International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 11 | Nov 2026 www.irjet.net p-ISSN: 2395-0072

Automated Operation Theatre Sterilization System Using Internet of Things and Artificial Intelligence

Chandana KR[1], Swapna KY[2], Shankar B Kori[3]

[123]*Department of Computer Science and Engineering, Sir M Visvesvaraya Institute of Technology, Bengaluru, India*

Abstract - *Manual operation theatre sterilization is time-consuming, inconsistent, and highly dependent on continuous staff supervision, creating challenges in maintaining reliable disinfection practices. Conventional approaches generally rely on fixed sterilization durations and manual safety verification, which may not adequately reflect changing room conditions. This work presents an Automated Operation Theatre Sterilization System that combines IoT-based environmental monitoring with machine-learning-assisted sterilization control. The proposed system continuously collects temperature, humidity, air-quality, occupancy, door-status, and ambient-light data using an ESP32-based sensing unit. Linear Regression is employed to estimate sterilization duration from environmental conditions, while Isolation Forest is used to identify abnormal sensor conditions. Based on the monitored data, the system coordinates UV-C irradiation, H_2O_2 fogging, and exhaust/HEPA ventilation while continuously monitoring safety conditions and pausing the cycle when an unsafe condition is detected. The implemented system was evaluated through functional testing of sensor communication, web monitoring, sterilization workflow execution, and safety-control operations. The AI module provides sterilization-duration prediction and abnormal-condition detection as an integrated decision-support component, while the implemented workflow demonstrates automated cycle execution and safety-aware control.*

Keywords - Automated OT Sterilization, UV-C Disinfection, IoT Environmental Monitoring, Linear Regression, Isolation Forest, H_2O_2 Fogging, Safety Monitoring.

I. INTRODUCTION

Hospital-acquired infections remain an important concern in healthcare environments, making reliable operation theatre (OT) cleaning and disinfection essential for patient safety. Conventional terminal disinfection commonly involves manual cleaning, chemical treatment, or fixed-duration UV-C exposure. Although these methods can reduce environmental contamination, their effectiveness depends on room conditions, exposure duration, proper execution, and cleaning procedures [1],[2],[3],[4].

UV-C-based systems have been increasingly used for automated hospital disinfection. Studies have demonstrated their application in healthcare environments, including surgical theatres and critical-care areas [5], while treatment duration can vary with room characteristics and operating conditions [6]. UV-C robots have also been used for automated cleaning in critical hospital areas and routine cleaning processes [7], [8]. However, treatment effectiveness may still be affected by surface accessibility, equipment positioning, and exposure conditions [3], [6].

Recent research has introduced artificial intelligence, IoT, and autonomous operation into disinfection systems. AI-based approaches have been explored for selective and directional UV irradiation [9]. ESP32-based IoT platforms enable continuous environmental sensing and communication [10], while machine-learning methods such as LSTM-based analysis and Isolation Forest have been applied to environmental anomaly detection [11], [12]. ESP32 has also been used in healthcare monitoring applications [13]. Further work has explored AI-powered UV sterilization for ICU hygiene and surgical-tool disinfection [14], as well as autonomous AI-IoT systems for maintaining air quality and sterility in surgical environments [15]. PIR-based sensing can support human-presence detection for sterilization safety [16].

Despite these developments, integration of real-time environmental sensing, sterilization-duration estimation, multi-stage disinfection, safety monitoring, and workflow management remains limited. Whole-room disinfection also requires proper process control [17]. Hydrogen-peroxide-based disinfection can provide complementary coverage, although its effectiveness depends on the delivery method [18]. Studies comparing UV-C and chemical treatment further highlight the need for appropriate process selection [19]. These factors motivate an integrated and low-cost OT sterilization architecture that combines sensing, intelligent control, safety, and disinfection within a single workflow [20].

This work presents an Automated Operation Theatre Sterilization System integrating ESP32-based IoT sensing, Spring Boot backend coordination, SQLite persistence, Python-based machine learning, relay-controlled actuators, and web-based monitoring. DHT22, MQ135, PIR, reed-switch, and LDR sensors provide environmental and safety information. Linear Regression estimates sterilization duration, while Isolation Forest identifies abnormal sensor conditions [12]. The system coordinates UV-C irradiation, H_2O_2 fogging, and exhaust/HEPA

ventilation as sequential phases. Continuous occupancy and door-status monitoring enables interruption during unsafe conditions, while stored workflow information supports controlled pause-and-resume operation.

