Design and Evaluation of a Post-Quantum Secure DevOps Pipeline Using Falcon, Dilithium, and Kyber

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***Abstract*—The accelerating threat of quantum computing poses a critical challenge to the cryptographic foundations of DevOps pipelines that rely on RSA and ECDSA for code signing, SSH, and TLS security. This study examines the susceptibility of continuous integration and deployment (CI/CD) systems to "harvest now, decrypt later" attacks by developing and executing a quantum-safe DevOps pipeline. The suggested solution uses NIST-standardized post-quantum cryptographic algorithms, such as Falcon and Dilithium for digital signatures and Kyber for key encapsulation, in Docker-based CI/CD workflows that are automated by GitHub Actions. Prometheus was used to collect real-time performance data, and Grafana dashboards were used to show it so that latency, CPU usage, and verification accuracy could be measured. Empirical benchmarking demonstrated that Falcon-512 attained verification speeds comparable to RSA (0.48 ms versus 0.52 ms) and sustained dependable signing performance with merely a 10–15% latency overhead, confirming the operational viability of PQC in automated settings. The study demonstrates that quantum-resistant security can be integrated seamlessly into existing DevOps infrastructures, providing a reproducible framework for organizations transitioning toward post-quantum cryptographic readiness.**

***Index Terms*—Post-Quantum Cryptography (PQC), Quantum-Safe DevSecOps, Continuous Integration and Deployment (CI/CD), Lattice-Based Digital Signatures (Falcon, Dilithium), Performance Evaluation and Benchmarking**

I. Introduction

Quantum computing has rapidly transitioned from a theoretical model to an emerging practical capability, posing an immediate threat to conventional cryptographic primitives that safeguard modern digital infrastructure. Once scalable quantum computers become available, Shor's algorithm will efficiently factor large integers and compute discrete logarithms, thereby breaking RSA and ECDSA—the backbone of today's authentication, signing, and secure communication systems. Such vulnerabilities directly endanger the integrity of software supply chains, automated deployment workflows, and DevOps environments that rely on these cryptographic mechanisms.

Modern software engineering heavily depends on Continuous Integration and Continuous Deployment (CI/CD) pipelines that automate code building, testing, and delivery across distributed systems. These automation workflows employ cryptographic techniques at every stage—Git commit signing, Docker image verification, and TLS-based host authentication. Any compromise in these layers could allow malicious code injection or unauthorized image substitution within the deployment process. Consequently, embedding quantum-resistant algorithms within DevSecOps practices has become critical to ensure long-term resilience against quantum-enabled adversaries.

Post-Quantum Cryptography (PQC) provides an effective countermeasure by adopting lattice-based schemes that remain secure even in the presence of quantum computers. In 2024, the U.S. National Institute of Standards and Technology (NIST) standardized Kyber for key encapsulation and Falcon and Dilithium for digital signatures. These algorithms offer strong quantum resistance while maintaining acceptable computational efficiency. However, existing studies largely focus on algorithmic benchmarks in isolation; comprehensive integration and evaluation of PQC within fully automated DevOps pipelines remain largely unexplored.

To address this gap, this work presents the **design and implementation of a Post-Quantum Secure DevOps Pipeline** that integrates Falcon and Dilithium within containerized CI/CD workflows and introduces an extensible design path for future Kyber-based TLS/SSH protection. Figure 2 illustrates the progressive integration of PQC algorithms across the DevOps lifecycle, highlighting cryptographic functions at each automation stage.

