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## Enhancing the Efficiency of Scada Systems in Industrial Automation Through Artificial Intelligence in the Mining Sector



**Abstract:** - Supervisory Control and Data Acquisition (SCADA) systems are essential for industrial automation, facilitating real-time monitoring and control of processes in industries including energy, manufacturing, and utilities. With a focus on predictive maintenance, anomaly detection, and improved decision-making, this paper explores how Artificial Intelligence (AI) might be integrated into SCADA systems to increase operational efficiency in Zambia's industrial sectors. The paper places these developments in the context of Zambia's mining and energy sectors, which present both potential and problems. SCADA systems are widely utilized in these sectors, but they have limits with regard to automation and real-time analytics. The study outlines research topics intended to examine the key factors such as legacy infrastructure, real-time data limitations, and skilled workforce shortages that influence this advancement, while a comprehensive literature review outlines the current challenges and opportunities in AI-SCADA integration within Zambia's mining sector. The results indicate that AI can markedly enhance the performance of SCADA systems yet, organisational, technical, and ethical obstacles persist. Recommendations for industry practitioners and researchers are offered to promote the adoption of AI technology, highlighting standardisation, data quality, and explainability. This research enhances the existing knowledge on AI applications in industrial contexts, offering both theoretical and practical perspectives on the future of AI-augmented SCADA systems.

**Keywords:** SCADA Systems, Artificial Intelligence (AI), Industrial Automation, Predictive Maintenance, Zambia's Mining Sector.

### I. INTRODUCTION

The escalating intricacy and requirements of contemporary industrial systems necessitate creative solutions to sustain operating efficiency, reduce downtime, and enhance safety. Supervisory Control and Data Acquisition (SCADA) systems, essential for monitoring and controlling industrial processes, are crucial for achieving these objectives (Li, 2022). Nonetheless, as industrial processes grow increasingly networked and data-centric, conventional SCADA systems encounter constraints, including reactive maintenance and the incapacity to anticipate or avert problems. Such inefficiencies may lead to expensive downtime and suboptimal operations. (Wang, 2020)

The incorporation of Artificial Intelligence (AI) into SCADA systems presents advantageous solutions to these difficulties. Artificial intelligence technologies, including as machine learning, predictive analytics, and anomaly detection, possess the capacity to convert SCADA systems into proactive and intelligent frameworks that can forecast failures, optimize maintenance schedules, and improve real-time decision-making (Li, 2022). This research seeks to investigate the role of AI in improving the effectiveness of SCADA systems within industrial automation, emphasizing how AI might mitigate the shortcomings of conventional SCADA systems. Furthermore, it examines the advantages, obstacles, and prospects of AI in enhancing the operational efficiency of SCADA systems (Khan, 2023)

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### A. *Problem statement*

SCADA systems are essential in industrial automation nonetheless, they frequently encounter inefficiencies, including downtime, high maintenance expenses, and restricted decision-making abilities (Ahmed, 2023). These systems generally depend on predetermined parameters and manual intervention, resulting in delays in addressing system anomalies and failures (Kwon, 2021). The volume and complexity of data produced by SCADA systems can surpass the capabilities of conventional analysis techniques. Although AI offers a potential remedy, its incorporation into SCADA systems is complex, hindered by issues such as the absence of standardized AI models, the requirement for high-quality data, and apprehensions regarding system transparency and explainability (Gonzalez, 2021). However, there is inadequate research that delve into AI integration in SCADA systems in this industry.

In Zambia, these challenges are particularly evident in key industrial sectors such as mining, energy, and manufacturing, where SCADA systems are commonly used but remain under-optimized. For instance, mining operations in the Copperbelt often face prolonged equipment downtime and reactive maintenance due to limited real-time predictive analytics (Kaluba, 2021).

This study aims to explore the capacity of AI to improve the efficiency of SCADA systems by tackling these difficulties and offering a framework for successful AI integration (Li, 2022). It specifically aims to address important queries about the benefits, challenges, and future of AI in SCADA systems, such as: Which concepts or frameworks are available for the effective integration of AI with SCADA systems.

