International Journal of Informatics and Computation (IJICOM)
Vol. 8, No. 1, 2026
ISSN: 2685-8711, E-ISSN: 2714-5263 DOI: 10.35842/ijicom

Development of an IoT-Based Smart Audio System to Support Smart Pesantren Using the System Development Life Cycle Approach

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Abstract

Educational institutions have increasingly adopted digital technologies to automate learning support facilities. This study develops an IoT-based Smart Audio System to support the smart pesantren concept using an adapted System Development Life Cycle (SDLC) approach. The research aims to transform a conventional manually operated audio system into an integrated, automated, and priority-based system capable of managing primary schedules, adhan, and announcements within a unified architecture. The development process follows structured stages of planning, analysis, implementation, integration, and testing to ensure systematic requirement traceability, logical stability, and controlled hardware–software integration. A rule-based priority mechanism is implemented to guarantee deterministic handling of scheduling conflicts, with adhan assigned the highest priority, followed by announcements and primary audio playback. Laboratory-scale validation demonstrates a 100% functional success rate across 10 repeated test scenarios for each core module, confirming system consistency and reliability. IoT-based remote control testing records an average response time of 1.63 seconds, indicating responsive and stable performance for operational needs. Compared to the previous manual system, which is prone to human error and execution delays, the proposed system significantly improves timing accuracy, priority logic stability, and management efficiency. These findings confirm that the structured application of SDLC effectively enhances the quality and reliability of integrated IoT-based systems while contributing to the digital transformation of audio management in Islamic boarding school environments.

Keywords:
Internet of Things, Smart Audio System, System Development Life Cycle

1. Introduction

The rapid growth of the Internet of Things (IoT) transforms how physical devices interact, communicate, and deliver intelligent services across various domains. IoT integrates sensors, embedded systems, and network protocols to enable real-time data exchange and automation. Researchers emphasize that IoT architectures must address scalability, interoperability, latency, and security challenges to support real-world applications effectively. In the context of audio systems, IoT enables distributed audio sensing, monitoring, and control through network-connected devices. However, many implementations still lack structured development methodologies, which results in limited reliability and maintainability. Therefore, integrating IoT with systematic software engineering approaches becomes essential for building robust smart audio systems [16], [20].

The concept of the Internet of Audio Things extends IoT capabilities specifically to audio acquisition, processing, and intelligent response. Smart microphones, edge processors,

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and cloud platforms collaborate to analyze environmental sounds, speech, and acoustic events in real time. Prior studies highlight that audio-enabled IoT systems support applications such as surveillance, smart cities, education, and assistive technologies. Despite these advancements, researchers identify challenges related to data synchronization, bandwidth consumption, and edge intelligence deployment. Many systems focus heavily on hardware innovation but provide limited discussion on structured lifecycle development. This gap indicates the need for a systematic development approach such as the System Development Life Cycle (SDLC) to ensure design consistency and performance validation [1], [2].

Urban sound monitoring represents one of the most relevant applications of IoT-based smart audio systems. Researchers implement IoT frameworks combined with machine learning to classify environmental sounds and detect anomalies in smart cities. These systems improve urban management by identifying traffic noise, emergency signals, and public disturbances. Although the results demonstrate high classification accuracy and real-time capability, the studies primarily emphasize algorithmic performance rather than system development structure. As a result, integration, testing, and maintenance strategies often remain unclear. A structured SDLC approach can improve requirement analysis, system modeling, and deployment reliability in such IoT audio infrastructures [3], [17].

In educational environments, IoT-based audio systems enhance learning experiences through smart classrooms, automated announcements, and interactive language training systems. Researchers demonstrate that IoT audio technologies improve communication efficiency and classroom management. Smart education frameworks integrate sensors, network modules, and cloud platforms to deliver adaptive learning environments. However, these implementations frequently prioritize functionality over long-term maintainability and documentation. Without a clear development lifecycle model, scalability and system upgrades become challenging. Applying SDLC ensures systematic planning, requirement validation, testing procedures, and sustainable deployment in educational audio applications [8], [23], [24].