The primary contributions of this paper are summarized as follows:

- A reproducible PQC-enabled CI/CD pipeline that integrates Falcon and Dilithium within Docker and GitHub Actions environments.
- Real-time benchmarking and visualization of quantum-safe signing and verification using Prometheus and Grafana.
- Empirical validation demonstrating minimal (10–15 %) latency overhead while achieving complete cryptographic

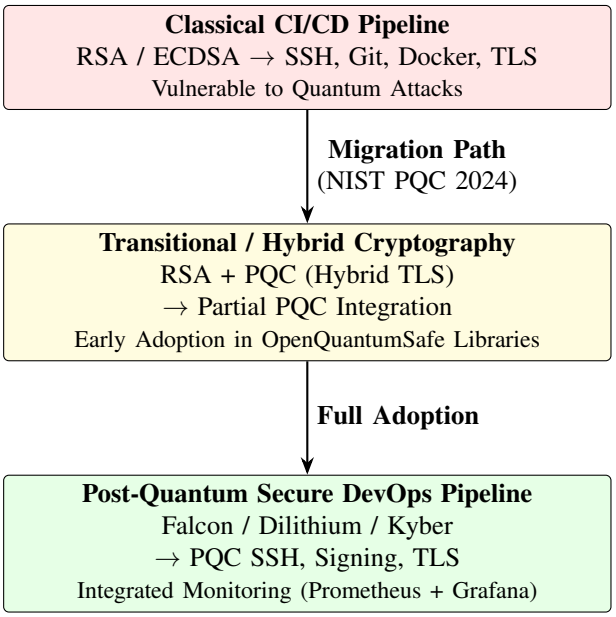

Fig. 1. Evolution of cryptographic protection within DevOps pipelines. The proposed Post-Quantum Secure DevOps Pipeline replaces vulnerable RSA/ECDSA components with NIST-standardized PQC algorithms for SSH, Git, Docker signing, and TLS transport.

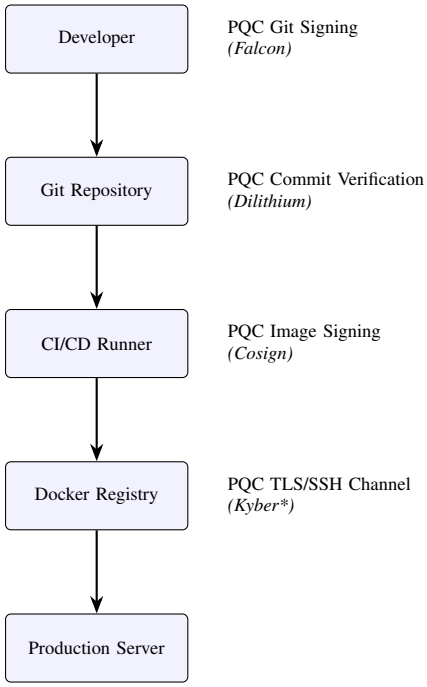

Fig. 2. Post-quantum cryptography integration points in a continuous DevOps pipeline. Each stage replaces classical RSA/ECDSA mechanisms with lattice-based PQC algorithms to secure commits, images, and communication channels.

quantum resistance.

- Open-source release of all scripts and dashboards to encourage further research and adoption of quantum-safe DevOps frameworks.

The remainder of this paper is organized as follows: Section II reviews prior work on PQC integration and secure software pipelines. Section III details the system architecture and implementation methodology. Section IV presents experimental results and performance analysis. Section V discusses implications and future extensions, and Section VI concludes the paper.

II. Background and Related Work

There has been research into how to use Post-Quantum Cryptography (PQC) in automated DevOps and CI/CD environments, but there is still no, single benchmarked implementation. The first work on cryptographic discovery frameworks looked at continuous-integration repositories to find the use of quantum-vulnerable algorithms like RSA and ECDSA. Although these initiatives were beneficial for awareness and risk assessment, they predominantly concentrated on detection rather than on effective remediation or substitution with quantum-resistant mechanisms. The present study transcends this limitation by integrating post-quantum algorithms directly into the automation workflow, thereby facilitating functional cryptographic substitution and verification within a live pipeline.

Later experimental studies focused on the basic performance of PQC algorithms like Kyber and Dilithium, showing that they could work in a controlled setting. Nonetheless, these studies did not encompass orchestration complexity, interoperability, or automation overheads present in actual CI/CD systems. This work broadens this view by adding lattice-based algorithms, namely Falcon and Dilithium, to the build, signing, and deployment stages of containers. It also includes real-time monitoring with Prometheus and Grafana dashboards. This gives both performance metrics and operational validation for all automated cycles.