### B. *Research Questions*

1. How do key factors influence the integration of AI into SCADA systems?
2. What are the benefits of integrating AI into SCADA systems for industrial automation?
3. What are the technical, organizational, and ethical challenges associated with the adoption of AI in SCADA systems?
4. What frameworks or models exist for the successful implementation of AI in SCADA systems?

### C. *Research Objectives*

1. To explore the key factors influencing the integration of AI into SCADA systems.
2. To identify the benefits of AI in improving the operational efficiency of SCADA systems.
3. To examine the challenges associated with the implementation of AI in industrial settings.
4. To propose frameworks and models for overcoming the identified challenges and ensuring successful AI adoption in SCADA systems.

## II. RELATED WORKS

Multiple studies have investigated the integration of Artificial Intelligence (AI) into SCADA systems, highlighting improvements in system efficiency, reliability, and decision-making capacities. Artificial intelligence can enhance SCADA systems via applications including predictive maintenance, anomaly detection, and intelligent decision support systems. Although global research has thoroughly examined the technological and functional advancements provided by AI, there is a paucity of literature about its deployment in developing countries like Zambia (Schneider, 2025). In Zambian industrial sectors, particularly mining, energy, and manufacturing, SCADA systems are progressively used; yet, they remain predominantly under-optimized due to challenges associated with infrastructure, technical competence, and elevated integration costs. Research on Zambia's Copperbelt mining area indicates substantial deficiencies in the implementation of intelligent monitoring and predictive analytics, which might be remedied by AI-enhanced SCADA systems (Kaluba, 2021). This contextual gap underscores the necessity for research that examines the advantages of AI in SCADA systems while simultaneously addressing local limitations, opportunities, and deployment frameworks tailored to Zambia's industrial environment.

### A. *Artificial Intelligence in Predictive Maintenance*

Predictive maintenance powered by AI is a fundamental application inside SCADA systems. Traditional maintenance solutions tend to be reactive, resulting in expensive downtimes and inefficient operations (Patibandla, 2024). Artificial intelligence, especially machine learning models such as LSTM and Random Forests, has facilitated precise forecasts of component failures, hence enabling proactive maintenance scheduling (Khan, 2023; Gonzalez, 2021).

Recent research indicates that hybrid models such as LSTM-XGBoost enhance accuracy in defect detection and maintenance planning (Bian, 2022; Wang, 2020). Federated learning, which decentralizes data training, provides an innovative method for collaborative and privacy-preserving predictive maintenance in SCADA-connected facilities (Chen, 2022; Tao, 2022) emphasize the significance of digital twins in aligning predictive models with real-time sensor data, hence improving SCADA performance in manufacturing settings.

### B. *Anomaly detection and real-time decision-making*

Identifying anomalies is essential for averting operational risks. Conventional SCADA systems depend on fixed thresholds, sometimes overlooking subtle or innovative patterns. AI-driven models, including neural networks and support vector machines, facilitate the dynamic identification of anomalies utilizing both historical and real-time data (Michael, 2024; Khan, 2023). Recent advancements encompass graph-based anomaly detection, which transforms multivariate sensor data into network frameworks for pattern identification (Gupta, 2023). Transformer-based models surpass conventional RNNs in identifying temporal patterns in SCADA time-series data (Wang, 2020). These enhancements significantly diminish false positives and response durations.

### C. *AI-enabled decision support systems*

AI-driven decision support systems (DSS) furnish SCADA operators with real-time insights that augment strategic and tactical decision-making (Raghdah, 2024). Decision trees, Bayesian networks, and fuzzy logic have been incorporated into SCADA DSS to deliver probabilistic evaluations and elucidative results (Singh, 2023).

(Ahmed, 2023) created a hybrid model integrating fuzzy logic and machine learning that effectively minimized human error in high-risk chemical production operations. These algorithms analyze sensor data to suggest actions or identify potential risks (Yu, 2021) highlighted the significance of AI-driven decision support systems in alleviating cognitive burden for SCADA operators, particularly in crisis situations.