Smart home and smart building environments also adopt IoT-driven audio systems for voice control, automation, and security monitoring. Voice-command systems enable users to manage lighting, appliances, and security features efficiently. Studies show that IoT-based smart home systems improve user convenience and operational efficiency. Nevertheless, researchers report issues related to system integration complexity, device compatibility, and security vulnerabilities. Many projects implement rapid prototyping without comprehensive lifecycle documentation. By applying SDLC phases including planning, analysis, design, implementation, testing, and maintenance which developers can reduce system failure risks and enhance reliability in IoT-based smart audio control systems [7], [9], [14].

Religious institutions and public facilities increasingly implement automated audio timer systems and sound-level controllers using IoT platforms. These systems regulate announcements, prayer schedules, and audio output levels to improve service quality and minimize noise disturbances. Several studies present Arduino-based and IoT-integrated audio control prototypes that function effectively in controlled environments. However, they often lack standardized requirement analysis and post-deployment evaluation strategies. The absence of structured development methodology can lead to inconsistent performance and limited scalability. Integrating SDLC into IoT-based smart audio design ensures systematic validation and documentation throughout the system lifecycle [15], [26], [27].

Edge and fog computing architectures further strengthen IoT audio systems by enabling low-latency data processing near the data source. Researchers show that fog computing reduces bandwidth usage and enhances real-time sound classification performance. Edge-based anomaly detection and distributed processing improve system responsiveness in dynamic environments. Despite these technical strengths, studies typically concentrate on computational models rather than development governance. A comprehensive SDLC framework can bridge this gap by aligning technical architecture with clear system requirements, risk management, and iterative evaluation processes [2], [19].

Based on these prior works, current IoT-based audio solutions demonstrate strong technical feasibility but reveal methodological gaps in structured development and lifecycle management. Many systems achieve functional success but do not explicitly apply standardized software engineering approaches. This condition creates challenges in scalability, maintainability, documentation, and quality assurance. Therefore, this study focuses on designing an IoT-Based Smart Audio System using the SDLC approach to ensure systematic requirement analysis, modular design, controlled implementation, and rigorous testing. By integrating IoT architecture with SDLC principles, this research aims to produce a reliable, scalable, and sustainable smart audio system framework [13], [20].

2. Related Works

Researchers extensively investigated the evolution of IoT architectures to support intelligent and distributed applications. Al-Fuqaha et al. presented a comprehensive survey of enabling technologies, communication protocols, and application domains in IoT systems. They identified interoperability, scalability, and security as critical challenges in large-scale deployments. Similarly, Sethi and Sarangi reviewed IoT architectures and emphasized the importance of layered frameworks for device management and data processing. These studies provided a strong theoretical foundation for IoT system design. However, they mainly discussed general architectures and did not specifically address audio-centric IoT implementations or structured development methodologies for smart audio systems [16], [20].

Adil et al. introduced the concept of the Internet of Audio Things and highlighted its future vision, open challenges, and research opportunities. They explained how interconnected audio devices, edge processors, and cloud platforms collaboratively process acoustic signals. Antonini et al. further demonstrated the feasibility of smart audio sensors deployed at the IoT edge for anomaly detection. Their work showed that distributed audio processing improved responsiveness and reduced cloud dependency. While these studies successfully established the technical feasibility of IoT-based audio systems, they primarily focused on communication models and signal processing performance. They provided limited discussion on systematic software development practices such as lifecycle management and requirement validation [1], [2].

Urban sound monitoring received significant attention in smart city research. İşler developed an IoT framework for urban sound recognition and applied machine learning techniques to classify environmental audio events. Rana et al. proposed a fog computing architecture for scalable real-time urban sound classification. Their findings demonstrated improved latency and classification efficiency in distributed environments. These works showed strong technical performance and real-world applicability. However, they emphasized algorithmic accuracy and computing efficiency while offering minimal insight into structured development approaches, documentation processes, or maintenance strategies for long-term deployment [3], [17].

