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Integrated SCADA Framework for Acid Deposition Monitoring with Occupational Safety Management

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Abstract

Background: Acid deposition is a transboundary environmental problem that demands a reliable and safe measurement system. Previous studies on the same chamber progressed from manual measurement to real-time IoT monitoring; however, they still lacked centralized supervision, automated safety mechanisms, and early detection of sensor faults.
Objective: This study aimed to develop and evaluate an integrated supervisory system that combines Occupational Health and Safety (OHS) management with condition-based maintenance for acid deposition monitoring.
Methods: The system was designed using a Software-in-the-Loop (SiL) architecture within the Siemens ecosystem, following the ISA-95 framework, and was subsequently evaluated through fault-injection scenarios.
Results: The system monitored pH, temperature, water level, and actuator status at 1-second intervals without communication failures or data loss. The safety module detected all three tested hazardous pH conditions below 5.6, resulting in a Probability of Detection (POD) of 100%. The maintenance module detected out-of-range values and triggered an emergency shutdown after three faults occurred within 60 seconds. Availability varied from 66% to 93%, depending on failure frequency and repair time, indicating that faster recovery and fewer repeated failures improved system reliability.
Conclusion: The findings indicate that integrating supervision, OHS management, and condition-based maintenance can strengthen the safety, traceability, and reliability of acid deposition monitoring. The main novelty lies in integrating these functions within a single SCADA architecture validated through Software-in-the-Loop simulation, providing a practical basis for safer environmental monitoring stations and subsequent field implementation.

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INTRODUCTION

Acid deposition remains a relevant environmental issue because of its transboundary and cumulative impacts on aquatic ecosystems, soil, vegetation, and infrastructure. Atmospheric modeling in East Asia shows that transboundary pollution accounts for more than 80% of sulfate and nitrate deposition in Japan and South Korea, indicating that emission sources in one region may determine the quality of precipitation in another. In Indonesia, this phenomenon is also widespread. Coastal areas show high concentrations of sulfate ions due to anthropogenic activities, while in Greater Bandung, the pH of rainwater has been recorded to drop to 4.8, with sulfate and ammonium as the dominant species associated with local industrial and transportation emissions. Even in areas far from industrial centers, most rainwater samples are still categorized as acid rain. Due to the nature of acid deposition, which may be local in origin but global in impact, the quality of monitoring data is a key determinant of the reliability of mitigation policies. Therefore, measurement systems that produce invalid data risk directly misleading scientific interpretations (Mohajan, 2018; Rievaldo et al., 2023; Syafaati & Kartika, 2023; Tanti et al., 2025; Yim et al., 2019).

Research on the acid deposition measurement chamber in Greater Bandung has developed through three complementary stages. The initial stage relied on manual measurements with laboratory analysis conducted once per month, making it unable to capture daily dynamics and extreme values between sampling periods. The next stage addressed instrument accuracy through temperature control that maintained the sample at a setpoint of 25 degrees Celsius, with an error of approximately 1.1%. The third stage developed IoT-based real-time monitoring but identified a negative correlation of −0.80 between pH and temperature, indicating that residual temperature deviations still affected the validity of pH measurements. This stage also recorded an extreme pH value of 1.73 in the absence of any alarms or safety protocols. Collectively, these three stages reveal clear gaps, namely, the lack of centralized monitoring that unifies the subsystems, the absence of an automatic safety mechanism when chemical parameters reach hazardous conditions, and the absence of proactive detection of instrument degradation before failure occurs (Muhammad, 2023; Ramadhan et al., 2024; Rievaldo et al., 2023) .

To address these gaps, this study proposes a centralized surveillance system based on Supervisory Control and Data Acquisition (SCADA), an automation system that integrates data acquisition, visualization, alarm management, and historical data recording within a single supervisory platform. This development is driven by two concrete needs. First, there is a need to mitigate the risk of exposure to corrosive chemicals through alarm-logic-based occupational health and safety (K3) management modules, in line with the growing integration of safety functions into laboratory and industrial monitoring systems. Second, there is a need to maintain data validity through condition-based preventive maintenance of instruments, enabling sensor deviations to be detected before they develop into failures. The novelty of this research lies in the integration of three dimensions (remote supervision, occupational safety, and preventive maintenance) into a single SCADA platform, which is tested using Software-in-the-Loop (SIL) simulation so that hazardous operational scenarios can be reproduced safely and controlled. Based on this approach, the study is directed toward answering three questions: how to design a SCADA simulation architecture for an acid deposition measurement system, how to implement an alarm-logic-based K3 management module to provide early warnings based on chemical-parameter thresholds, and how to design a preventive maintenance strategy based on instrument condition monitoring to proactively detect sensor deviations (González-Cañizalez et al., 2024; Gu et al., 2025; Maseda et al., 2021; Šverko et al., 2022).