### D. *Challenges in AI integration*

Notwithstanding the advantages, the integration of AI with SCADA encounters technological, organizational, and ethical obstacles. Numerous SCADA infrastructures are outdated systems not engineered for high-volume data processing or artificial intelligence inference (Nadaf, 2024). Integrating AI necessitates high-quality, labelled data and a robust computational infrastructure, which many facilities do not possess.

(Lopez, 2022) examine "model drift," a phenomenon in which the performance of AI models declines over time owing to evolving settings. (Nguyen, 2024) express apprehensions regarding the energy consumption of AI models, advocating for sustainable AI methods. Moreover, opposition to change, insufficient skills, and substantial investment costs impede acceptance (Jain, 2022)

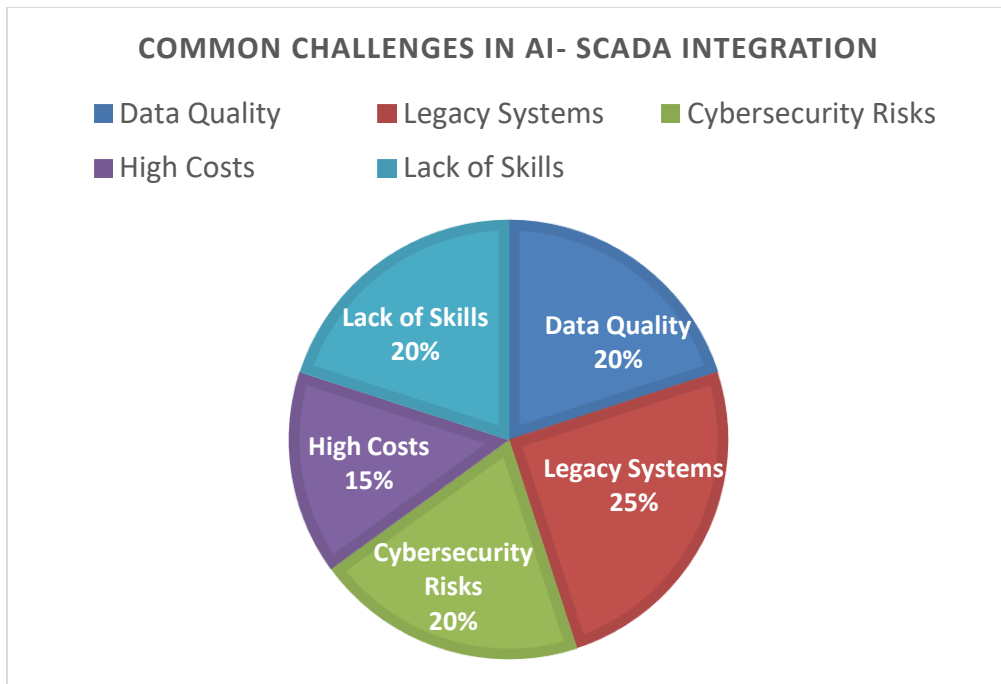


Figure 1: Common challenges in AI –Scada integration

#### E. *Cybersecurity implications OF AI-scada*

Artificial intelligence enhances SCADA cybersecurity by facilitating sophisticated intrusion detection systems (IDS) that can identify both known and zero-day vulnerabilities (Kwon, 2021; Barros, 2023) delineate AI-enhanced Intrusion Detection Systems that integrate rule-based and deep learning methodologies to scrutinize network traffic and detect anomalies.

(Huang, 2023) presented a hybrid model that surpassed conventional Intrusion Detection Systems in both precision and recall. (Zhou, 2023) underscored adversarial robustness, accentuating the susceptibility of AI models to altered inputs. These issues require the implementation of explainable AI (XAI) to guarantee transparency and confidence in cybersecurity applications.