Several studies explored IoT-based smart audio systems in educational contexts. Wang et al. implemented IoT audio technology integrated with sensor networks to enhance speaking and listening training systems. Zeeshan et al. reviewed IoT applications in sustainable smart education and highlighted how connected technologies improved classroom interaction. Terzieva et al. discussed the role of IoT in enabling adaptive and interactive learning environments. These studies demonstrated clear educational benefits and system functionality. Nevertheless, they largely concentrated on system outcomes and user engagement metrics. They rarely detailed systematic lifecycle processes or validation frameworks to ensure reliability and scalability of the developed audio platforms [8], [23], [24].

Smart home automation systems frequently integrated voice-based control mechanisms. Chen et al. developed an IoT-driven smart home system that utilized voice commands for automation and security enhancement. Effendi et al. implemented a smart home framework combining IoT modules and mobile applications to improve user convenience. These studies proved that IoT-based audio control increased operational efficiency and accessibility. Despite their practical contributions, most implementations relied on rapid prototyping approaches. They offered limited explanation regarding structured requirement analysis, iterative testing procedures, or long-term maintenance planning, which are essential for sustainable system development [7], [9].

Research in religious and public facility environments also applied IoT to automate audio systems. Al-Oudat designed an IoT-based sound-level control system for audio amplifiers and demonstrated effective regulation of acoustic output. Fadlil et al. developed an Arduino-based automatic sound timer for mosques and prayer rooms. Hasby et al. designed an automated bell system equipped with audio output for educational institutions. These works successfully addressed real operational needs and showed practical feasibility. However, they primarily focused on hardware configuration and functional deployment. They did not comprehensively apply a structured development lifecycle model to guide planning, risk assessment, and system evaluation [15], [26].

Edge and fog computing architectures strengthened IoT-based audio processing capabilities. Bonomi et al. introduced fog computing as a distributed paradigm that reduced latency in IoT systems. Antonini et al. and Rana et al. applied edge-based processing for anomaly detection and real-time sound classification. Their findings confirmed that decentralized computation improved system responsiveness and reduced bandwidth consumption. Although these approaches enhanced technical performance, the studies rarely addressed structured development governance. They lacked detailed explanation of requirement traceability, validation phases, or iterative refinement aligned with software engineering standards [2], [19].

Recent research began incorporating structured methodologies into IoT applications. Melinda et al. implemented the System Development Life Cycle (SDLC) in developing an IoT-based lending locker application and demonstrated improved system documentation and validation clarity. Their study showed that applying SDLC phases that enhanced development transparency and system reliability. However, their work did not focus on audio systems or real-time acoustic processing environments. Therefore, a gap remained in integrating IoT-based smart audio system development with a comprehensive SDLC framework. This limitation motivated the present study to bridge technical IoT audio implementation with structured lifecycle management to achieve reliability, scalability, and maintainability [13].

Previous studies examined system automation only partially. They focused on specific features such as scheduled audio control, remote access, or hardware implementation. However, no study integrally combined scheduled audio automation, adhan and announcement priority mechanisms, IoT-based remote control, and a systematically documented SDLC framework within the context of Islamic boarding schools. This research addresses that gap. We develop an IoT-based Smart Audio System that integrates all technical components into a unified architecture. We apply a structured SDLC approach to ensure requirement traceability, stable priority logic, and consistent system testing.

3. Proposed Method

This study applies the System Development Life Cycle (SDLC) as a structured and systematic framework for developing the IoT-based Smart Audio System. We select SDLC because it supports sustainable, iterative, and well-documented system development, particularly for complex IoT environments that require integration between hardware controllers, web-based platforms, network modules, and audio priority mechanisms. Unlike previous studies that focused on single-domain implementations, this research integrates multiple system layers within a distributed Pesantren environment, which demands strong interoperability and risk management. We adapt SDLC into four main stages including Planning, Analysis, Implementation, and Integration while extending the Analysis phase to include hardware specifications, network topology, scheduling logic, and priority control validation. The Integration stage ensures stable communication between IoT devices and the web platform, guaranteeing reliable system performance under real operational conditions. Table 1 presents a detailed explanation of each research stage to be conducted.