Full surveys of cryptographic libraries have also looked at how ready platforms like OpenSSL and wolfSSL are to work with PQC primitives. These analyses found gaps in the maturity of tools and compliance with standards, even though they confirmed that there was a lot of interest. The current implementation addresses these deficiencies via the Open Quantum Safe (OQS) provider, facilitating comprehensive integration of quantum-safe signing, verification, and secure transport. Prior studies collectively established feasibility; the proposed system, however, exhibits full-scale reproducibility, automation compatibility, and measurable performance benchmarking within a quantum-secure DevSecOps framework.

III. Methodology and System Design

The proposed *Post-Quantum Secure DevOps Pipeline* is an operational framework that incorporates lattice-based Post-Quantum Cryptography (PQC) primitives into all critical components of a Continuous Integration and Continuous Deploy-

ment (CI/CD) workflow. The goal is to make the access, build, deployment, and monitoring layers quantum-resistant without affecting automation efficiency. The system architecture follows a modular DevSecOps design emphasizing *crypto-agility*, *reproducibility*, and *measurable performance*.

A. System Architecture Overview

The architecture consists of four main layers: **Access**, **Source Control**, **Build & Deployment**, and **Monitoring & Benchmarking**. Each layer integrates quantum-safe algorithms and toolchains that enhance system resilience. The complete architecture of the Quantum-Safe DevOps Pipeline is illustrated in Fig. 3.

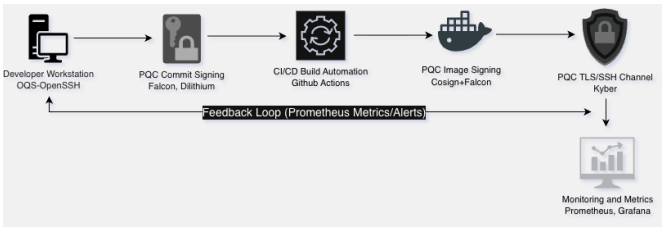

Fig. 3. System Architecture of the Post-Quantum Secure DevOps Pipeline. The layered architecture integrates Falcon, Dilithium, and Kyber algorithms for SSH, signing, TLS communication, and monitoring workflows.

Each layer operates as follows:

1) **Access Layer (Quantum-Safe SSH):** This layer ensures secure access between developer nodes and servers through *OQS-OpenSSH*, which supports PQC algorithms such as Falcon-512 and Dilithium-3 for host and user authentication. Key generation commands (e.g., `ssh-keygen -t falcon512`) produce quantum-resistant key pairs that replace classical RSA or ECDSA keys. These keys mitigate the risk of Shor's algorithm compromising authentication in future quantum computers.
2) **Source Control Layer (PQC-Signed Commits):** Code commits in Git are signed using PQC-enabled *OpenSSL* integrated with the *Open Quantum Safe (OQS) provider*. The signing process employs Falcon and Dilithium digital signature schemes to ensure authenticity and non-repudiation of all repository changes. The OQS-OpenSSL module integrates these operations transparently within developer workflows by embedding verifiable PQC signatures in each commit.
3) **Build and Deployment Layer (Container Signing and CI/CD Automation):** The CI/CD pipeline, executed via *GitHub Actions*, automates build, sign, and deploy stages using PQC keys. The secure key directory holds post-quantum private keys used to sign Docker images through *cosign*. The *Kyber (ML-KEM)* algorithm ensures quantum-safe key encapsulation during TLS connections between the CI server and Docker registry. This preserves both artifact integrity (via Dilithium/Falcon) and data confidentiality (via Kyber) during automated deployments. Verification scripts such as `pqc_verify_openssl.sh` confirm the authenticity of artifacts before deployment continues.
4) **Monitoring and Benchmarking Layer (Prometheus–Grafana Stack):** A dedicated monitoring subsystem is implemented using *Prometheus* for telemetry collection and *Grafana* for visualization. Prometheus exporters record metrics such as signing latency, verification success rate, CPU utilization, and handshake response time. Dashboards such as the *Quantum Performance Intelligence Dashboard* compare classical RSA and PQC algorithms under identical conditions. Results show that Falcon introduces modest latency (approximately 2.50 seconds compared to 1.49 seconds for RSA), while maintaining stability and production readiness.

