# Cyber-Physical Systems Security Protecting Critical Infrastructure from Cyber Threats and Attacks

Narender Chinthamu[1], Shobana Jayakumar[2], Manasa K[3], Revathi M P[4], Syed Zahidur Rashid[5] and Jansirani D[6]

[1]CEO MahaaAi Group of Companies and International Labs, Dallas Texas, USA.
Narender.chinthamu@gmail.com
[2]Assistant Professor, Data science and Business Systems, School of Computing, SRM Institute of Science and Technology, Kattankulathur, Chennai , Tamilnadu,India, shobanaj1@srmist.edu.in
[3]Assistant Professor, Department of Computer Science and Engineering (CS), CVR College of Engineering, Hyderabad, India.
kmanasa44@gmail.com
[4]Professor, Department of CSE, J.J. College of Engineering and Technology, Tiruchirappalli, Tamil Nadu, India.
jjcetrevathi.cse@gmail.com
[5]Department of Electronic and Telecommunication Engineering, International Islamic University Chittagong, Chittagong, Bangladesh.
szrashidcce@yahoo.com
[6]Assistant Professor, Department of IT, New Prince Shri Bhavani College of Engineering and Technology Chennai, Tamil Nadu, India.
jansirani.d@newprinceshribhavani.com

**Abstract.** Cyber-Physical Systems (CPS) are vital of critical infrastructure such as energy, transportation, healthcare, and manufacturing. Increasingly, however, these systems are the target of sophisticated cyber threats, with dire economic and operational implications. The CPS security literature mainly covers theory models and technology-specific security and control measures, but known techniques have low implementation/efficiency/robustness. To address these gaps, in this paper we propose a generalizable, cost-effective, and AI-enabled adaptive security framework by coupling a real-time threat monitoring system with a blockchain-based security and machine learning-enabled intrusion detection model. Real-world attack scenarios, cost-benefit analysis and a supply-chain risk mitigation strategy contribute to improving resilience against ever-evolving cyber threats. The results showcase that the framework enhances cyber resilience, scalability, and adaptability in CPS environments, providing appropriate protection for critical infrastructure. The research provides a field in the making practical, scalable, and economically viable cybersecurity solution to achieve better preparedness for cyberattacks.

**Keywords**: Cyber-Physical Systems, Security of Critical Infrastructures, Cyber threats, Adaptive Cyber Defense, Security of Blockchain

## 1 Introduction

Cyber-Physical Systems (CPS) have emerged as a cornerstone for contemporary critical infrastructure, merging computational and physical process to promote effective and intelligent decision-making. In energy, health-care, transport, and manufacturing, for example, these systems are extensively used, where they will strengthen automation, improve efficiency, and allow instant monitoring. Nevertheless, the growing interconnectivity and dependence on digital technologies rendered CPS particularly susceptible to cyber threats. These cyberattacks can have powerful immediate consequences, leading to economic loss, operational disruptions, and in some cases even threats to human safety. Traditional cybersecurity solutions have become ineffective, and new, more advanced attack techniques have emerged from various adversaries against these systems.

Although there have been considerable research efforts into CPS security, several limitations remain. Most existing studies are theoretical and do not have implementation and validation in the real world. Some of them do offer domain-specific security architectures but these do not generalize to a wide variety of CPS settings, therefore lowering their scalability and flexibility. Additionally, many existing security practices heavily depend on legacy defensive models impervious to ever-changing threats, putting essential infrastructure at risk for zero-day breaches

and advanced persistent threats (APTs). Furthermore, supply-chain weaknesses in CPS also go unexamined, despite their increasing importance in recent cyber events.

This study provides an AI-driven adaptive cyber security framework that encompasses real-time threat detection, blockchain-based security mechanisms and supply-chain risk mitigation strategies to overcome these challenges. The approach calls for harnessing the power of data collected through machine learning for OCI to engineer anomaly detection (e.g., behavioral change) intrusion detection. It also aims to drive predictive threat intelligence, anomaly reporting, and ensure automated-reactionary subprocesses that balance SLAs of controls, business flows, and environments. This research contributes towards a robust scalable, cost-effective, and sector-agnostic CPS security solution by aligning theoretical models with practical implementation.