Table 1. Description of Research Stages / Methodology

No.	Stage	Stage Description	Achievement Indicators
1	Planning	Problem formulation, data collection on existing conditions in the pesantren environment, determination of objectives, scope definition, resource estimation, and project scheduling.	Identified problems and existing conditions, with clear and structured planning.
2	Analysis	Comprehensive system requirements analysis covering user needs, workflow mapping, audio priority mechanism definition, identification of potential disturbances and technical constraints, and formal system specification documentation.	A complete requirement specification document that becomes the validated basis for system design, integration logic, and testing scenarios.
3	Implementation / System Build	Hardware assembly, development of IoT-based control logic with embedded priority rules, dashboard interface development, network configuration, and installation of integrated system components.	All hardware and software components operate individually and are technically ready for system-level integration.
4	Integration & Testing	Calibration of each system component, system integration, and functional testing at laboratory scale to ensure proper operation according to design.	All integrated modules operate according to predefined functional scenarios, and the system demonstrates stable execution under repeated laboratory-scale testing conditions.

5	Deployment	Prototype-level deployment preparation, including system configuration for real-environment implementation and validation planning.	The system is technically feasible for field implementation, although full-scale operational deployment is beyond the scope of this study.
6	Evaluation & Maintenance	Post-integration evaluation, identification of potential improvements, and formulation of maintenance recommendations based on laboratory validation findings.	Evaluation outcomes provide refinement guidelines for future large-scale implementation and long-term operational monitoring.

Although the SDLC stages in the table are presented separately, several phases were implemented in an integrated manner in this study. The *Implementation* stage encompasses not only system development (*system build*), but also technical system design and system deployment in the actual operational environment. This approach was adopted because in IoT-based system development, architectural design, hardware and software implementation, and field installation are closely interconnected and carried out continuously. Once the system was deployed and operational, the *Evaluation and Maintenance* stage was conducted to assess system performance based on testing results and real-world usage, including error correction, performance optimization, and feature refinement to ensure stable and reliable system operation in accordance with user requirements. Below are concise mathematical formulations that conceptually support the conduct IoT-Based Smart Audio System Using the SDLC Approach. The formulas model scheduling logic, priority control, IoT communication performance, and system reliability.

1. Audio Scheduling Function

We define the scheduled audio trigger as:

$$A(t) = \begin{cases} 1, & \text{if } t = t_s \\ 0, & \text{otherwise} \end{cases}$$

where:

- $A(t)$ = audio activation state
- t = current system time
- t_s = predefined schedule time

The system activates audio when the real-time clock matches the scheduled time.

2. Priority Control Mechanism

To manage adhan, announcements, and regular audio playback, we define a priority function:

$$P_i > P_j \Rightarrow A_i \text{ overrides } A_j$$

where:

- P_i = priority value of audio event i
- Higher P indicates higher execution precedence

Example priority order:

$$P_{\text{adhan}} > P_{\text{announcement}} > P_{\text{regular}}$$

This ensures adhan playback interrupts other lower-priority audio events.

3. IoT Communication Latency

System communication delay is measured as:

$$L = t_r - t_s \tag{1}$$

where:

- L = latency
- t_s = timestamp when command is sent
- t_r = timestamp when device responds

Stable IoT performance requires:

$$L \le L_{max}$$

4. System Reliability Model

System reliability during operation time T:

$$R(T) = e^{-\lambda T} \tag{2}$$

where:

- $R(T)$ = probability of failure-free operation
- λ = failure rate
- T = operating time

Lower λ indicates higher system stability.