The main contributions of this work are:

- An ESP32-based IoT system for continuous environmental and safety monitoring of the operation theatre.
- A machine-learning decision layer using Linear Regression for sterilization-duration estimation and Isolation Forest for anomaly detection.
- An automated multi-stage sterilization process combining UV-C irradiation, H_2O_2 fogging, and exhaust/HEPA ventilation with continuous safety monitoring.
- A persistent backend and web dashboard for workflow control, data logging, real-time monitoring, and controlled pause-and-resume operation.

The rest of the paper is organized as follows. Section II presents the literature review. Section III describes the proposed methodology. Section IV presents the implementation and experimental results. Section V concludes with the major findings, advantages, limitations, and future scope.

II. LITERATURE REVIEW

Research on automated healthcare disinfection has expanded from conventional UV-C treatment toward autonomous systems, connected sensing, artificial intelligence, and whole-room chemical disinfection. Existing studies demonstrate that these technologies can improve disinfection effectiveness and reduce dependence on manual intervention; however, treatment duration, environmental conditions, safety, room coverage, and workflow coordination remain important challenges.

Barakat et al. [1] investigated an AI-enabled autonomous UV-C system for reducing pathogens in an endoscopy environment and demonstrated the potential of intelligent UV-C operation for reducing microbial contamination. Maugeri et al. [2] reviewed UV-light disinfection technologies used across healthcare environments and highlighted their effectiveness while emphasizing variation in outcomes across different applications. Yui et al. [3] evaluated a targeted UVC decontamination system under laboratory and practical conditions, demonstrating the importance of controlled exposure for achieving effective decontamination. Bosco et al. [4] studied UV-C treatment in hospital theatres and reported improved environmental disinfection following its implementation. Herrera et al. [5] evaluated an autonomous programmable UV-C system in surgical and intensive-care environments, demonstrating the feasibility of automated terminal disinfection. These studies demonstrate the potential and practical applicability of UV-C technology but primarily concentrate on UV-based treatment rather than coordinating several disinfection stages through a condition-aware control system.

The duration of UV-C exposure is another important consideration. Dexter et al. [6] analyzed a large collection of room-disinfection treatments and reported considerable variation in treatment time across rooms and individual cycles. Their findings indicate that applying one fixed exposure duration may not provide an appropriate solution for different room conditions. Casini et al. [7] investigated the use of a UV-C robot within hospital critical areas, while Füszl et al. [8] examined its integration into routine hospital cleaning. Both studies demonstrated the practical value of robotic UV-C systems while also illustrating the importance of room configuration and operational procedures. Zierdt et al. [9] introduced artificial intelligence for selective UV irradiation, using intelligent targeting to improve the efficiency and safety of UV-based treatment. Although these approaches introduce automation and intelligence, they do not provide a complete workflow in which environmental measurements determine the duration of multiple sequential sterilization phases.

IoT-based sensing provides a suitable foundation for continuous monitoring of environmental conditions. Hercog et al. [10] investigated ESP32-based IoT devices for sensing, communication, and embedded control, demonstrating the suitability of the platform for connected applications. Wei et al. [11] investigated anomaly detection in indoor air-quality time-series data using an LSTM autoencoder, demonstrating the usefulness of machine learning for identifying unusual environmental patterns. Huang et al. [12] applied Isolation Forest to air-quality monitoring for detecting abnormal observations, providing a comparatively lightweight approach for environmental anomaly detection. Beri et al. [13] demonstrated an ESP32-based IoT health-monitoring system capable of collecting and transmitting sensor information. These works provide technical foundations for the proposed sensing and monitoring architecture, but they do not combine environmental sensing, intelligent decision-making, and automated OT disinfection within one system.

AI and sensor-based automation have also been explored specifically for sterilization applications. Rinshad et al. [14] investigated an AI-assisted UV sterilization system for ICU hygiene and surgical-tool disinfection, demonstrating the potential of intelligent exposure control. Ratna Raju et al. [15] explored an autonomous robotic platform combining AI and IoT for air-quality management and sterility maintenance in surgical environments. Amrullah et al. [16] developed an automatic sterilization gate using

PIR-based motion detection, demonstrating how occupancy information can be used to control automated disinfection. These studies support the use of AI, IoT, and occupancy sensing in automated sterilization; however, they do not integrate these functions with sequential UV-C, chemical fogging, ventilation, persistent workflow control, and continuous safety monitoring.