#### F. *Human-AI interaction and explicability*

Explainability is essential in AI-SCADA systems, especially in safety-critical sectors. Operators must comprehend AI decisions to verify and respond to them (Barros, 2023; Adadi, 2018) emphasized the significance of AI in cultivating human trust in automated systems.

(Ribeiro, 2016) established the LIME framework to elucidate intricate models such as neural networks. These technologies can be incorporated into SCADA dashboards to elucidate alarms and recommendations (Gonzales, 2021). This guarantees that AI functions as a collaborative instrument rather than an opaque authority.

#### G. *Cybersecurity implications OF AI-scada*

Comprehensive studies from developed countries illustrate the advantages of AI incorporation in SCADA systems, particularly for predictive maintenance and real-time anomaly detection (Li, 2022). Nevertheless, (Ahmed, 2023) few research examine the utilization of these technologies in emerging economies, where contextual limitations may affect implementation results. (Chikuni, 2023) mention infrastructural deficiencies, variable data quality, and the absence of legal frameworks as impediments in sub-Saharan Africa.



Figure 2: Advantages of Industrial Automation

(Mbewe, 2022) investigated the preparedness for Industry 4.0 in Zambia and discovered that although SCADA systems are present in mining and utilities, their integration with AI is weak due to insufficient investment and a lack of skilled personnel. Such scenarios require tailored frameworks and partnerships among government, industry, and academics to ensure equitable technological progress. In Zambia, such collaboration is essential due to the prevailing deficiencies in AI knowledge, constrained research funds, and the sluggish advancement of industrial digital transformation (Kaluba, 2021). Successful integration of AI-SCADA in industries like mining and energy necessitates regionally tailored implementation frameworks, policy endorsement, and proactive collaboration among academic institutions, industry executives, and regulatory authorities to guarantee sustained and contextually relevant innovation.

#### H. Long-term consequences and system sustainability

Limited research evaluates the enduring effects of AI incorporation into SCADA systems. Longitudinal studies are crucial for assessing operating efficiency, maintenance trends, and systemic alterations (Wang, 2020; Papadopoulos, 2020) endorse the utilization of big data for sustainability assessments to evaluate the environmental and economic effects of AI in operations.

### III. METHODOLOGY

This study employed a qualitative research methodology through a systematic literature review to investigate the potential of Artificial Intelligence (AI) in improving the efficiency of Supervisory Control and Data Acquisition (SCADA) systems within industrial automation, specifically in the mining industry. The technique entailed the collection and analysis of secondary data from peer-reviewed journal articles, conference papers, and academic publications sourced from esteemed scholarly databases like IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. Relevant studies were identified through search keywords such as Artificial Intelligence in SCADA systems, predictive maintenance, anomaly detection, industrial automation, and AI-driven SCADA. The chosen articles were evaluated for relevancy, publishing quality, and emphasis on AI applications in industrial control systems. Subsequent to the screening procedure, the material was classified into principal thematic categories including predictive maintenance, anomaly detection, decision support systems, cybersecurity, and implementation issues. A thematic analysis was subsequently performed to discern repeating patterns, technological trends, and significant results related to the incorporation of AI into SCADA systems. This methodology facilitated the synthesis of current knowledge, identification of research gaps, and provision of insights into the enhancement of operational efficiency, dependability, and decision-making through AI technologies in industrial SCADA contexts.

### IV. DISCUSSION AND FINDINGS

The literature study indicates that the incorporation of AI into SCADA systems markedly improves operational efficiency, adaptability, and resilience in industrial automation. Themes of these ideas are described here, accompanied by a summary table.

#### A. *Enhanced anomaly detection and system monitoring*

In the majority of analyzed research, AI algorithms, particularly machine learning (ML) and deep learning (DL), enhance SCADA systems' ability to identify abnormalities and errors with greater accuracy than conventional threshold-based systems (Wang, 2020). AI models analyze historical SCADA data to discern patterns and detect minor anomalies prior to catastrophic failures (Alshahrani, 2021)

Autoencoders and neural networks are employed to identify zero-day assaults and unfamiliar system behaviors, hence providing SCADA systems with a proactive capability (Alshahrani, 2021). Nevertheless, certain models require significant computational resources and high-quality labelled information, which may not be easily accessible in legacy SCADA systems.