METHOD

This study is a simulation-based system engineering and evaluation study with a quantitative approach, which was chosen because the main objective was to design and validate the supervision, safety, and diagnostic functions of the instrument in a measurable manner, rather than to analyze the chemical composition of the sample. The object of the research was a system for measuring acid deposition in the same chamber used in previous research, so that the results could be positioned as a direct continuation of the existing temperature control and IoT systems. The system architecture was developed following the ISA-95 industrial automation hierarchical framework, with Level 1 represented by a virtual PLC that executed control, safety, and diagnostic logic; Level 2 by a SCADA system that served as the supervision and alarm management interface; and a historical data logging function representing Level 3 (Scholten & Brandl, 2026; Zhang et al., 2026) . The complete architecture, along with the data flow between the layers, is shown in Figure 1. Recent implementations exhibited operational isolation, in which individual sensor networks operated independently without centralized supervisory oversight, as well as insufficient integration of occupational safety protocols within the measurement infrastructure.

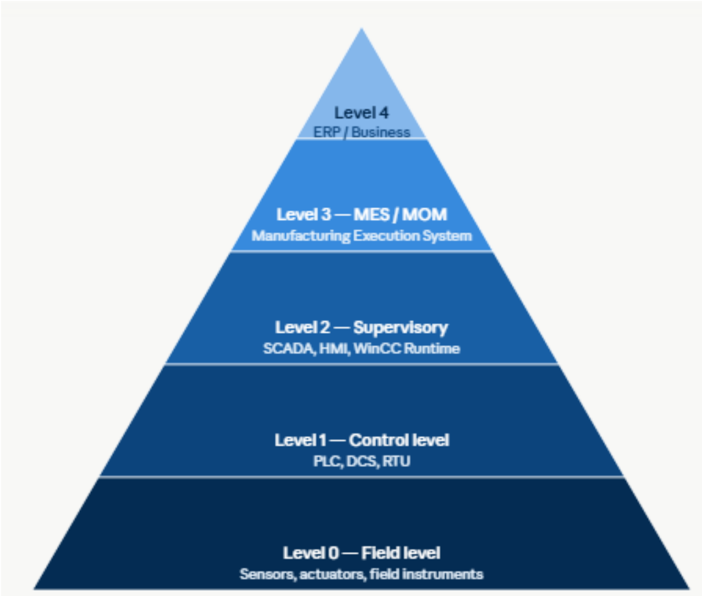

Figure 1. Software-in-the-Loop based supervision architecture based on the ISA-95 hierarchy

The simulation environment was built using a Software-in-the-Loop approach within the Siemens ecosystem. SIMATIC Manager was used as the programming environment, PLCSIM as a virtual CPU simulator for the S7-300 314C-2 DP, and WinCC Explorer as the SCADA platform for visualization, alarm management, and historical data logging. All logic was implemented using the Ladder Diagram language in a single Main Organization Block (OB1), allowing the execution sequence to be observed within a single scan cycle, in accordance with common PLC programming practices. The monitored parameters included pH, temperature, water level, and actuator status. Testing was conducted using the fault injection method, in which fault conditions were directly injected into the virtual PLC memory to reproduce abnormal conditions safely and repeatedly. The injected faults were classified as intermittent faults based on an established failure taxonomy. Process variables, alarm statuses, and protection conditions were mapped to PLC memory addresses and configured as tags in WinCC Explorer. A summary of the virtual input and output mapping, on which data exchange between the control and supervision layers was based, is presented in Table 1. Three fault scenarios were systematically selected: (1) communication loss, simulating a network interruption; (2) sensor malfunction, representing the propagation of measurement errors; and (3) software crash, representing system failure. Each scenario was tested at failure frequencies ranging from 1 to 10 events per 8-hour operational cycle.