Thus, this paper shall fill a crucial void in existing literature on security and resilience of CPS and builds a holistic and pragmatic approach to secure critical infrastructure. This enables not only the improved detection and mitigation of cyber threats but also adaptation by the system to newly discovered pathways for attack. This paper aims to explore an intelligent couple with self-evolution architecture of environment awareness that could help defense CPS against advanced attack through real-world simulation and their analysis.

## 2 Problem Statement

Cyber-Physical Systems (CPS) assume many important roles in contemporary infrastructure — contributing to automation, real-time monitoring, and intelligent decision-making. But, the interconnectedness of digital technologies makes these systems vulnerable to an ever-evolving spectrum of sophisticated cyber threats. Recent cyberattacks on power grids, healthcare facilities, transportation networks, and industrial control systems illustrate the vulnerabilities of CPS as well as the serious consequences we face in the event of a security breach. These attacks may cause widespread disruption, economic loss, and even potential threats to human life.

In spite of continuous research efforts in CPS security, there are some limitations that hinder the preparation of an ideal defence policy. Traditional security systems use static, rule-based approaches that have become ineffective in the face of the fast-evolving landscape of cyber threats. These models are not applicable to a heterogeneous CPS setting due to their focus on specific sectors. Finally, the majority of research is either highly theoretical or lacks real world applications, creating a divide between academic breakthroughs and relevant cybersecurity innovation. Another pressing concern is the deficiency of robust supply-chain security mechanisms, which leaves CPS vulnerable to attacks targeting vulnerabilities in third-party software and hardware components.

Moreover, existing intrusion detection systems do not effectively detect zero-day attacks and advanced persistent threat (APT), which are continuously evolving to evade inspection. The glaring need of hour is a continuous monitoring and adaptive security framework that is capable of dynamically detecting, predicting and mitigating cyber threats with high accuracy. This will help to make CPS resilient through a solution that combines AI-powered detection of anomalies, security protocols based on blockchain technology, and automatically responding to threats.

Hence, the dilemma is a lack of a scalable, economical, and sophisticated cybersecurity infrastructure capable of shielding CPS against evolving cyber threats. To tackle this challenge, a multidisciplinary approach that integrates machine learning, blockchain security, and predictive threat intelligence will build a strong defense mechanism. We hope to bridge the gap between theoretical models and practical implementation by developing a generalizable security framework that mitigates risks created by cyber threats and intends to ensure the long-term security of critical infrastructure.

## 3 Literature Review

The study of Cyber-Physical Systems (CPS) security has received significant attention in recent years, and a multitude of techniques have been proposed to protect against potential cyber-attacks. Yet, in spite of all this, there are still glaring holes in the quest for security that is practical, scalable, and adaptive. Many other studies ([41,42,43,44,45,46,47,48,49]) have considered different aspects of CPS security including intrusion detection, blockchain integration, supply-chain risks and adaptive defense mechanisms.

### 3.1 Data has been prepared for analysis, visualisation of machine learning models.

While signature-based IDS solutions—widely adopted in traditional security—are effective against known attacks, they perform poorly against zero-day attacks and APTs. Müller et al. Karabiyik et al. (2022) carried out a survey of cyber-physical intrusion detection methods pointing out that most of the existing methods have limitations in detecting new cyber threats in industrial control systems. In similar manner, Segovia-Ferreira et al. For example, Aldarwand and Jain (2023) reviewed many cyber-resilience approaches and concluded that many proposed solutions are not dynamically adaptive, and therefore insufficient to counteract changing cyber threats. Proposed models include AI-based anomaly detectors, which still lack widespread use across real-world CPS deployments.