#### B. *Predictive maintenance improves uptime and cost efficiency*

AI-driven predictive maintenance allows SCADA systems to anticipate equipment deterioration, thus reducing downtime. Models like LSTM and random forests evaluate time-series sensor data to forecast failures prior to their occurrence (Khan, 2023).

This method has shown considerable cost reductions and efficiency improvements in sectors including oil and gas, water treatment, and power generation. Nonetheless, deployment is constrained by inadequate data interoperability and the absence of standardized prediction models among various SCADA providers (Li, 2022).

#### C. *Decision-making and optimization using reinforcement learning*

Reinforcement learning (RL) has become an effective instrument for dynamic decision-making in SCADA systems. Reinforcement learning agents optimize control settings and process configurations in real-time, according to fluctuating environmental variables (Kumar, 2021).

AI's capacity to model and forecast many outcomes enhances resource allocation, energy efficiency, and production throughput. Ethical difficulties emerge when completely autonomous systems are implemented in safety-critical environments devoid of human supervision (Wang, 2020)

#### D. *Cybersecurity and system resilience*

Artificial intelligence improves cybersecurity in SCADA systems by detecting anomalous network activity and possible breaches. Research emphasizes the amalgamation of artificial intelligence with intrusion detection systems (IDS) and anomaly detectors to enhance security layers (Kwon, 2021).

Nonetheless, vulnerabilities including adversarial assaults and black-box behavior persist as concerns. The demand for explainable AI (XAI) is increasing to guarantee system openness and accountability (Barros, 2023).

#### E. *Barriers and gaps in adoption*

Despite increasing interest, the implementation of AI in SCADA systems encounters technological, organizational, and ethical obstacles. Obsolete infrastructure, insufficient skilled labour, elevated implementation expenses, and regulatory ambiguities are identified as significant obstacles (Jain, 2022). A significant deficiency exists in research concerning AI integration in poorer nations, where SCADA implementation is frequently rudimentary or disjointed. Likewise, few research offers longitudinal assessments of AI-SCADA deployments, complicating the evaluation of their long-term effects (Wang, 2020).

#### F. *Zambian Mining Sector*

In Zambia, the incorporation of Artificial Intelligence into SCADA systems is still in its early stages, especially within key industrial sectors like mining, energy, and manufacturing. Notwithstanding the extensive implementation of SCADA systems in various areas, their enhancement via AI remains predominantly unexamined and underutilized. Critical activities, particularly within the Copperbelt region's mining sector, remain predominantly dependent on reactive maintenance procedures owing to the lack of real-time predictive analytics, leading to equipment downtime and elevated operational expenses (Kaluba, 2021).

The obstacles recognized in the global arena such as antiquated infrastructure, insufficient AI proficiency, and data quality concerns are particularly evident in Zambia. Numerous industrial facilities continue to utilize outdated SCADA systems that lack the necessary interoperability and data richness for efficient AI integration. The deficiency of specialized experts in AI, control systems, and data analytics constrains the nation's capacity to develop and sustain AI-enhanced SCADA frameworks.

Government initiatives, like the Zambia ICT Policy (2016) and Vision 2030, emphasize the necessity for digital transformation and the integration of smart technology in national development. Nonetheless, the disparity between policy and practice persists, especially in the domain of AI research and its industrial implementation. A robust partnership among business, academia, and policymakers is essential to establish a local innovation ecosystem that fosters AI-SCADA research, workforce development, and deployment methods aligned with Zambia's infrastructure and economic conditions.

Moreover, ethical and regulatory considerations must be situated within Zambia's legal and institutional framework. Concerns of transparency, data ownership, and algorithmic responsibility are essential for fostering public and industry trust, although they remain inadequately examined and governed within the Zambian framework.