Chemical whole-room disinfection provides another complementary approach. van der Starre et al. [17] reviewed automated whole-room disinfection technologies and discussed factors that influence their practical implementation. Amaeze et al. [18] investigated how hydrogen-peroxide delivery mechanisms affect disinfection performance, demonstrating the importance of the delivery method in chemical treatment. Fickenscher et al. [19] compared UV-C and chemical treatment approaches for operating-room disinfection, highlighting the relevance of both methods for environmental cleaning. Xie et al. [20] examined operating-room cleaning and disinfection from a human-factors and systems-engineering perspective, emphasizing the interaction between technology, procedures, and human operation. These studies support the use of complementary disinfection methods while indicating the need for appropriate process coordination and safety measures.

Overall, the reviewed literature covers several important aspects of automated OT disinfection, including UV-C treatment [1]–[9], IoT-based sensing [10], [13], machine-learning-based anomaly detection [11], [12], AI-assisted sterilization [14], [15], occupancy-based automation [16], whole-room disinfection [17], [18], and operating-room cleaning practices [19], [20]. However, these capabilities are largely investigated independently rather than as a single integrated workflow. The proposed system addresses this gap by combining continuous environmental sensing, machine-learning-based duration estimation, anomaly detection, UV-C irradiation, H_2O_2 fogging, exhaust/HEPA ventilation, occupancy and door-status monitoring, persistent workflow management, and digital logging within a low-cost architecture. The integration of ESP32, Spring Boot, SQLite, Python-based machine learning, relay-controlled actuators, and a web dashboard provides a unified framework for automated and traceable OT sterilization.

III. PROPOSED SYSTEM AND METHODOLOGY

A. System Design and Architecture

The proposed system follows a closed-loop architecture integrating environmental sensing, IoT communication, machine-learning analysis, automated actuation, and monitoring. As shown in Fig. 1, the ESP32 acts as the edge controller and acquires temperature, humidity, air-quality, occupancy, door-status, and ambient-light information. The collected data are transmitted through Wi-Fi using HTTP/REST communication to the Spring Boot backend. The backend coordinates the sterilization workflow, validates safety conditions, stores system information in SQLite, and communicates with the Python Flask AI service. The AI module performs sterilization-duration estimation using Linear Regression and detects abnormal environmental conditions using Isolation Forest. Based on the AI output and safety status, the backend sends control commands to the ESP32, which operates the relay-controlled UV-C lamp, H_2O_2 fogging unit, and exhaust/HEPA fan. The dashboard provides real-time visualization of sensor values, device status, workflow progress, and stored records.

B. Sensor and Embedded Control

The ESP32 serves as the central embedded unit for sensor acquisition, communication, safety monitoring, and actuator control. DHT22 provides temperature and humidity measurements, MQ135 provides an indicative air-quality/gas reading, PIR detects occupancy or motion, reed switch monitors door status, and LDR measures ambient light. Sensor readings are periodically transmitted to the backend along with the current device state. The ESP32 also receives commands from the backend and controls the connected relay channels. The relay module provides switching control for the UV-C lamp, H_2O_2 fogging unit, and exhaust fan, while the buzzer provides a local alert during safety interruptions or system events.

C. IoT and Software Framework

The software layer consists of ESP32 firmware, Spring Boot backend, SQLite database, Python Flask AI service, and browser-based dashboard. The Spring Boot backend provides REST communication, workflow coordination, data storage, device control, and session management. SQLite stores sensor measurements, sterilization sessions, AI recommendations, and system events. The Python Flask service provides machine-learning prediction and anomaly-detection functions using scikit-learn. Thymeleaf, Bootstrap, and Chart.js are used to provide the operator with real-time sensor information, workflow status, and historical data. The ESP32 exchanges sensor data and control commands with the backend through Wi-Fi and HTTP communication. This integration enables coordinated operation between sensing, AI-based analysis, device control, and real-time monitoring.