Table 1
Virtual input/output mapping

Tags	Address	Data Type	Remarks
Start_BT	I 0.0	BOOL	System operation start button
Stop_BT	I 0.1	BOOL	System operation stop button
Machine_Run	Q 0.0	BOOL	Running system indicator
Stat_Temp	MD 14	REAL	Actual temperature
Stat_pH	MD 18	REAL	Actual pH
Alarm_K3	M 0.5	BOOL	K3 hazard warning
Sensor_Error	M 100.0	BOOL	Sensors cross safe boundaries
Fault_Count_Val	MW 120	INT	Number of sensor failures
Counter	C1	COUNTER	Failure counter (targel 3 times)
Timer	T1	TIMER	Counter reset time window (60 seconds)

The K3 management module was designed with pH as the main safety parameter. When the pH fell below the threshold of 5.6, the PLC activated the locking logic (interlock) that maintained the alarm status, displayed a safety alarm along with a message instructing the use of personal protective equipment on the interface, and held the alarm until the operator confirmed it through a single-acknowledgment mechanism. The functional safety principles of IEC 61508 and IEC 61511 were used as the basis for designing the alarm functions, interlock, and emergency shutdown, although this study was not intended for safety certification (Bond, 2002; IEC, 2010; Okoh & Myklebust, 2024) . Alarm-level management and response referred to the principles of process alarm management. The preventive maintenance module was structured into two layers, namely out-of-range detection, which marked measurement values outside the valid range, and counter-based fault detection, which calculated the frequency of interference occurrences so that the system could distinguish momentary interference from repeated failures. If an outage reached three events within a 60-second window, the system activated the maintenance alarm and automatically executed an emergency shutdown. All process data, alarm statuses, and protection events were recorded using the Tag Logging feature in CSV format with automatic timestamps at 1-second intervals, which then served as the primary source for evaluation. The evaluation indicators used were the probability of detection for assessing hazard-detection capability and system availability, calculated from mean time between failures (MTBF) and mean time to repair (MTTR), to assess operational reliability (Kurz et al., 2012; Tai et al., 2025). This study did not involve human or animal subjects and therefore did not require ethical approval; however, all data were collected in accordance with institutional ethical standards (Goeritno et al., 2024; ISA, 2009; Martins et al., 2023; van Limpt et al., 2026). The fault-calculation logic, together with the reset and triggering mechanisms of the protection system, is shown in Figure 2.