5. Integration Validation Accuracy

To evaluate system testing performance:

$$Accuracy = \frac{N_{success}}{N_{total}} \times 100\% \tag{3}$$

where:

- $N_{success}$ = successful test executions
- N_{total} = total test scenarios

These mathematical representations support scheduling automation, priority logic validation, communication performance evaluation, and reliability assessment within the SDLC-based IoT Smart Audio System framework.

5. Result and Analysis

We identified the audio system requirements in the pesantren environment based on observations and analysis of the existing conventional system. The primary requirements include the automation of scheduled audio playback, prioritization of adhan and announcement functions, integration of all audio functions into a centralized system, and the capability for IoT-based remote control. In addition, key hardware requirements were defined, including the ESP32 microcontroller, relay modules, and audio system components, as well as software requirements in the form of an IoT dashboard for system management. This stage resulted in a system requirements specification document that serves as a reference for subsequent development stages, thereby minimizing design changes during the implementation process. Table 1 presents the list of system requirements.

Table 1. List of System Requrements.

No	Requirement Type	Requirement Description	Remarks
1	Functional	The system plays scheduled murottal and Islamic music	Daily scheduling
2	Functional	The system automatically plays the call to prayer (Adhan) according to prayer times	Highest priority
3	Functional	The system receives and executes announcements	Local and remote control
4	Functional	The system stops or lowers audio during Adhan or announcements	Priority management
5	Functional	The system can be controlled via an IoT-based dashboard	Internet-based
6	Functional	The system stores audio activity logs	System monitoring
7	Non-Functional	The system is easy for operators to use	Usability
8	Non-Functional	The system remains stable on standard Wi-Fi connections	Reliability
9	Non-Functional	The system is safe from basic operational errors	Safety
10	Non-Functional	System requirements are systematically documented to minimize design changes during implementation	Change control
11	Non-Functional	Priority definitions and schedule conflict scenarios are determined during the planning stage	Improvement of system logic accuracy

The analysis results show that the audio system must manage three main operations: primary scheduling (murottal recitation and Islamic music), priority scheduling (adhan), and announcement interruptions. The study defines clear priority rules, placing adhan at the highest level, followed by announcements, and then the primary schedule. The analysis also examines system behavior during scheduling conflicts, such as automatically pausing murottal playback when adhan or announcements occur. These findings form the foundation for designing the control logic and developing structured testing scenarios. Table 2 illustrates the mapping of system functions and their respective priority levels.

Unlike the previous manual system that depended on operator responsiveness, the SDLC-based analysis enables systematic modeling of conflict scenarios before implementation. The study applies a rule-based priority model to evaluate interactions among system functions and resolve audio conflicts deterministically. Clearly defined and documented priority levels improve logical accuracy and reduce human-related errors. In the manual system, execution delays for adhan or announcements could exceed 20 seconds due to operator readiness. By contrast, the SDLC-based approach relies on programmed logic to eliminate variability and supports override, pause–resume, and sequential command handling mechanisms to enhance consistency and reliability.

Table 2. Mapping of System Functions and Their Priority Levels

No	System Function	Function Description	Priority Level	Conflict Resolution Mechanism	Impact on Other Audio
1	Adhan	Automatic call to prayer at prayer times	High	Full override mechanism for Adzan (highest priority)	Stops all audio
2	Announ-	Audio-based	Medium	Pause–resume mechanism	Pauses main

	cement	information delivery		for announcements	audio
3	School Bell	Indicator for class start/change	Medium	Pause–resume mechanism for school bell	Pauses main audio
4	Murottal	Scheduled Islamic recitation audio	Low	No override for scheduled recitation (murottal)	Paused during priority events
5	Islamic Music	Islamic background music	Low	No override for Islamic background music	Paused during priority events

The implementation phase began with the design of the system workflow in the form of a flowchart as a representation of the control logic that had been defined in the analysis phase. This flowchart describes the process of time identification, schedule reading, playlist activation, and priority mechanisms when the call to prayer, announcements, or school bells occurs. Each decision branch is designed using a rule-based priority modeling approach so that the system is able to apply a full override mechanism for the call to prayer and a pause-resume mechanism for announcements and bells in a deterministic manner. This workflow design ensures that all schedule conflict scenarios have been modeled before being implemented in hardware, so that the implementation becomes a form of validation of the system logic that has been analyzed previously. Fig. 1 illustrates the system workflow used as a reference for implementation.