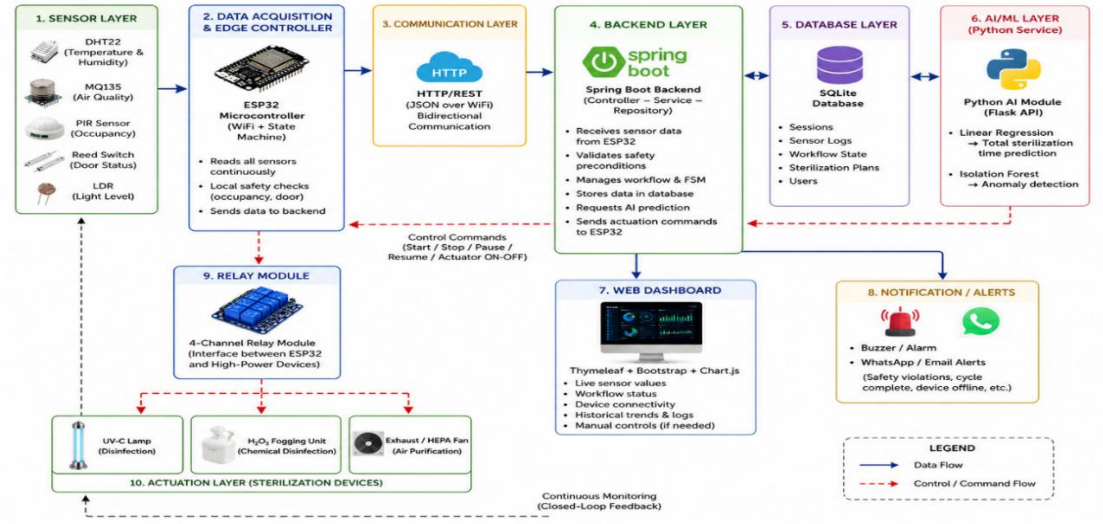

Fig. 1. System architecture of proposed Automated OT Sterilization System, showing sensor, communication, backend, AI, database, dashboard, actuation, and notification layers.

D. AI-Based Decision Process

The machine-learning module processes the environmental conditions obtained from the sensing layer before and during the sterilization cycle. Linear Regression is implemented to estimate sterilization duration using the available environmental parameters, while Isolation Forest is used to identify abnormal environmental patterns. The AI service receives the relevant sensor information through the backend and returns the estimated duration and anomaly information to support sterilization decision-making.

E. Sterilization Workflow and Safety Control

The complete operating sequence of the proposed system is illustrated in Fig. 2. The process begins with initialization of the ESP32, sensors, communication interface, and relay outputs, followed by a system self-check. Before sterilization, the backend verifies device status and checks the OT door and occupancy conditions. If the door is open or motion is detected, the system remains in the waiting state until the room is confirmed safe. The latest environmental readings are then sent to the AI service for analysis.

Based on the AI output, the backend prepares the sterilization plan and sends the required control information to the ESP32. The cycle proceeds through UV-C irradiation, H_2O_2 fogging, and exhaust/HEPA ventilation. Safety monitoring remains active throughout all phases.

If motion is detected or the door is opened, active actuators are immediately stopped, the safety event is recorded, and the workflow enters a paused state. After the unsafe condition is cleared and authorized resume is performed, the cycle continues from the stored workflow state rather than restarting.

After ventilation, the system performs post-cycle environmental verification. The sterilization session, sensor readings, AI recommendation, workflow state, and safety events are stored in the database, while the dashboard is updated with the final status. A notification can also be generated for the configured operator.

F. Data Logging and Monitoring

All important information generated during operation is maintained through the backend and SQLite database. Sensor measurements, sterilization-session details, AI predictions, workflow states, and safety events are recorded to provide a persistent history of system operation. The web dashboard displays current environmental conditions, device connectivity, sterilization status, and historical information through graphical visualization. The stored records can also be used for reviewing previous sterilization cycles and evaluating system operation. After successful completion of a cycle, the notification mechanism can provide a WhatsApp alert to the configured recipient.