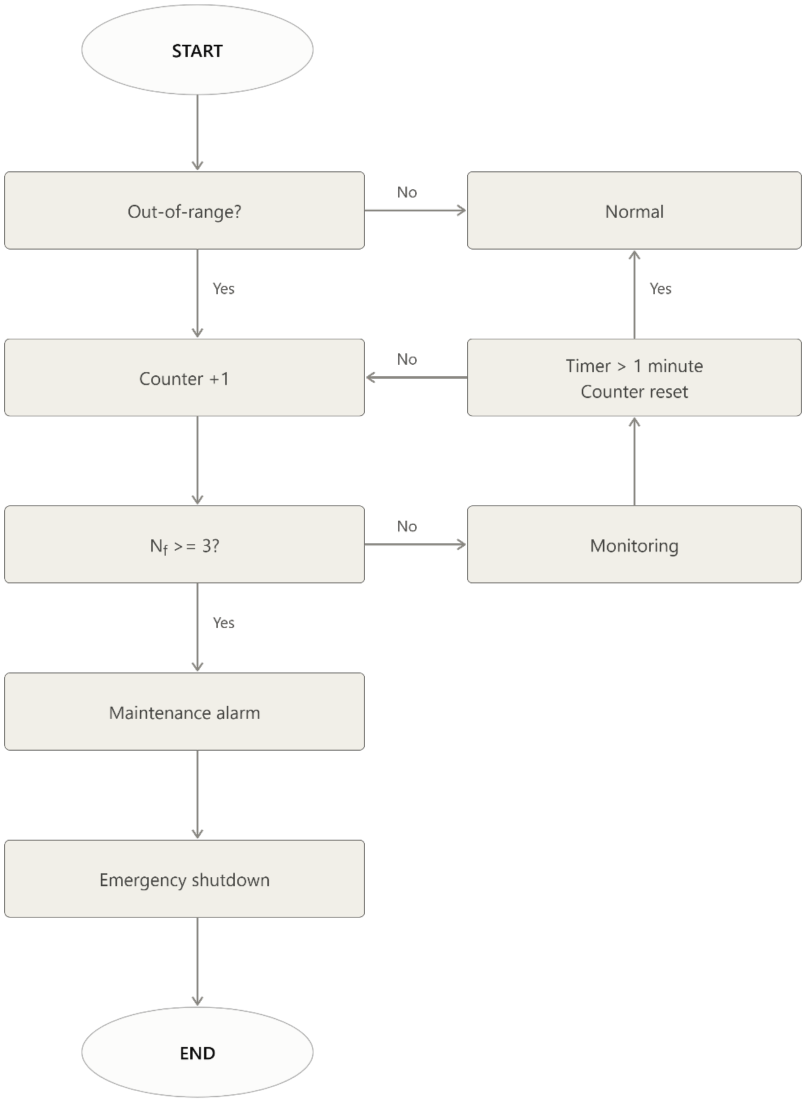

Figure 2. Logic flow of interference calculation

RESULTS AND DISCUSSION

Results

The system architecture successfully integrates SIMATIC Manager, PLCSIM, WinCC Explorer, and historian functionality within a single, real-time, connected simulation environment. During testing, no communication failures were detected, and all data from the virtual PLC were received and visualized on the interface without significant delays. The interface successfully displays pH values, temperature, water level, and actuator status on a single, integrated supervision page and provides an alarm acknowledgment button for the operator. All parameters are automatically recorded via Tag Logging in CSV format with consistent timestamps, allowing each event to be traced chronologically. A view of the supervision interface, which integrates all process information on a single page, is shown in Figure 3.

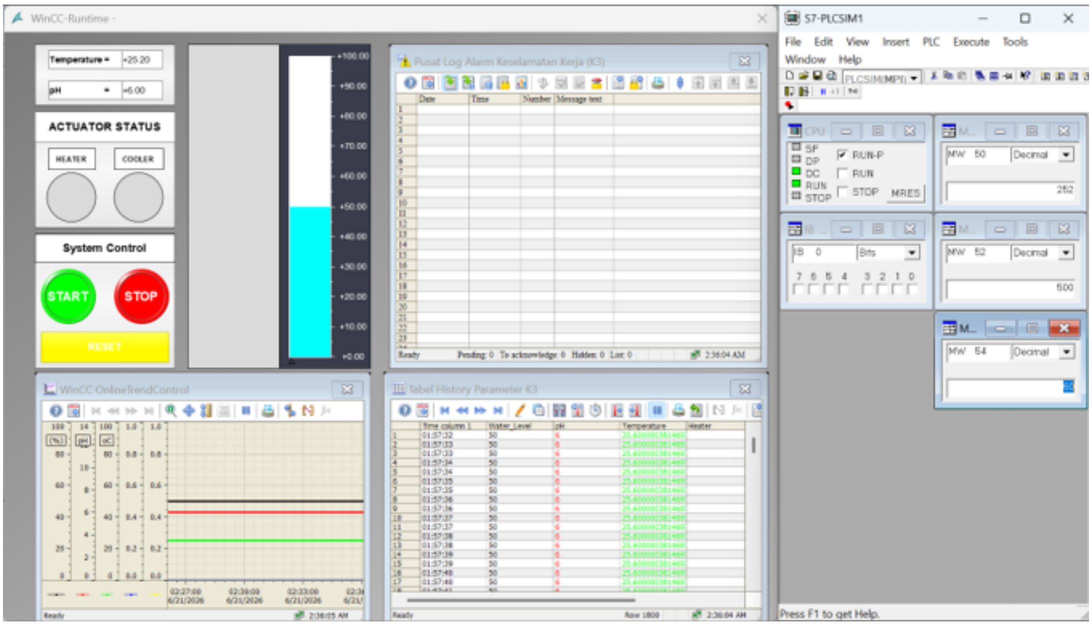

Figure 3. Supervision interface view

Evaluation of the safety function showed that the safety alarm appeared in all tested scenarios when the pH dropped below 5.6, without a single hazardous condition being missed. The single-acknowledgment mechanism successfully distinguished an unacknowledged alarm from a confirmed one, and the alarm remained active as long as the causative condition persisted. Of the three injected hazardous-condition scenarios, all three were correctly detected, resulting in a Probability of Detection of 100%. The K3 alarm condition displayed on the interface when the system detected abnormal conditions is shown in Figure 4.

