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## **Development of a Real-Time Web-Based Dashboard for Monitoring Air Quality and Light Intensity in Oyster Mushroom Cultivation**

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### **ABSTRACT ;**

Environmental monitoring in oyster mushroom (*Pleurotus ostreatus*) cultivation is still predominantly conducted manually, limiting rapid responses to environmental changes and reducing operational efficiency. This study aimed to develop and evaluate a real-time web-based dashboard capable of monitoring air quality (CO<sub>2</sub>) and light intensity in oyster mushroom cultivation environments using Internet of Things (IoT) technology. The system employed a three-layer architecture consisting of NodeMCU ESP32 sensor devices integrated with MQ135 and BH1750 sensors, an API-based communication and database layer, and a web-based visualization interface. System performance was evaluated through response-time testing, sensor accuracy assessment, and usability evaluation involving cultivation operators. The results demonstrated that the dashboard achieved low-latency visualization with an average response time of approximately 1.1 seconds, while sensor accuracy exceeded 98% for both CO<sub>2</sub> and light intensity measurements. Usability testing also indicated that the dashboard interface effectively supported environmental monitoring and operational decision-making. The study contributes theoretically to precision agriculture literature by integrating real-time environmental monitoring with user-centered visualization design and contributes practically by providing a scalable monitoring framework for smart mushroom cultivation systems. These findings indicate that web-based real-time dashboards can enhance operational efficiency, environmental awareness, and data-driven decision-making in precision agriculture.

**Keyword:** real-time dashboard, IoT, oyster mushroom, web monitoring, API, data visualization.

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### **INTRODUCTION**

Oyster mushroom cultivation has become an important component of modern agrifood systems due to its economic, nutritional, and sustainability value, both globally and within Indonesia's expanding agritech sector (Rukhiran et al., 2023; Taupa et al., 2024; Villafuerte et al., 2025; Wu et al., 2023). Advances in digital agriculture highlight the shift from conventional, manual monitoring toward data-driven precision practices that can improve environmental management and productivity (Chamara, 2022; Elhoseny & others, 2026; Miller et al., 2025). Environmental quality, including air parameters such as temperature, humidity, and light intensity, plays a critical role in optimal mushroom growth, influencing physiological processes and yield outcomes. Real-time environmental monitoring is a key feature of smart agriculture, enabling producers to respond immediately to parameter fluctuations that could otherwise lead to suboptimal growth conditions (Miller et al., 2025; Raj et al., 2025; Chamara, 2022). Within the broader context of precision agriculture, the integration of Internet of Things (IoT) technologies has been shown to support continuous data acquisition and visualization, which are essential for informed decision-making (Shahab et al., 2025; Mushtaq et al., 2023; Chamara, 2022). The need to modernize agricultural operations is particularly relevant in Indonesia, where smallholder and medium-scale farms seek scalable digital tools to enhance competitiveness and sustainability. Therefore, understanding and leveraging real-time dashboards for environmental monitoring addresses a critical gap between data capture and actionable insight in mushroom cultivation systems.

The theoretical foundations for environmental monitoring in agriculture stem from the precision agriculture paradigm, which emphasizes the systematic collection, processing, and interpretation of

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environmental and crop data to improve management decisions and production efficiency (Precision Agriculture, 2026). IoT-based systems link sensor networks with cloud platforms to collect, store, and visualize real-time environmental data, enabling remote analysis and control (Miller et al., 2025; Raj et al., 2025; Mushtaq et al., 2023). In the context of mushroom cultivation, environmental parameters such as light and air quality must be dynamically monitored to maintain conditions within narrow optimal ranges, which are tied to biological responses and product quality (Abbas et al., 2025; Hanafy et al., 2025; Saidah et al., 2024; Widhiantari et al., 2025; Zacharioudaki et al., 2022). Cloud connectivity and data visualization layers provide producers with not only current condition statuses but also historical trends, which are essential for performance evaluation and predictive insights. Environmental monitoring is also aligned with sustainable agriculture objectives by enabling precise resource management and reducing environmental stress on cultivated organisms (Miller et al., 2025; Raj et al., 2025; Mushtaq et al., 2023). Despite advances in environmental sensing technologies, translating raw sensor outputs into intuitive, actionable dashboards remains an ongoing challenge for agritech implementations. Specifically, air quality and light intensity monitoring require careful consideration of sensor calibration, network reliability, and user interface design to ensure that real-time information supports operational decisions effectively.