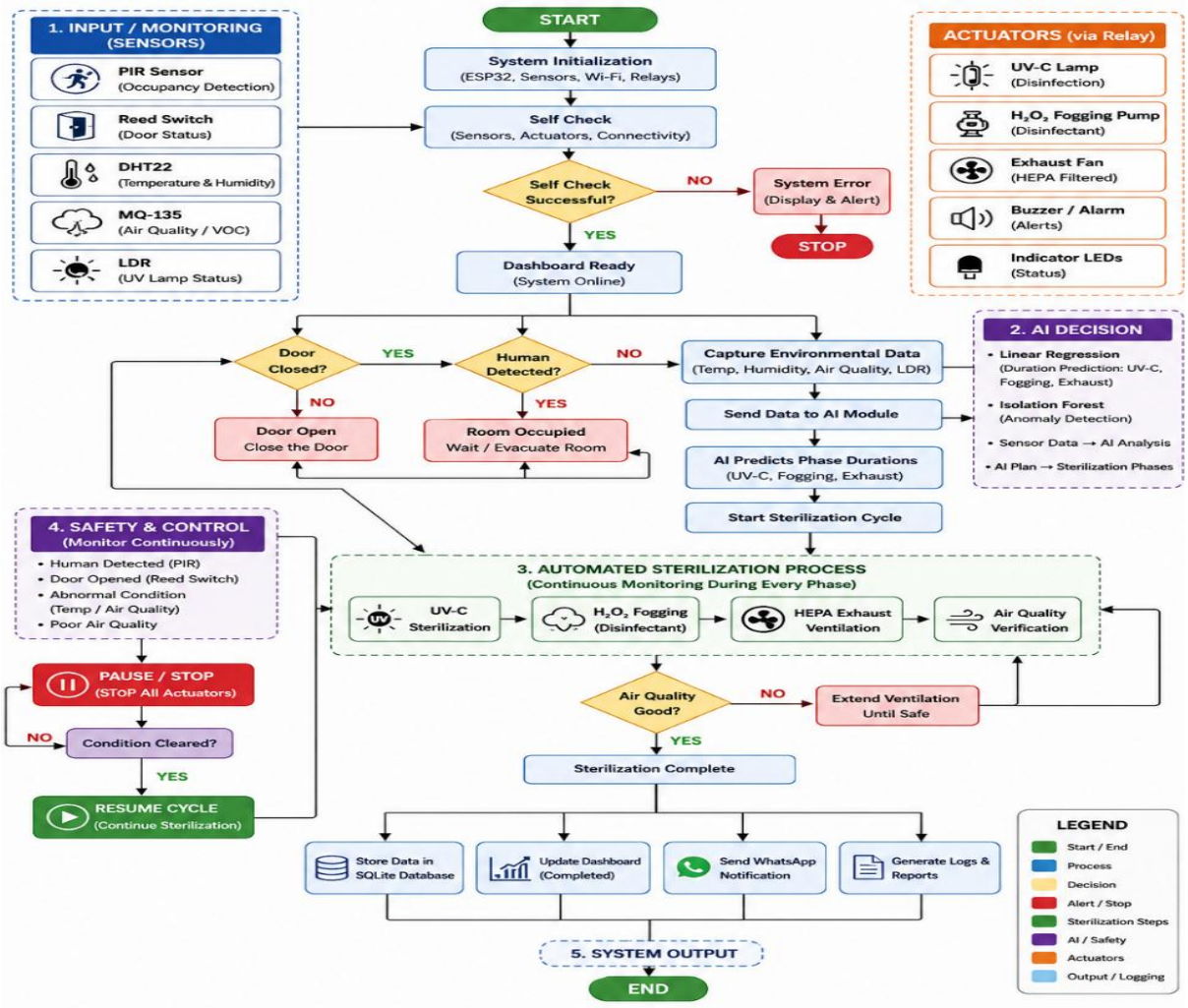

Fig. 2. Complete workflow of Automated OT Sterilization System, from initialization through sterilization phases to completion, with continuous safety monitoring.

IV. RESULTS AND IMPLEMENTATION

This section presents the implementation and software-level results obtained from the developed Automated Operation Theatre Sterilization System. The implemented system integrates the ESP32 sensing node, Spring Boot backend, database, AI service, and web-based monitoring interface. The developed dashboard and control modules were tested to verify sensor communication, system status monitoring, sterilization workflow execution, and data visualization.

A. Implementation of the Proposed System

The proposed system was implemented using an ESP32 as the sensing and control node, connected to the DHT22, MQ135, PIR, reed-switch, and LDR sensors. The ESP32 acquires environmental and safety information and communicates the readings to the Spring Boot backend through Wi-Fi. The backend manages sensor data, system states, sterilization sessions, and control commands, while the relay module provides control of the connected sterilization devices.

The implemented system successfully displays the current OT condition, door status, sterilization status, air-quality condition, and sensor values through the web dashboard. The dashboard also provides control options for starting and resetting the sterilization process. The implemented interface is shown in Fig. 3.

B. Web Monitoring and Sterilization Control

The live monitoring module provides continuous visualization of the sensor information received from the ESP32. Temperature, humidity, air quality, room occupancy, door status, UV-lamp status, fan status, and fogger status are displayed on the monitoring interface. During testing, the dashboard displayed a temperature of approximately 28.3 °C, humidity of approximately 60.3%,

and MQ135 air-quality readings of approximately 656 ppm. The PIR sensor indicated that the room was empty and the door-status sensor indicated that the door was closed.

The monitoring page also plots the sensor readings over time, allowing variations in temperature, humidity, and air quality to be observed during operation. These observations demonstrate the operation of the real-time sensing and visualization layer of the proposed system, as shown in Fig. 4.