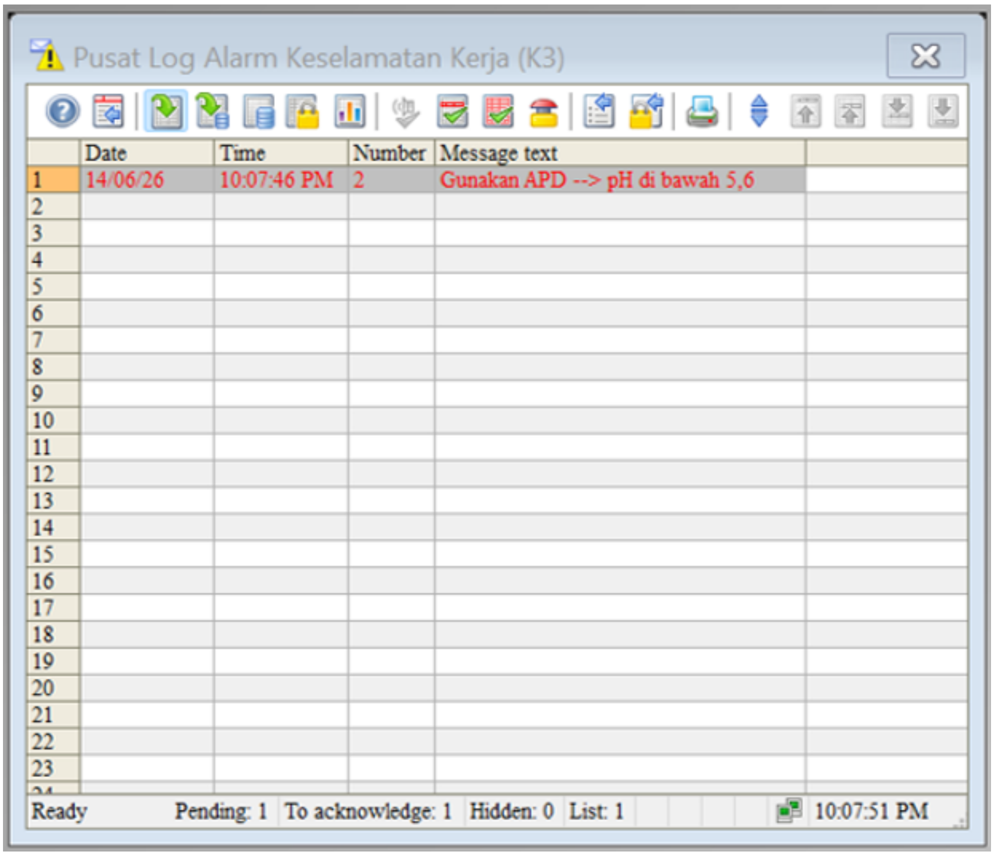

Figure 4. Condition of the K3 alarm

Preventive maintenance evaluation showed that Out-of-Range Detection was able to identify extreme values for temperature (0 and 100 °C) and pH (0 and 14) by consistently activating the sensor error bits. Counter-Based Fault Detection increased the counter value for each fault occurrence and maintained the monitoring status after the first and second faults, then automatically activated maintenance alarms and emergency shutdowns upon the third fault within a 60-second window. The stages of increasing the counter value and changing the system state at each fault event are shown in Table 2. Reliability evaluation across three scenarios resulted in different availability values, as shown in Table 3. Comparison of the first and second scenarios showed that shortening the repair time increased availability from 66% to 83.3%, while comparison of the second and third scenarios showed that reducing the number of failures increased availability to 93%.