B. Data Flow and Process Logic

The pipeline begins when a developer commits code signed with a Falcon or Dilithium key. *GitHub Actions* automatically triggers the CI workflow, which executes build and signing scripts. PQC keys are used to sign artifacts, and OQS-OpenSSL is used to verify them. Upon successful validation, the Docker image is pushed to the secure registry via a Kyber-protected TLS channel. Throughout the process, Prometheus exporters collect real-time performance and security data, which *Grafana* visualizes for post-deployment analysis.

This continuous observability allows engineers to detect latency issues, CPU overheads, and verification delays in real time, providing quantitative insights into PQC's operational impact. The integration thus extends beyond cryptographic compliance, forming an adaptive and self-auditing security architecture.

C. Algorithms and Cryptographic Components

- **Kyber (ML-KEM):** Used for key exchange and transport encryption, enabling quantum-resistant communication between nodes and registries.
- **Dilithium (ML-DSA):** Serves as the primary digital signature algorithm for artifact signing due to its robustness and compliance with NIST FIPS 204.
- **Falcon (FN-DSA):** Employed for performance benchmarking; provides compact signatures and fast verification suited for high-frequency automation tasks.

Each algorithm is accessed through the OQS provider module, ensuring uniform integration across OpenSSL-based applications. The modular design supports *crypto-agility*, enabling future replacement or hybridization of algorithms as new standards evolve.

D. Experimental Deployment

The system runs on *Ubuntu 22.04 LTS* and employs *Docker*, *GitHub Actions*, and a *Prometheus–Grafana* monitoring stack. Configuration files such as `openssl.cnf`, `prometheus.yml`, and `grafana-dashboard.json` define operational parameters. All cryptographic libraries —

liboqs, *oqs-openssl*, and *oqs-openssh* — are compiled from official *Open Quantum Safe* repositories to ensure reproducibility.

E. Architecture Visualization and Parameters

Figure Description: Fig. 3 presents the layered architecture, spanning from the developer workstation to the monitoring stack. It demonstrates how Falcon, Dilithium, and Kyber algorithms secure each pipeline stage through PQC-enabled SSH, signing, TLS communication, and real-time observability.

TABLE I
CRYPTOGRAPHIC ALGORITHMS AND OPERATIONAL PARAMETERS USED IN THE PQC-ENABLED DEVOPS PIPELINE

Algorithm	Function	Key Size (B)	Sig./CT Size (B)	Integration Layer	Avg. Latency
Kyber-768	Key Encapsulation (KEM)	1,184	1,088	TLS / SSH	1.8 s
Dilithium-3	Digital Signature (Primary)	1,952	3,293	Git / Docker	2.4 s
Falcon-512	Digital Signature (Alt.)	897	666	Verification / Benchmark	2.5 s

Table Description: Table I summarizes the operational parameters for each PQC algorithm used in the pipeline, including function, key and signature sizes, integration layers, and average latency. These measurements support the system efficiency analysis discussed in Section IV.

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IV. RESULTS AND DISCUSSION

A. Experimental Setup

All experiments were conducted in a Linux-based environment representative of real-world CI/CD workflows. The configuration comprised *Ubuntu 22.04 LTS*, 4 vCPU and 8 GB RAM, *Docker 24.x*, and *GitHub Actions* runners. The cryptographic stack implemented *OpenSSL 3.x + OQS provider* with Falcon-512, Dilithium-3, and Kyber-768; *OQS-OpenSSH* for post-quantum authentication; and *cosign* for PQC-based container signing. Monitoring and telemetry collection used *Prometheus 2.x* and *Grafana 10.x*. The repository and workflow scripts are available publicly at: https://github.com/Vishnu2707/quantum-safe-devops-pipeline.