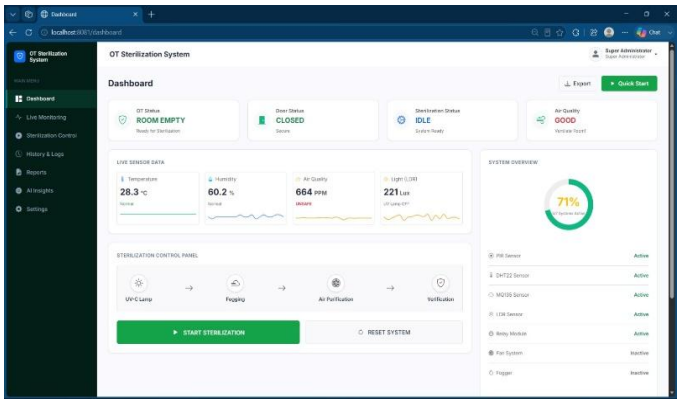

Fig. 3. Dashboard of the implemented Automated OT Sterilization System showing OT status, door status, sterilization status, air-quality condition, live sensor values, and device status.

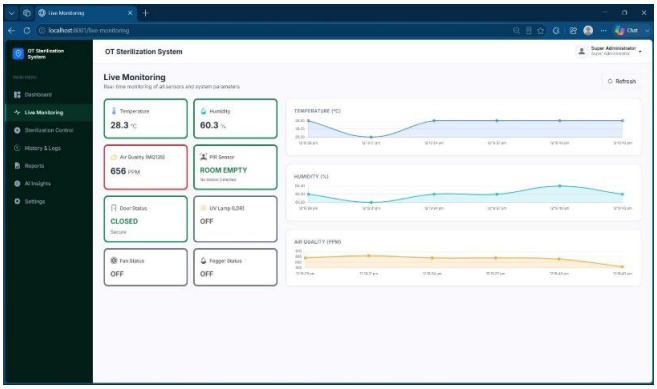

Fig. 4. Live monitoring interface displaying real-time sensor readings and corresponding temperature, humidity, and air-quality trends.

C. Sterilization Control and Workflow Implementation

The sterilization control module implements the sequential workflow required for the proposed system. The implemented sequence consists of Room Empty, Door Closed, UV-C Lamp, Fogging, Air Purification, Air Quality Check, and Room Ready states. The control interface provides Start, Pause, and Emergency Stop operations, allowing the sterilization cycle to be controlled from the web application.

During the prototype test cycle, all seven workflow stages were completed and the process indicator reached 100%, with the interface reporting 'Cycle Complete.' The configured test durations displayed for UV-C irradiation, fogging, and air purification were 45 s, 30 s, and 25 s, respectively. The completed workflow is shown in Fig. 5.

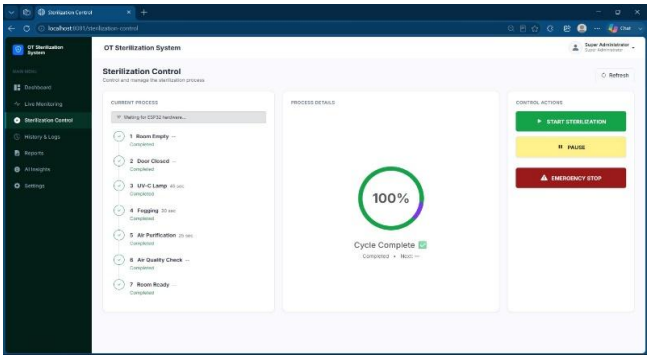

Fig. 5. Sterilization control interface showing the implemented seven-stage workflow and completed sterilization cycle.

D. Machine-Learning and Decision Support Implementation

The AI component was implemented as a separate Python Flask service using scikit-learn. Linear Regression is used to estimate sterilization-cycle duration from environmental parameters, while Isolation Forest is used to identify abnormal environmental conditions. The AI service receives the relevant sensor information through the backend and returns prediction and environmental-analysis results to the web application.

The AI Insights interface displays the predicted next-cycle duration, air-quality trend, recommended action, and accumulated cycle statistics. In the implemented system, the dashboard displayed a predicted next-cycle duration of 1.7 min along with an improving air-quality trend and a "No Action Needed" recommendation. These results demonstrate the integration of the AI prediction and decision-support layer with the IoT monitoring and sterilization-control system. Quantitative model-accuracy evaluation using a larger experimental dataset remains part of future validation.