Table 2

Counter-based fault detection testing

Fault Occurrence	pH	Temperature (ºC)	Counter
Fault 1	7.0	0.0	1
Fault 2	0.0	25.5	2
Fault 3	7.0	100.0	3

Table 3

Comparison of the first and second scenarios

Scenario	Number of Failures (times)	Repair Time per Occurrence (minutes)	MTBF (min)	MTTR (minutes)	Availability (%)
1	5	2	4	2	66
2	5	1	5	1	83,3
3	2	1	14	1	93

Discussion

The above findings suggest that the three gaps identified in previous research can be addressed simultaneously on a single platform. The successful uninterrupted communication and consistent historical recording confirm that the ISA-95-based separation of functions effectively coordinates previously separate subsystems, thereby overcoming the lack of centralized oversight in real-time IoT systems. The 100% Probability of Detection achieved by the K3 module demonstrates that the principle of functional safety can be implemented not merely as an administrative procedure but as an automatic detection and response logic embedded in the supervisory system. This is important because previous studies reported extreme pH conditions of 1.73 without any response, whereas in the proposed system, similar conditions would immediately trigger layered alarms and protective measures. Thus, the integration of a simple Safety Instrumented System (SIS) into SCADA has proven feasible for application in the context of environmental monitoring, complementing the view that SIS implementation needs to consider the suitability of the system's scale relative to the associated risk.

On the preventive maintenance side, the combination of Out-of-Range Detection and Counter-Based Fault Detection demonstrates the advantages of a fault-frequency-based approach over single-anomaly detection, as protection decisions are not made based on a single deviant reading but on a recurring pattern of interference. This approach is consistent with the principle of Condition-Based Maintenance, which uses the actual condition of an instrument as the basis for maintenance decisions while simultaneously maintaining data validity, which is central to the acid deposition monitoring problem. The variable availability values demonstrate that system reliability is determined by both the frequency of failures and the speed of recovery. Therefore, maintenance strategies that accelerate recovery and suppress recurring failures contribute directly to the continuity of environmental data acquisition.

The novelty of this research lies in the unification of supervision, safety, and preventive maintenance within a single architecture that was safely tested through Software-in-the-Loop, an approach that has not been implemented across all three previous stages of research within the same chamber. Theoretically, these findings extend the application of the industrial automation framework to environmental monitoring by incorporating the dimensions of occupational safety and instrument diagnostics. In practical terms, this system can serve as a blueprint for safer and more reliable acid deposition monitoring stations. Its international relevance is also strong because acid deposition is a transboundary issue coordinated through regional monitoring networks. Therefore, an integration framework that ensures data validity and traceability has the potential to support data interoperability among stations at the regional level. In addition, the integration of safety into the monitoring system is consistent with the global direction of occupational safety management, which increasingly emphasizes technology-based prevention (Güney & Kahraman, 2022; Ramos et al., 2022).

CONCLUSION

This study demonstrates that supervisory control, Occupational Health and Safety management, and condition-based preventive maintenance can be integrated within a single SCADA architecture for acid deposition monitoring. The Software-in-the-Loop evaluation showed uninterrupted data acquisition at 1-second intervals, a 100% Probability of Detection across the three tested hazardous scenarios, and availability ranging from 66% to 93%, depending on failure frequency and repair time. These findings indicate that integrating safety and condition-based diagnostics into the supervisory layer can improve monitoring reliability while supporting the validity and traceability of environmental measurement data. The scientific contribution of this study lies in extending the application of industrial automation and ISA-95-based supervisory architecture to acid deposition monitoring by integrating operational safety and instrument diagnostics within a single system. Future research should prioritize: (1) physical hardware validation under operational field conditions; (2) expansion of monitored parameters to include conductivity and ion concentration; (3) integration of machine-learning-based predictive maintenance; and (4) implementation of IoT and web-based dashboards for remote monitoring and environmental data accessibility.

However, the findings remain limited to Software-in-the-Loop simulation, three hazard scenarios, and a restricted set of monitored parameters; therefore, the 100% Probability of Detection should not be interpreted as universal field performance. Further research should validate the system using physical hardware and field measurements under real environmental conditions, expand the monitored parameters to include conductivity and ion concentration, and incorporate machine-learning-based predictive maintenance. Integration with IoT and web-based dashboards can also be explored to support remote monitoring, interoperability, and broader environmental data accessibility.

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AUTHOR CONTRIBUTION STATEMENT

Tsaqif Muhammad: Conceptualization, Methodology, Software, System Design, Formal Analysis, Data Curation, and Writing Original Draft Preparation. Faiz Husnayain: Methodology, Validation, Supervision, Data Interpretation, and Project Administration. Both authors contributed to the development and evaluation of the research and approved the final version of the manuscript.

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