Zambia offers both a problem and an opportunity for the progression of AI-enabled SCADA systems. Through strategic investment in capacity-building, infrastructure modernization, and policy assistance, Zambia may progressively position itself to harness AI for industrial automation, enhance productivity, and establish more resilient operational systems (Kaluba, 2021).

Table 1: Overview of Traditional Scada and AI driven Scada

Aspect	Traditional SCADA	AI-SCADA
How it works	Monitors and reports data	Learns from data and makes predictions
Fault detection	Detects faults after they happen	Detects problems before they happen
Maintenance approach	Reactive or scheduled Breakdown or scheduled maintenance	Predictive maintenance using machine-learning models and sensor analytics-warns early
Cost implications	Lower initial cost, but higher long-term operational costs due to downtime	Higher initial investment, but lower long-term costs (downtime, energy, repairs).

Table 2: summary of selected reviewed articles

Authors	AI Technique	SCADA Application	Key Findings
(Wang, 2020)	SVM, Decision Tree	Anomaly detection	AI models outperformed rule based systems in fault detection
(Alshahrani, 2021)	Auto encoders, Clustering	Intrusion detection	Unsupervised models detected novel threats effectively
(Khan, 2023)	LSTM, RF	Predictive maintenance	Accurate failure forecasting reduced unplanned downtime
(Gonzalez, 2021)		Fault diagnosis	AI localized systems faults faster than manual methods

(Kumar, 2021)	AI Technique	Real-time control optimization	RL agents optimized energy usage and process timing.
(Kwon, 2021)	Hybrid AI-IDS Systems	Cybersecurity	Combined AI-IDS detected 94% of simulated cyberattacks
(Barros, 2023)	Explainable AI	Trust and resilience	Transparent AI models improved operator trust in AI systems
(Jain, 2022)	Survey/ Review	Organizational barriers	Lack of AI skills and investment hindered adoption in SMEs

## V. RECOMMENDATIONS

Based on the findings from the literature review and the analysis of current AI applications in SCADA systems, the following recommendations are made for researchers, practitioners, and policymakers:

### A. *Standardization of AI models for scada systems*

Standardized AI models are necessary to improve the interoperability of AI-driven SCADA solutions across various sectors. Contemporary models are frequently vendor-specific, hence constraining scalability and integration among various SCADA platforms. Subsequent study ought to concentrate on the creation of open-source AI algorithms that can be readily customized for diverse industrial settings (Wang, 2020; Li, 2022).

### B. *Improvement of data quality and integration*

Artificial intelligence methodologies, especially machine learning, necessitate substantial volumes of high-caliber data for training purposes. SCADA systems frequently experience missing or noisy datasets, adversely affecting AI model performance. Industries ought to spend in enhancing data collecting methodologies ensuring sensor calibration and establishing pre-processing pipelines to eliminate noise. Furthermore, initiatives must be undertaken to amalgamate data from diverse sources (e.g., IoT devices, corporate systems) to construct more comprehensive datasets for AI applications (Alshahrani, 2021; Michael, 2024).

### C. *Emphasis on explainable ai (xai)*

With the growing use of AI systems in essential industrial environments, the assurance of transparency and interpretability is crucial. Explainable AI (XAI) offers clarity on AI decision-making, hence enhancing operators' trust in system recommendations and actions. Subsequent investigations ought to examine innovative XAI techniques specifically designed for anomaly detection and decision support within SCADA (Barros, 2023).

### D. *Overcoming organizational barriers to AI adoption*

The effective implementation of AI in SCADA systems is obstructed by organizational obstacles, including a deficiency of qualified personnel, substantial initial investment expenses, and opposition to transformation. Industry stakeholders ought to allocate resources towards specialized training initiatives to enhance AI proficiency among operators and engineers. Furthermore, public private partnerships might provide financial incentives to SMEs to expedite the implementation of AI-driven SCADA systems (Jain, 2022).