E. Obtained Implementation Results and Discussion

The implementation demonstrates that the major software and control components of the proposed system operate together as an integrated system. The ESP32 successfully provides sensor information to the monitoring interface, the dashboard displays the current

environmental and safety conditions, and the sterilization-control module represents the complete sequential workflow. The successful completion of the seven-stage workflow to **100%** demonstrates that the control logic and workflow-management components have been implemented and tested.

The developed system provides real-time visualization, sterilization workflow control, AI-based prediction, and historical monitoring through the web interface. The AI module is successfully integrated into the system and provides sterilization-duration estimation and environmental decision support. However, quantitative evaluation of prediction accuracy and clinical sterilization efficacy, including microbial reduction and pathogen inactivation, requires controlled experimental validation. The obtained results therefore demonstrate the functional integration and operation of the IoT, AI, backend, monitoring, and sterilization-control components.

V. CONCLUSION

This work presents an Automated Operation Theatre Sterilization System that combines IoT sensing, machine learning, automated disinfection, and web-based monitoring into a single platform. The ESP32 is used to collect environmental and safety-related information from the operation theatre, while the Spring Boot backend, SQLite database, Python machine-learning service, and web dashboard coordinate and monitor the overall sterilization workflow. The system uses sensor readings such as temperature, humidity, air quality, human presence, and door status to support safer and more controlled operation. Linear Regression is used to estimate sterilization duration, while Isolation Forest helps identify abnormal environmental conditions. The sterilization process is divided into sequential stages involving UV-C irradiation, H_2O_2 fogging, and exhaust/HEPA ventilation, with continuous monitoring throughout the cycle. Storing sensor values, predictions, workflow states, and sterilization sessions also provides a useful digital record for analysis and future improvement.

The implemented system demonstrates how IoT, AI, and software-based workflow management can be combined to reduce manual involvement and improve monitoring of OT sterilization activities. Continuous occupancy and door monitoring provides an additional safety layer by allowing the process to be interrupted when unsafe conditions are detected, while the pause-and-resume mechanism helps maintain workflow continuity. However, the current work is still a prototype, and complete physical and clinical validation has not yet been carried out. Future development will focus on full hardware integration, validation of sterilization-time predictions under different environmental conditions, verification of air quality after H_2O_2 treatment, and controlled testing of actual microbial reduction. Larger datasets collected from different operating conditions can also help improve the machine-learning models. Further testing in real OT environments would be required to evaluate reliability, safety, scalability, and practical deployment across multiple operating theatres.

REFERENCES

[1] M. T. Barakat, M. Noshad, and T. Angelotti, “Pathogen reduction in an endoscopy unit using AI-enabled autonomous UV-C disinfection,” Amer. J. Infect. Control, vol. 54, no. 2, pp. 158–162, 2026, doi: 10.1016/j.ajic.2025.09.006.

[2] A. Maugeri, B. Casini, E. Esposito, S. Bracaloni, M. Scarpaci, F. Patanè, G. Milazzo, A. Agodi, and M. Barchitta, “Impact of ultraviolet light disinfection on reducing hospital-associated infections: A systematic review in healthcare environments,” J. Hosp. Infect., 2025.

[3] S. Yui, K. Karia, M. Muzslay, P. Wilson, and S. Ali, “In-vitro and in-use efficacy of a rapid, targeted UVC decontamination system,” J. Hosp. Infect., 2025.

[4] R. Bosco, G. Cevenini, S. Gambelli, N. Nante, and G. Messina, “Improvement and standardization of disinfection in hospital theatre with ultraviolet-C technology,” J. Hosp. Infect., vol. 128, pp. 19–25, 2022, doi: 10.1016/j.jhin.2022.07.006.

[5] S. Herrera, I. Roca, A. Del Río, J. Fernández, C. Pitart, I. Fortes, B. Torralbo, G. Santana, R. Parejo-González, A. Veà-Baró, J. M. Campistol, M. Aguilar, S. Degea, C. Casals-Pascual, A. Soriano, and J. A. Martínez, “Performance of an autonomous sanitary sterilisation ultraviolet machine (ASSUM) on terminal disinfection of surgical theaters and rooms of an intensive-intermediate care unit,” Infection Prevention in Practice, vol. 6, no. 4, Art. no. 100396, 2024, doi: 10.1016/j.infpip.2024.100396.

[6] F. Dexter, B. Birchansky, R. H. Epstein, and R. W. Loftus, “Average and longest expected treatment times for ultraviolet light disinfection of rooms,” Amer. J. Infect. Control, vol. 50, no. 1, pp. 61–66, 2022, doi: 10.1016/j.ajic.2021.08.020.