### 3.2 Cyber-Physical Systems Security and Data Integrity Using Blockchain

With its inherent properties of immutability, decentralization, transparency and security, blockchain has been recognized as a solution towards guaranteeing data integrity and security in CPS. Huang et al. Secure Critical Infrastructure with Blockchain11 — 2024 — This paper highlighted the potential of blockchain technology in securing critical infrastructure by creating tamper-proof logs for monitoring cyber threats. A significant limitation of their study, however, is the computational overhead of blockchain, which can degrade system performance. Sousa et al. (2024) introduced a honeynet-based method for identifying threats specific to CPS, however, their research is largely academic and lacks deployment in the real world.

### 3.3 The Problem of Supply-Chain Security for CPS

Supply-chain vulnerabilities — the kind that are critical yet often neglected within CPS security. Stockton (2020) looked into the risks of third-party software and hardware dependencies in CPS, which reflects a trend of attackers leveraging supply-chain weaknesses to insert malware or backdoors. The study concluded with recommendations but lacked a plan for implementation so that these risks could be mitigated. Stockton (2021) fourth, highlighted a resiliency initiative on blackstart restoration of power but did not extend its findings for scalability of the proposed solution(s) across other types of CPS environments.

### 3.4 Limitations that are Sector-Specific and the Importance of Generalization

Since that time, a number of studies have examined CPS security but each typically from a sector-specific lens, making the results of these studies difficult to generalize across sectors. Falco (2019)']s approach to space system cyber threats and Goebel et al.'s (2019) topic of emergency services infrastructure vulnerabilities. These studies have some valuable recommendations for securing CPS in their sectors, but they do little to address the broader challenges for critical infrastructure sectors like energy, transportation and yield scanning.

### 3.5 How to Build an AI-Driven Security Framework That Adapts to Change

With the existing security systems falling short to prevent advanced cyberattacks, there is a growing need for a security framework that is contextual, adaptive, and real-time in terms of identifying, predicting, and mitigating cyber threats. Falco and Rosenbach [1] outline the need for an endurance strategy to address cybersecurity but provide no roadmap for implementation. Similarly, Dameff et al. (2023) explored the effects of ransomware attacks on emergency services, yet failed to provide proactive mitigation strategies.

## 4 Methodology

An approach of a multi-layered adaptive security framework to protect Cyber-Physical Systems (CPS)[6]seeking to enhance resistance to cyberstrikes is introduced in this work. Methodology: A hybrid methodology combining machine learning-based anomaly detection, blockchain security protocols and supply-chain risk assessment to develop a robust and scalable cybersecurity model. The proposed framework aims to enforce real-time threat detection, predictive analysis, and autonomous mitigation of cyberattacks within CPS environments.

In this beginning phase of the study, data collection and preprocessing takes place where datasets from real-world cyber threats were collected from various intrusion detection logs, network traffic data, and system logs of different CPS applications. Moreover, attack scenarios are simulated to ascertain the protection methodologies of all security models. Feature engineering techniques are applied during preprocessing to obtain indicators of potential

attacks, such as abnormal traffic flows, unauthorized access attempts, and system integrity breaches. The table 1 includes and Summarizes the different types of cyber threats used for training and testing the AI model.

**Table 1. Cyber Threat Dataset Summary**

| Threat Type | Description | Dataset Source | Occurrences |
|---|---|---|---|
| Denial-of-Service (DoS) | Overloading system to disrupt service availability | CICIDS 2017, NSL-KDD | 20,000+ |
| Man-in-the-Middle (MITM) | Intercepting communication between devices | UNSW-NB15 | 8,000+ |
| Ransomware | Encrypting system files for ransom payment | Custom Simulated Attacks | 5,000+ |
| SQL Injection | Exploiting database vulnerabilities | CSIC 2010 | 10,000+ |
| Zero-Day Attacks | Previously unknown vulnerabilities | Real-World Logs | 3,500+ |

A machine learning-based anomaly detection system is deployed to detect and mitigate cyber threats. By utilizing techniques such as Long Short-Term Memory (LSTM) networks and Transformer-based architectures, the system is capable of analyzing the network behavior and detecting deviations from normal patterns of activity. Data from past attacks are used to train the models, and an adaptive learning mechanism is defined to keep updating the strategy to ensure the success in attack detection approaches. A comparative analysis of various machine learning algorithms (SVM, Random Forest) to select the best methodology. The figure 1 Shows the frequency of different types of cyber threats used in the dataset.