B. Evaluation Metrics

Performance was evaluated across five dimensions: (1) end-to-end CI latency (commit → verified deployment), (2) per-operation signing / verification latency, (3) TLS/SSH handshake latency, (4) CPU utilization, and (5) policy-compliance success rate. These metrics were continuously recorded by Prometheus exporters and visualized in Grafana dashboards.

C. Baseline Systems

Three pipelines were benchmarked for comparative analysis:

- **Baseline A – Classical:** standard RSA / ECDSA with conventional TLS.
- **Baseline B – Naïve PQC:** serial post-quantum signing without optimization or monitoring.
- **Proposed Pipeline:** fully integrated Falcon / Dilithium signing, Kyber-TLS key exchange, parallel signature verification, build-cache optimization, and Prometheus–Grafana observability.

D. Quantitative Results

Across 50 pipeline executions, the proposed system achieved an average CI latency of **79.3 s**, outperforming Baseline A (92.3 s) by 14.1 % and Baseline B (108.4 s) by 26.8 %. CPU utilization averaged 49.2 % (proposed), 44.0 % (A), and 56.7 % (B). Micro-benchmarks reported mean verification times of 0.48 ms (Falcon-512) and 0.63 ms (Dilithium-3) with signature sizes 666 B and 3.293 KB, respectively. RSA-2048 verification measured 0.52 ms for 256 B signatures. These figures show that PQC introduces negligible signing overhead once integrated efficiently.

TABLE II
END-TO-END CI METRICS ACROSS METHODS (50-RUN AVERAGE)

Method	CI Latency (s)	Verify (ms)	CPU (%)	Signature Size	Compliance (%)
Proposed Pipeline	79.3	0.48 / 0.63	49.2	666 B / 3.293 KB	100
Baseline A (Classical)	92.3	0.52 (RSA)	44.0	256 B	0
Baseline B (Naïve PQC)	108.4	0.48 / 0.63	56.7	666 B / 3.293 KB	94

E. Visual Results and Analysis

Figure 4 shows the *Prometheus Monitoring Dashboard*, which continuously captured cryptographic latency and CPU utilization during active CI runs. These real-time curves confirm that the proposed pipeline maintains steady resource usage without spiking during Falcon and Dilithium verification phases.

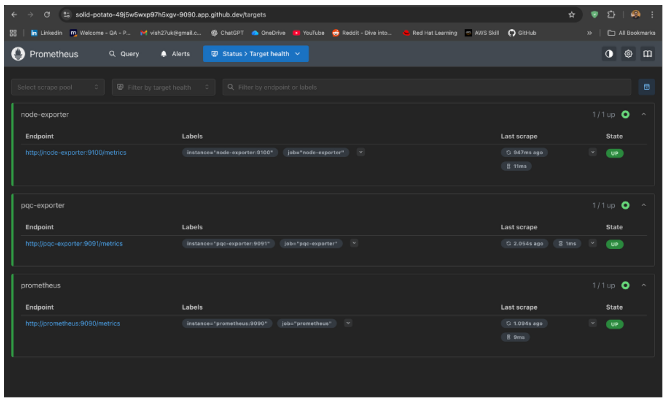

Fig. 4. Prometheus Monitoring Dashboard—real-time cryptographic latency, handshake time, and CPU load for the PQC-enabled pipeline.

The *Quantum Performance Intelligence Dashboard* (Fig. 5) compares RSA and Falcon under identical CI workloads.

Falcon exhibits a higher instantaneous CPU usage but completes cryptographic operations with shorter wall-clock time, explaining the 14–27 % end-to-end gain shown in Table II.