[7] B. Casini, B. Tuvo, M. Scarpaci, M. Totaro, F. Badalucco, S. Briani, G. Luchini, A. L. Costa, and A. Baggiani, “Implementation of an environmental cleaning protocol in hospital critical areas using a UV-C disinfection robot,” International Journal of Environmental Research and Public Health, vol. 20,

no. 5, Art. no. 4284, 2023, doi: 10.3390/ijerph20054284.

[8] A. Füszl, B. Zatorska, M. Van den Nest, J. Ebner, E. Presterl, and M. Diab-Elschahawi, "The use of a UV-C disinfection robot in the routine cleaning process: a field study in an academic hospital," Antimicrobial Resistance & Infection Control, vol. 10, no. 1, 2021, doi: 10.1186/s13756-021-00945-4.

[9] B. Zierdt, T. Shi, T. Degroat, S. Furman, N. Papas, Z. Smoot, H. Zhang, and B. Wu, "Selective disinfection based on directional ultraviolet irradiation and artificial intelligence," Electronics, vol. 10, no. 20, Art. no. 2557, 2021, doi: 10.3390/electronics10202557.

[10] D. Hercog, T. Lerher, M. Truntič, and O. Težak, "Design and implementation of ESP32-based IoT devices," Sensors, vol. 23, no. 15, Art. no. 6739, 2023, doi: 10.3390/s23156739.

[11] Y. Wei, J. Jang-Jaccard, W. Xu, F. Sabrina, S. Camtepe, and M. Boulic, "LSTM autoencoder-based anomaly detection for indoor air quality time-series data," IEEE Sensors Journal, vol. 23, no. 4, pp. 3787–3800, 2023, doi: 10.1109/JSEN.2022.3230361.

[12] L. Huang, W. Dai, Z. Zhang, and J. Xiao, "Anomaly detection in air quality monitoring systems using Isolation Forest," Environmental Monitoring and Assessment, vol. 193, no. 7, Art. no. 412, 2021, doi: 10.1007/s10661-021-09158-5.

[13] M. Beri, B. Kumar, S. Tiwari, N. Sharma, H. Vashishtya, and P. Chaudhary, "IoT based health monitoring system built on ESP32," in Proc. 2022 2nd Int. Conf. Advance Computing and Innovative Technologies in Engineering (ICACITE), 2022, pp. 454–458, doi: 10.1109/ICACITE53722.2022.9823528.

[14] M. Rinshad et al., "AI-powered automated UV sterilization system for ICU hygiene and surgical tool disinfection," International Journal of Innovative Research in Science, Engineering and Technology, vol. 14, no. 5, 2025.

[15] A. Ratna Raju et al., "Autonomous robots for air quality control and sterility maintenance in surgical rooms using AI and IoT," in Proc. 2025 Int. Conf. Smart & Sustainable Technology (INCSST), 2025, doi: 10.1109/INCSST64791.2025.11210254.

[16] F. F. Amrullah, D. Khairani, and S. U. Masruroh, "Design of an automatic sterilization gate tool using PIR motion sensor," Jurnal Pilar Nusa Mandiri, vol. 17, no. 1, pp. 25–30, 2021, doi: 10.33480/pilar.v17i1.1937.

[17] C. M. van der Starre et al., "The in situ efficacy of whole room disinfection devices: a literature review with practical recommendations for implementation," Antimicrobial Resistance & Infection Control, vol. 11, Art. no. 149, 2022, doi: 10.1186/s13756-022-01183-y.

[18] N. J. Amaeze et al., "Influence of delivery system on the efficacy of low concentrations of hydrogen peroxide in the disinfection of common healthcare-associated infection pathogens," J. Hosp. Infect., vol. 106, no. 1, pp. 189–195, 2020, doi: 10.1016/j.jhin.2020.06.031.

[19] M.-C. Fickenscher et al., "Operating room disinfection: operator-driven ultraviolet 'C' vs. chemical treatment," Infection Prevention in Practice, vol. 5, no. 3, Art. no. 100301, 2023, doi: 10.1016/j.infpip.2023.100301.

[20] A. Xie et al., "Environmental cleaning and disinfection in the operating room: a systematic scoping review through a human factors and systems engineering lens," Infection Control & Hospital Epidemiology, vol. 45, no. 7, pp. 880–889, 2024, doi: 10.1017/ice.2023.280.