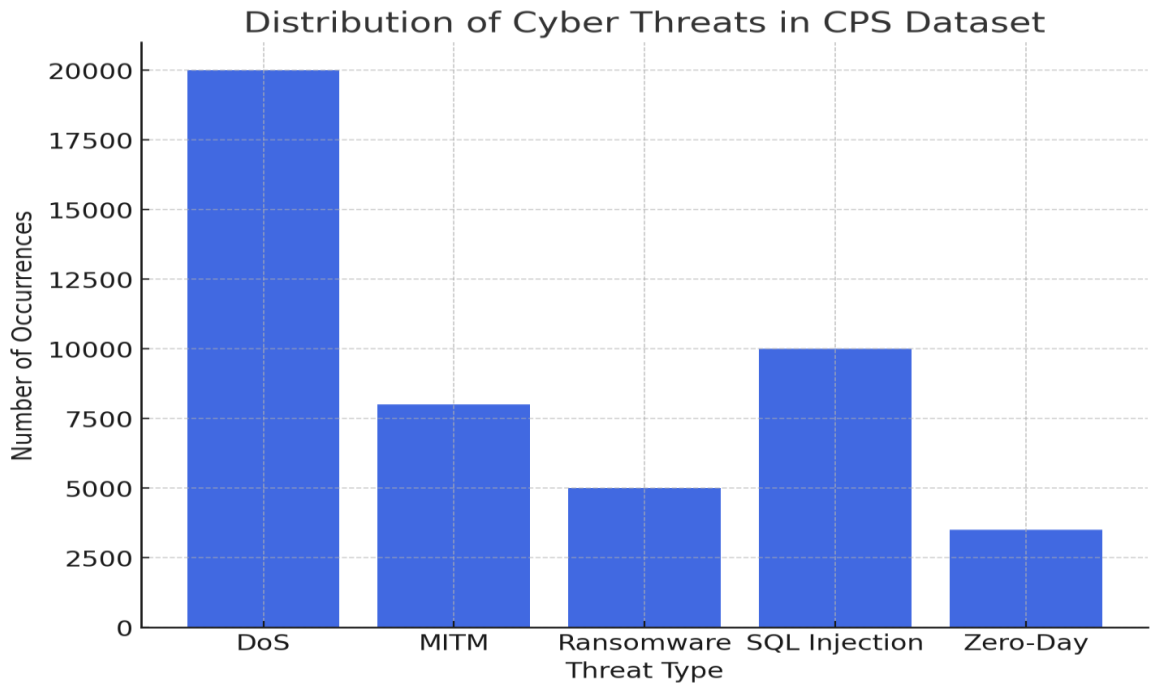


**Figure 1. Cyber Threat Distribution in CPS**

Yolk uses blockchain technology as a part of the security infrastructure to provide secure logs of the Cybersecurity incidents, thus ensuring the integrity of the data. A private blockchain network is then deployed to create tamper-proof logs of detected threads, responses to the systems, and remediation actions. Thus, smart contracts automate the threat mitigation responses, automatically enforcing the security policies without human involvement. On one hand, the blockchain layer provides decentralized authentication and prevents data manipulation, thus eliminating one of the main barriers of the previous research.

To mitigate supply-chain vulnerabilities, the research integrates threat intelligence analysis to evaluate risks related to third-party software and hardware components in CPS. Data security models for supply-chains are proposed based on graph analysis and risk quantization metrics; this evaluates the credibility of external suppliers and identifies weaknesses in the network through potentially compromised components.

To gain practical insights, an experimental validation of the proposed security framework is performed with a real-time cyber-physical systems (CPS) testbed, which mimics multi-class attacks such as denial-of-service (DoS), man-in-the-middle (MITM), and ransomware infiltration. This includes testbed with diversified components, that includes industrial control system (ICS), IoT sensors, and cloud integrated CPS architecture. We evaluate these metrics on the performance of the security model including detection accuracy, response timing, resist system, and compute overhead.