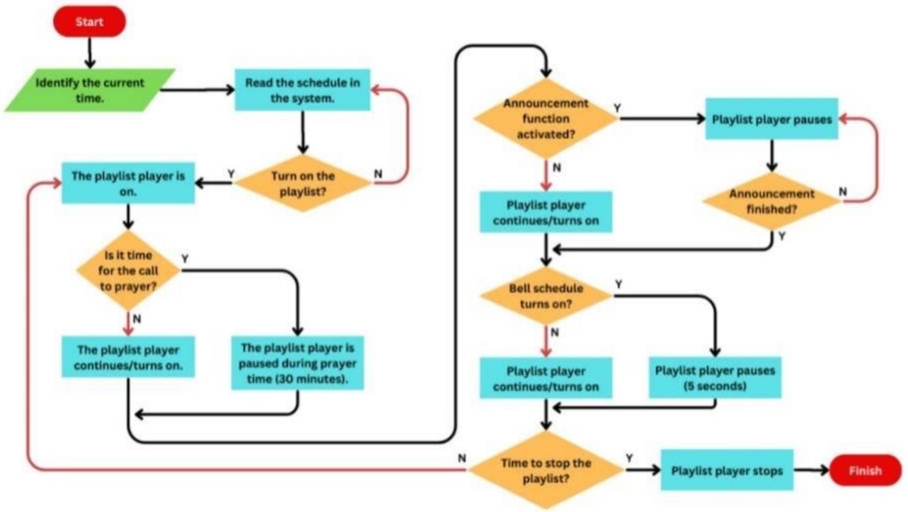

Fig. 1 The System Workflow

After establishing the system logic, we design the hardware architecture and build a laboratory-scale prototype. We use the ESP32 microcontroller as the control center and connect it to a relay module for audio routing, an RTC module for time synchronization, and audio output devices such as speakers or bells. We test the prototype under various operational scenarios, including main schedule activation, adhan interruptions, announcements, and school bells, to verify that the priority mechanism operates according to specifications. We then develop an IoT dashboard to enable remote monitoring and control, displaying playlist status and priority activities while allowing manual control via the internet. After confirming hardware stability, we integrate the IoT layer with the core system to ensure validated functionality before full deployment. During integration, we combine the scheduling, adhan priority, announcement, and IoT modules into a unified system that operates based on deterministic logic defined in the analysis phase. We conduct black-box testing with 10 repetitions per main scenario and achieve a 100% success rate without logical conflicts or system failures. Compared to manual systems, this SDLC-based implementation improves consistency, eliminates human-related variability, and ensures reliable real-time audio management for the Islamic boarding school environment.

Table 3. System Integration and Module Validation Results.

No	System Module	Integration Status	Test Frequency	Success Rate	Description
1	ESP32 Microcontroller	Integrated	10 times	100%	Functions as the main control unit
2	Relay Module	Integrated	10 times	100%	Controls audio signal routing
3	Scheduling Module	Integrated	10 times	100%	Manages main scheduling and priorities
4	Adhan Module	Integrated	10 times	100%	Operates based on prayer times
5	Announcement Module	Integrated	10 times	100%	Supports local and IoT-based control
6	IoT Dashboard	Integrated	10 times	100%	Monitoring and control interface

IoT integration in the Smart Audio System is designed to enable real-time remote control while increasing the operational flexibility of the system. Testing was conducted by sending commands through the IoT dashboard under laboratory Wi-Fi network conditions with an average speed of 20–30 Mbps to simulate normal operating conditions. The tests showed that the system response time was in the range of 1.4–1.9 seconds with an average of 1.63 seconds, and no execution failures were found during 10 repeated tests for each type of command. Compared to manual systems, which have the potential for delays of more than 20 seconds due to operator dependence, this SDLC and IoT-based system shows a significant improvement in execution accuracy and consistency. During testing, no freezing, extreme delays, or priority conflicts were found. Table 4 presents the IoT response tests of System Response Testing to Remote Commands.