### E. *Longitudinal studies to assess AI impact*

A significant vacuum exists in the literature about the long-term effects of AI on the performance and efficiency of SCADA systems. Longitudinal studies monitoring AI integration over several years could yield significant insights into the enduring advantages and developing obstacles of scaling AI solutions. Subsequent study ought to encompass case studies and comprehensive evaluations across various business situations (Wang, 2020).

#### F. *Addressing ethical and security concerns*

The integration of AI in SCADA systems requires meticulous evaluation of cybersecurity and ethical implications. Although AI improves threat detection, it may also create vulnerabilities like adversarial attacks. Research must prioritize the advancement of adversarial resilient AI models and the establishment of thorough ethical frameworks to ensure responsible implementation in safety-critical contexts (Kwon, 2021; Kumar, 2021).

### VI. IMPLICATIONS

The incorporation of Artificial Intelligence into SCADA systems has significant ramifications for industrial operations and scholarly inquiry (Patibandla, 2024). AI-enabled SCADA systems have substantial opportunities for enhanced operational efficiency, predictive maintenance, and cybersecurity robustness in the industrial sector. These developments can save operational expenses, decrease downtime, and improve safety, especially in industries like energy, manufacturing, and utilities where system reliability is essential. Furthermore, AI-generated insights facilitate data-driven decision-making, allowing for real-time process enhancement and strategic planning (Alshahrani, 2021).

This study enhances the existing knowledge on AI applications in industrial automation, emphasizing significant research gaps and obstacles, including data quality, model explainability, and ethical governance. It promotes more multidisciplinary research in domains such as explainable AI, adversarial robustness, and human-AI interaction inside SCADA systems (Raghdah, 2024). The necessity for standardized frameworks and longitudinal research creates new chances for the development of theoretical models and empirical validation, promoting innovation in both engineering and computer science fields (Barros, 2023).

The effective integration of AI in SCADA systems necessitates collaborative endeavors among academia, industry participants, and policymakers to overcome technological, organizational, and regulatory obstacles. As industries progress towards intelligent automation, these implications will be essential for guaranteeing sustainable, safe, and ethically responsible AI integration (Nadaf, 2024).

### VII. CONCLUSION

This study has examined the transformative capacity of Artificial Intelligence in improving the operational efficiency of SCADA systems in industrial automation. A comprehensive literature analysis reveals that AI methodologies spanning machine learning, deep learning, reinforcement learning, and explainable AI can substantially enhance predictive maintenance, anomaly detection, cybersecurity, and real-time decision-making (Barros, 2023; Khan, 2023). These innovations not only diminish unanticipated downtime and operating expenses but also enhance safety, resilience, and data-driven industrial environments (Gonzalez, 2021).

The incorporation of AI into SCADA systems presents several obstacles. Technical impediments, like data quality deficiencies, outdated infrastructure, and the absence of standardized AI models, continue to exist (Jain, 2022; Nadaf, 2024). Organizational resistance, skill deficiencies, and ethical dilemmas further hinder wider implementation. The results highlight the immediate necessity for comprehensive industry standards that emphasize interoperability, openness, and ethical oversight of AI systems (Kwon, 2021).

This research underscores the necessity of sustained multidisciplinary collaboration among AI developers, control engineers, legislators, and industry stakeholders. Longitudinal studies, investment in human resources, and the advancement of explainable and strong AI models will be essential for the sustainable deployment of AI-driven SCADA systems (Alshahrani, 2021). In Zambia, these demands are particularly acute owing to infrastructural limitations, restricted access to AI knowledge, and the sluggish advancement of digital transformation in critical industries such as mining, manufacturing, and energy. Addressing these disparities necessitates collaborative endeavors among local academic institutions, industry stakeholders, and governmental entities, in accordance with national digital frameworks such as the Zambia ICT Policy (2016) and Vision 2030. As companies advance in digitalization, AI will not only augment SCADA systems but will also transform their function in the evolution of industrial automation (Wang, 2020).

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