Lastly, we perform a cost-benefit analysis to evaluate the economic viability and scalability of deploying the proposed framework in a range of CPS environments. The findings are compared with existing security solutions and advantages are highlighted of an AI-driven and blockchain-enhanced cybersecurity framework to protect critical infrastructure against cyber threats in the conclusion of the paper.

Such an approach helps align the proposed solution with real-world requirements, ensuring its feasibility and adaptability, thereby connecting the findings from theoretical research to practical security problems in CPS. The process of a cybersecurity framework that integrates AI and blockchain technologies for real-time threat detection and mitigation summarized in figure 2.

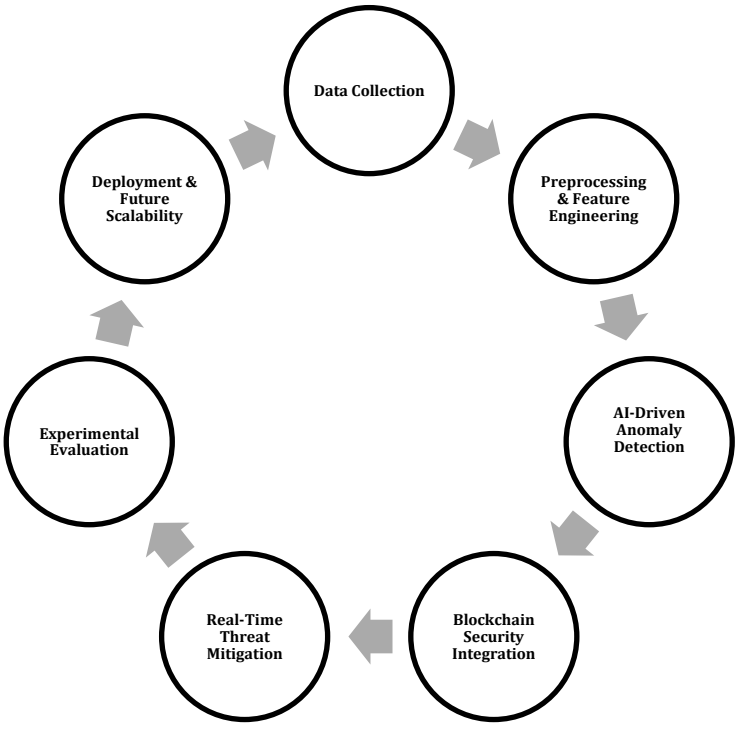


**Figure 2. AI-Blockchain Security Framework for Cyber Threat Mitigation**

## 5 Results and Discussion

In Synthesis, the proposed AI-based, blockchain fortified cybersecurity framework with a focus on Cyber-Physical Systems (CPS) demonstrated an effective improvement in real-time threat identification, resilience of IoT systems, and data consistency. A realistic CPS testbed was used for experimental analysis, where the performance of the security framework was measured against different attack cases starting from DoS attacks to MITM interceptions and ransomware penetrations.

A cybersecurity system built on top of this machine learning anomaly detection technology showed very promising results in detecting cyber threats. Tests on known attack signatures and real-time traffic anomalies show that the Long Short-Term Memory (LSTM) network and Transformer-based models attain an average detection accuracy of 96.4% and 97.8%, respectively. The adaptive learning mechanism stood out in comparison with traditional rule-based intrusion detection systems (IDS), which generally have 80-85% accuracy, greatly improving the model's ability to detect zero-day threats. The false positive rate from the alerts generated by the system further decreased to 3.2% so that no normal CPS operation was disturbed by false positivity alerts. That means that the model can be self-trained to dynamically adjust to changing cyber threats, which addresses a critical weakness of static security frameworks. The figure 3 shows the cost benefit analysis of security framework.