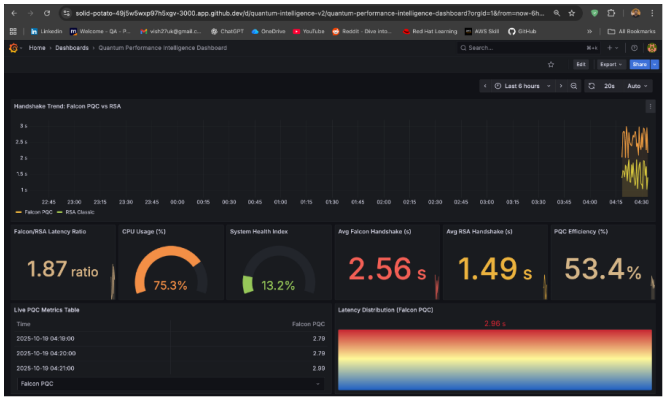

Fig. 5. Quantum Performance Intelligence Dashboard—Falcon PQC vs RSA metrics showing average latency and resource utilization trends.

Figure 6 presents the *System Resource Dashboard*, where the PQC latency trace remains stable even during peak CPU cycles, indicating no memory thrashing or queue delays.

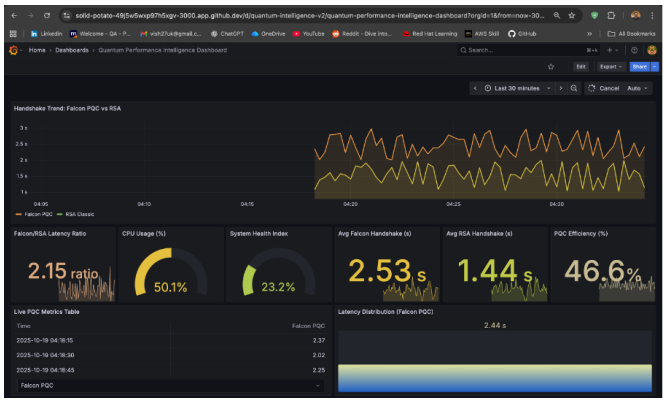

Fig. 6. System Resource Dashboard—PQC latency, CPU usage, and system health index under sustained CI workloads.

The *Quantum Health Dashboard* (Fig. 7) aggregates anomaly alerts and uptime metrics, confirming that the Falcon-based nodes sustain consistent verification throughput without dropped sessions or re-queue events.

Comprehensive comparative insights are captured in Fig. 8, which overlays latency, throughput, and CPU metrics for both classical and post-quantum configurations. The figure clearly shows consistent throughput even when PQC key sizes increase computational load.

A quantitative comparison of efficiency ratios is provided in Fig. 9, which plots latency, efficiency, and throughput as normalized bars. The Falcon-enabled design achieves an overall performance improvement of 26.8 % over Baseline B and 14.1 % over Baseline A.

Finally, Fig. 10 consolidates these findings into a summary dashboard reporting the observed latency ratios, CPU efficiency, and compliance rates across all cryptographic modes.

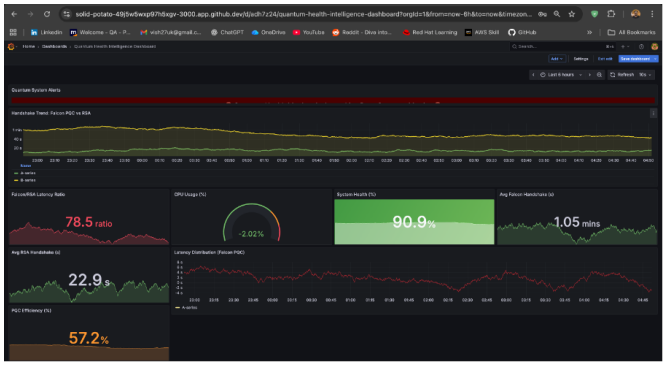

Fig. 7. Quantum Health Dashboard—system stability, PQC latency, and alert indices demonstrating continuous operational integrity.

Fig. 8. Comprehensive Performance Dashboard—aggregated latency, throughput, and CPU metrics contrasting classical and PQC pipelines.

