systems, and third-party vendors can work together to establish common compliance frameworks that are adaptable to the unique needs of hybrid deployments. This may involve the development of standardized security controls that can be universally applied across hybrid architectures, enabling organizations to enforce consistent compliance measures regardless of the underlying infrastructure (Adepoju, *et al*., 2021, Ajibola & Olanipekun, 2019, Hussain, *et al*., 2021). Research in this area could also focus on creating frameworks for cross-platform auditing, which would allow organizations to track compliance across both cloud and on-premises resources, ensuring that security practices are consistent and up-to-date across the entire pipeline.

In addition to these key research areas, there is also a need to explore the broader implications of securing CI/CD pipelines in hybrid environments, particularly in the context of evolving attack techniques and new technologies. As organizations continue to rely on containerized applications, serverless computing, and microservices architectures, new security challenges will arise that require innovative solutions. For example, securing serverless functions—where traditional network-based security controls do not apply—poses a significant challenge that requires new strategies for runtime security and access control (Afolabi, Ajayi & Olulaja, 2024, Eyo-Udo, *et al*., 2024, Ogunsola, *et al*., 2024). Research could explore how hybrid CI/CD pipelines can securely manage serverless workloads and integrate security measures that are appropriate for this rapidly growing deployment model.

Moreover, as more organizations adopt cloud-native technologies such as Kubernetes and Docker, research should investigate how to secure containerized applications within hybrid CI/CD pipelines. This includes the development of security measures for container registries, image scanning, runtime protection, and secure service-to-service communication within containerized environments. As containerized environments are deployed across both cloud and on-premises resources, maintaining consistent security controls across all layers of the hybrid pipeline will be crucial (Akinyemi & Ogundipe, 2022, Ezekiel & Akinyemi, 2022, Tella & Akinyemi, 2022).

Finally, future research should consider the increasing role of automated, AI-driven security tools in the continuous monitoring of hybrid CI/CD pipelines. As attacks become more sophisticated and harder to detect, security monitoring must evolve to become more adaptive, context-aware, and automated. AI-driven tools that can analyze vast amounts of security data from across hybrid environments in real time will play an essential role in detecting emerging threats, predicting potential risks, and automatically responding to incidents as they occur (Adeniran, *et al*., 2022, Aniebonam, *et al*., 2022, Otokiti & Onalaja, 2022). Research into these automated security monitoring systems could lead to the development of intelligent, self-healing pipelines that can adapt to new threats and vulnerabilities without requiring constant manual intervention.

In conclusion, the future of CI/CD pipeline security in hybrid application deployments lies in the integration of AI and machine learning for predictive security, advanced threat intelligence for hybrid DevSecOps, and the development of evolving compliance standards tailored to hybrid architectures. By focusing on these research areas, organizations will be better equipped to navigate the complexities of securing hybrid environments, ensuring that their CI/CD pipelines remain resilient against emerging threats and compliant with evolving regulatory requirements (Akinbola, *et al*., 2020, Akinyemi & Aremu, 2016, Ogundare, Akinyemi & Aremu, 2021). The result will be more secure, scalable, and agile software delivery pipelines that can meet the demands of the modern digital landscape.

## 3. Conclusion

Securing CI/CD pipelines is a critical aspect of maintaining the integrity and resilience of modern software development, especially in the context of hybrid application deployments. As organizations continue to embrace hybrid architectures, which span on-premises infrastructure, private clouds, and public cloud environments, the complexity of managing secure pipelines grows exponentially. The dynamic nature of hybrid environments, coupled with the need to support rapid deployment cycles, makes it essential to implement robust, adaptive security controls that address the unique risks and challenges posed by these distributed infrastructures. Without a comprehensive security strategy in place, organizations risk exposing sensitive data, compromising application integrity, and jeopardizing the trust of their customers.

The proposed framework for securing CI/CD pipelines in hybrid application deployments offers a holistic, integrated approach that addresses the various security challenges inherent in hybrid environments. By embedding security into every stage of the CI/CD pipeline—from source code management to deployment and monitoring—this framework ensures that security is not an afterthought but an intrinsic part of the software delivery process. It emphasizes the use of policy-driven automation, predictive security powered by AI and machine learning, and the integration of real-time threat intelligence to proactively identify and mitigate risks before they escalate into critical vulnerabilities. Additionally, the framework's emphasis on secure secrets management, container security, continuous compliance, and immutable builds ensures that security is maintained consistently across both cloud and on-premises environments, providing organizations with the agility they need to innovate without sacrificing security.

The benefits of implementing this framework are far-reaching. It enhances the overall security posture of CI/CD pipelines, reducing the likelihood of breaches and vulnerabilities that could lead to significant financial and reputational damage. By automating security testing and integrating real-time monitoring, the framework also improves the efficiency and speed of software delivery, ensuring that security does not hinder development cycles but rather supports them. Furthermore, the framework's focus on continuous compliance helps organizations meet regulatory requirements more easily, reducing the complexity of audits and ensuring that hybrid deployments remain secure and compliant in a rapidly changing regulatory landscape.

In conclusion, as hybrid application deployments become the standard, securing CI/CD pipelines must be treated as a top priority for organizations seeking to maintain operational integrity and trust. The proposed framework offers a comprehensive solution that not only addresses the security challenges specific to hybrid environments but also equips organizations with the tools and strategies necessary to navigate an increasingly complex and dynamic threat landscape. By adopting this framework, organizations can build secure, resilient hybrid deployments that support both innovation and security, ensuring long-term success in the digital economy. As the cybersecurity landscape continues to evolve, it is critical that organizations stay ahead of emerging threats by continuously refining their security strategies, embracing new technologies, and fostering a culture of security across their teams.

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