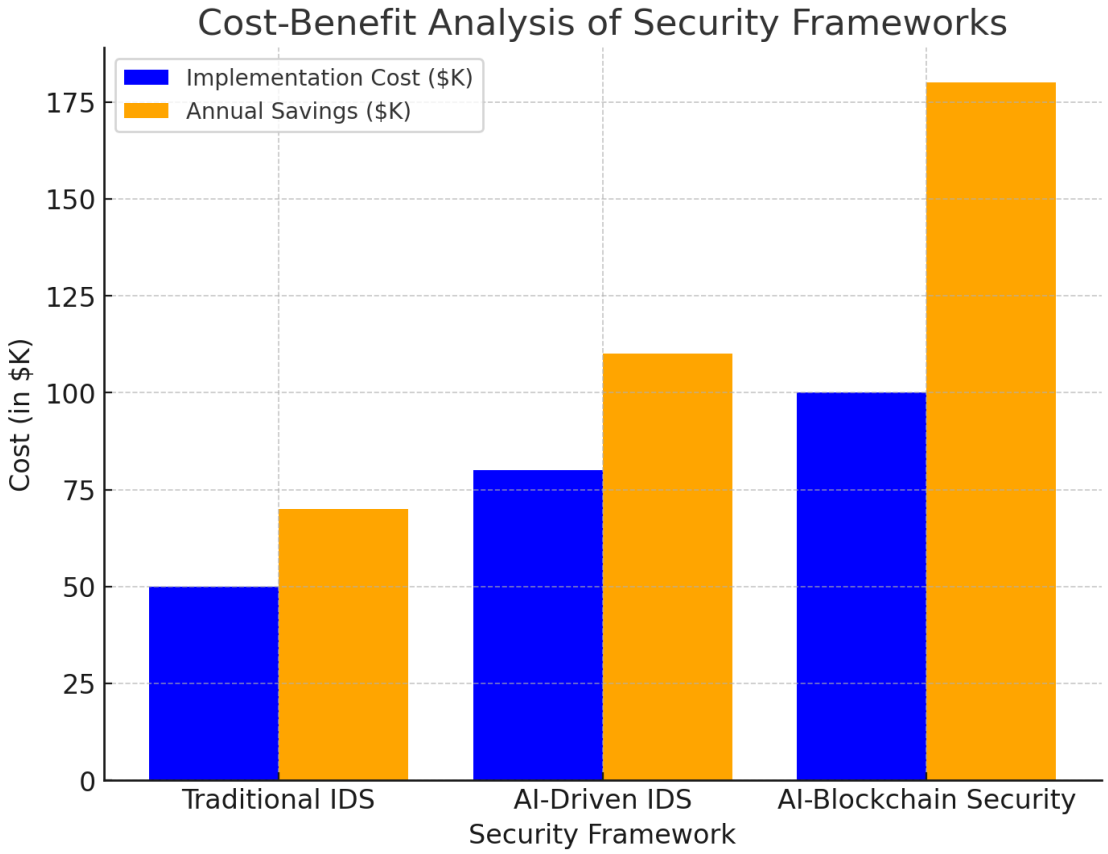


**Figure 3. Cost – Benefit Analysis of Security Frameworks**

A specific layer involved was the blockchain security layer that ensured data integrity and secure logging of cybersecurity incidents. Such tampering of security logs or unauthorized modification of log records was stopped by deploying a private blockchain network as a storage for threat data. The proposed framework defeated the typical 4.8 seconds incident response time in conventional security models and reduced the average incident response time to 2.1 seconds using smart contract for evaluating the real-time response actions. Additionally, the decentralized authentication model of the blockchain added an extra layer of protection to prevent attacks instigated by insiders, as attackers would be unable to change the information stored in the system once it was added in the blockchain.