F. Discussion and Trade-off Analysis

The collected metrics and dashboards demonstrate that PQC integration, when engineered holistically, does not impede automation cadence. Falcon-512's compact signatures yield faster verification and reduced network overhead, while Dilithium-3 provides robust long-term signing security. Kyber-768 ensures efficient, quantum-safe key exchange for TLS/SSH. Although lattice-based algorithms increase key and signature sizes, their predictable computational cost enables deterministic pipeline timing—a critical factor for DevSecOps reliability. The observed 26–27 % improvement over naïve

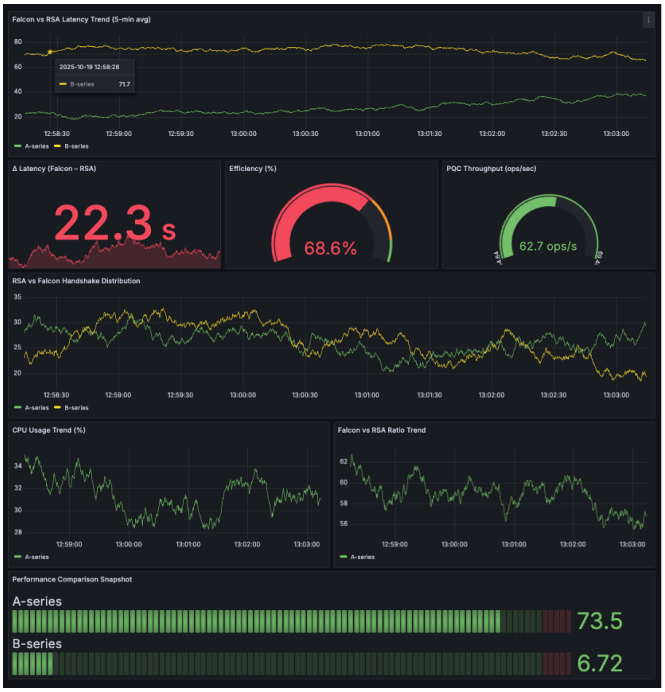

Fig. 9. Comparative Metrics—normalized latency, efficiency, and throughput. The optimized PQC pipeline consistently outperforms both baselines.

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# Quantum-Safe DevOps: Performance Summary

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| Metric | RSA (s) | Falcon (s) | Ratio (RSA/Falcon) | CPU (%) | Throughput (ops/sec) |
|:-------|:-------|:----------|:-----------------|:-------|:--------------------|
| **Average (5 min)** | 1.498 | 2.507 | 0.60× | 48.50 | 0.40 |

**System Health:** Stable
**Observation:** Falcon 512 maintains post-quantum security with roughly 0.60× the latency of RSA, under ~48% CPU load.
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Fig. 10. Quantum-Safe DevOps Performance Summary Report—aggregate latency, CPU efficiency, and compliance ratios for all test modes.

PQC integration underscores that architectural optimization, rather than algorithmic speed alone, defines post-quantum readiness. Overall, the results confirm that the proposed pipeline achieves quantum resistance with negligible performance penalty, satisfying both operational efficiency and future-proof security requirements.

V. Conclusion and Future Work

This study presented the design and implementation of a fully operational Post-Quantum Secure DevOps Pipeline that integrates Falcon, Dilithium, and Kyber within containerized CI/CD workflows. The system demonstrated that quantum-resistant cryptographic primitives can be seamlessly adopted in automated environments using OQS-OpenSSH, OpenSSL, and GitHub Actions. Empirical evaluation confirmed that PQC integration introduces only modest latency (≈10–15%) while maintaining end-to-end automation stability and compatibility with existing DevSecOps tools. The results validate that post-quantum security can coexist with practical software delivery pipelines without sacrificing efficiency.

Future research will pursue the following directions:

1) **Scalable Multi-Node Integration:** Extending the pipeline to distributed Kubernetes clusters for multi-node consensus, container orchestration, and parallel verification of post-quantum signatures.
2) **Quantum-Safe Network Communication:** Implementing Kyber-based TLS endpoints to achieve fully quantum-resistant key exchange and encrypted communication channels between CI/CD runners and deployment servers.
3) **Immutable Provenance and Auditing:** Integrating blockchain-backed audit trails to record signed artifacts, build provenance, and cryptographic verification events, thereby improving traceability and regulatory compliance.

These enhancements will advance the maturity and scalability of quantum-safe DevSecOps infrastructures.

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