Table 4. Results of System Response Testing to Remote Commands

No	Command Type	Number of Tests	Average Response Time (seconds)	Maximum Deviation (seconds)	Result
1	Activate Adhan	10	1.5	±0.2	Stable
2	Activate Announcement	10	1.75	±0.2	Stable
3	Activate Schedule	10	1.6	±0.2	Stable
4	Stop Schedule	10	1.9	±0.1	Stable
5	Activate Bell	10	1.7	±0.2	Stable

This discussion interprets the methodological contribution of SDLC and the technical impact of IoT integration on system performance and reliability. The implementation results show that SDLC provides a structured and systematic development process. The planning and analysis stages clearly define functional requirements, priority rules, and scheduling conflict mechanisms for the Islamic boarding school audio system. These early specifications reduce logic revisions during integration and prevent priority conflicts between modules. Laboratory-scale testing confirms that the approach accommodates the complexity of an integrated IoT-based audio system. Quantitative results show a 100% success rate across 10 test executions for each main scenario, demonstrating consistent priority logic and eliminating variability caused by manual operator intervention.

The integration of IoT significantly improves system flexibility and operational efficiency. The system successfully receives and executes remote commands through the IoT dashboard with an average response time of 1.63 seconds across repeated tests. All commands execute without failure or logic conflict, indicating stable connectivity and responsive performance. The remote-control mechanism reduces dependence on on-site operators and automatically restores the system state after priority execution. Compared to manual systems that experience delays exceeding 20 seconds due to human response, the proposed system demonstrates substantial improvement in timing accuracy and execution consistency. Therefore, the combination of SDLC and IoT integration produces a reliable, responsive, and systematically validated Smart Audio System for Islamic boarding school environments.

6. Conclusion

This study concludes that the development of an IoT-based Smart Audio System to support the smart pesantren concept can be implemented systematically using an adapted System Development Life Cycle (SDLC) approach. Through the stages of planning, analysis, implementation, integration, and testing, the previously manual audio system was successfully transformed into an integrated and automated system with clearly defined functional priorities among adhan, announcements, and primary audio schedules. The structured approach ensures that scheduling logic and priority mechanisms operate consistently within a unified architecture.

The integration and testing results demonstrate a 100% functional success rate across 10 repeated test scenarios for each core module, confirming logical stability and execution consistency. In addition, IoT-based remote control testing records an average response time of 1.63 seconds, indicating responsive and reliable performance for operational needs. Compared to manual operation, which is prone to human error and timing delays, the proposed system significantly improves accuracy, consistency, and overall management efficiency.

Laboratory-scale validation further confirms that the SDLC-driven process strengthens system reliability through systematic documentation, iterative validation, and controlled integration of hardware, software, and network components. This study reaffirms the relevance of SDLC for IoT-based system development and contributes practically to the digital transformation of educational support facilities in pesantren environments. Future research should focus on full-scale field implementation, long-term performance evaluation, enhanced network security mechanisms, and integration with mobile-based notification systems to improve scalability and functionality.

Acknowledgment

The authors gratefully acknowledge the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia for supporting this research through the Penelitian Dosen Pemula (PDP) grant, which strengthens the capacity of early-career lecturers. They also thank the Institute for Research and Community Service of Universitas Nahdlatul Ulama Yogyakarta for institutional support and facilities, as well as all research team members for their cooperation and dedication.

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