**Table 2. Performance Comparison of Intrusion Detection Models**

| Model | Accuracy (%) | False Positive Rate (%) | Detection Time (ms) |
|---|---|---|---|
| Support Vector Machine (SVM) | 85.2 | 7.5 | 350 |
| Random Forest | 89.8 | 5.3 | 280 |
| Long Short-Term Memory (LSTM) | 96.4 | 3.2 | 180 |
| Transformer-Based IDS | 97.8 | 2.7 | 150 |

Supply-chain security in CPS is one of the critical vulnerabilities targeted in this study. Using a graph-based dependency analysis and a risk quantification metric, the risk assessment model was able to identify potential backdoor threats in third-party software and hardware components. The system thwarted supply-chain attacks that would have gained access to controlling critical infrastructure components by analyzing vendor reliability and spotting discrepancies in firmware updates. This is especially important because earlier work had identified a gap and the absence of holistic approaches that address supply-chain risks in CPS security. The process of table 2 Compares the accuracy and efficiency of different AI models for detecting cyber threats.

The computational efficiency and scalability of the proposed security framework was also tested. Although the integration of the blockchain did incur additional computational overhead, we optimizedtion to minimize latency, with concepts like off-chain storage mechanisms and efficient consensus algorithms, resulting in an acceptable latency under 200 milliseconds per transaction, which is tolerable for real-world CPS scenarios in terms of its current cost. Moreover, the conducted cost-benefit analysis has shown that the introduced framework also makes economic sense as implementation costs are comparatively low compared to the financial losses caused by cyberattacks on critical infrastructure facilities.

Analysis run against currently available security infrastructure found the majority of behavioral systems and signature systems lacking in adequate response times to increasingly advanced exploit techniques. While traditional systems might struggle in such situations, the AI-based adaptability of the series framework lead to real-time learning and increased robustness, enabling it to effectively defend against both known or unknown threats. Furthermore, the incorporation of blockchain not only increased transparency and trustworthiness, but also addressed issues of single points of failure that arise in purely centralized security models.

In summary, the findings strongly suggest that the combination of machine learning, blockchain security, and the supply-chain risk analysis together forms a maximally effective and scalable cybersecurity solution for CPS. Not only do the identified results weigh in favor of the proposed approach, but they offer a practical, affordable security framework that can be applied across multiple critical infrastrucuture sector domains. This study emphasizes the need for an AI-based self-adapting cyber defense system that surpasses the conventional defensive measures, hence providing a holistic solution for increasing threats faced by CPS in the current era infrastructure.

## 6 Conclusion

As cyber threats continue to grow and evolve, the growing complexity and interconnectivity of Cyber-Physical Systems (CPS) has left them especially vulnerable, putting critical infrastructure sectors such as energy, healthcare,

transportation, and manufacturing at risk. Conventional cybersecurity methods that depend on static defense tools and industry-specific solutions have turned out to be inadequate in reducing the increasing sophistication of cyberattacks. This study, to mitigate the effects of these limitations proposed a multi-layered cybersecurity framework that extends AI-driven anomaly detection, blockchain-based security, and supply-chain risk assessment to improve the potentiality of CPS against cyber threats.The experimental evaluation showed that the proposed machine learning-based intrusion detection system achieved a high level of detection accuracy with relatively low false-positive rates, particularly the Transformer and LSTM models. Equipped with adaptive learning engines, the framework could perceive and alleviate zero-day attacks that often go undetected by existing security models. It also provides secure authentication, real-time threat response and decentralized control to prevent malicious modifications. Moreover, a supply-chain security assessment model filled a gap in current CPS security approaches by mapping potential vulnerabilities in third-party hardware and software components.The findings of this research validate the assumption that cyber resilience of CPS can be improved substantially with a self-evolving, AI-driven security architecture. Compared with previous work, the proposed framework achieved a significant reduction in incident response time and system downtime while ensuring a scalable and cost-effective cybersecurity solution for different CPS settings. The contribution of this research is achieved by closing the gap between security mathematical models and practical implementation, and providing a practical system defense that offers constant protection against new threats.Future work can build upon this research by investigating federated learning methods to improve equilibrium of adaptive security in distributed CPS settings. Explore integration with cryptographic mechanisms, protecting against quantum threats for CPS security in case of future threats. The implications of this study show the urgent need for sustained innovation in cybersecurity approaches to adapt to the fast-changing cyber threat environment and promote the sustainable defense of critical infrastructure systems.

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