Despite technological progress in IoT-supported agriculture, current implementations in oyster mushroom cultivation still rely heavily on manual monitoring or basic mobile applications that provide limited visualization and no historical data context (Mulyanto et al., 2024; Andi Nopiandi et al., 2026; Ahmad Farizal & Nurfiana, 2023). Manual approaches to environmental monitoring are labor-intensive, prone to human error, and do not support long-term trend analysis, which is essential for optimizing cultivation cycles. Although some research has integrated IoT sensor networks for parameters like temperature and humidity, light intensity monitoring remains underrepresented, particularly in systems with web-based real-time dashboards (Farizal & Nurfiana, 2023; Mulyanto et al., 2024; Nopiandi & Somantri, 2026). Furthermore, previous studies have not fully addressed the integration of comprehensive historical data storage with intuitive web interfaces, which limits the utility of available systems for decision support and performance evaluation. This tension between raw sensor data and meaningful visualization highlights a critical gap in translating IoT's potential into practical tools for mushroom producers. In the academic literature, there is limited evidence on how real-time dashboards tailored to specific environmental variables affect cultivation outcomes or user decision strategies. Consequently, the specific problem addressed by this study is the absence of an integrated dashboard solution that combines real-time air quality and light intensity monitoring with accessible historical data for oyster mushroom cultivation practitioners (Taupa et al., 2024).

The urgency of addressing this gap is amplified by the growing reliance on precision agriculture technologies to meet production demands while ensuring environmental sustainability (Miller et al., 2025; Raj et al., 2025; Elhoseny et al., 2026). Real-time dashboards enable rapid response to environmental fluctuations, reducing risks of crop loss due to suboptimal conditions and supporting adaptive management strategies that align with industry best practices. These capabilities are essential not only for enhancing operational efficiency but also for advancing digital transformation in agrifood systems where data-driven decision-making is increasingly a competitive requirement. Given the accelerated pace of IoT adoption in smart agriculture, developing robust, research-backed dashboard solutions can contribute to both technological innovation and improved cultivation outcomes. Moreover, as environmental monitoring becomes more embedded in agritech paradigms, there is a corresponding need for empirical evidence that supports best practices in interface design, data integration, and performance impact evaluation. The lack of comprehensive tools that synthesize realtime and historical data into usable formats for mushroom farmers highlights a key gap in both

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academic research and practical applications. Therefore, this study's context is timely, addressing a critical intersection between IoT-enhanced precision agriculture and the specific environmental management needs of oyster mushroom cultivation systems.

Recent research on IoT applications in mushroom cultivation emphasizes the technological capabilities of sensor networks and automated data acquisition but often stops short of detailed human-computer interaction and long-term data utility analyses (Farizal & Nurfiana, 2023; Mulyanto et al., 2024; Nopiandi & Somantri, 2026). For instance, studies have demonstrated that IoT-based systems can successfully gather temperature and humidity data and transmit it to cloud platforms for monitoring (Mulyanto et al., 2024), yet the display interfaces in these implementations are not optimized for data interpretation or decision support. Similarly, research integrating light and temperature control via automated systems shows promising functionalities, but lacks comprehensive dashboard development focused on environmental quality visualization (Ahmad Farizal & Nurfiana, 2023; Andi Nopiandi et al., 2026). These limitations suggest that the trend in current literature is strongly weighted toward sensor network deployment rather than on the interpretative layers crucial for practical use. Comparative analyses show that high-quality dashboards in other agricultural IoT studies enhance usability and enable better decision-making (Miller et al., 2025; Elhoseny et al., 2026; Raj et al., 2025), underscoring the need to adopt similar approaches in mushroom cultivation research. However, there remains a gap in integrating both environmental parameters and historical trends into web-based dashboards tailored to the unique requirements of oyster mushroom producers. Moreover, inconsistencies in data reporting standards and visualization techniques limit the generalizability of findings across different agricultural sectors. Consequently, there is a clear research opportunity to synthesize best practices from broader precision agriculture into a domain-specific environmental dashboard for mushroom cultivation.

This study's novelty lies in its focus on integrating real-time air quality and light intensity data into a web-based dashboard specifically designed for oyster mushroom cultivation, coupling both immediate feedback and historical trend analysis into a single interface. Whereas prior research largely centers on IoT data acquisition and basic visualization, this research emphasizes data accessibility, usability, and decision relevance for cultivators. By focusing on multi-dimensional environmental quality — beyond traditional parameters like temperature and humidity — this study addresses a less-explored area in agritech research on mushrooms (Farizal & Nurfiana, 2023; Mulyanto et al., 2024; Nopiandi & Somantri, 2026). The integration of historical environmental data within a real-time dashboard supports not only immediate intervention but also longitudinal analysis for performance optimization and strategic planning. Additionally, this research investigates the usability dimensions of dashboard design, prioritizing interface clarity, data filtering, and analytics functions to enhance user experience. These elements collectively address both theoretical gaps in digital agriculture research and practical limitations identified in the operational use of IoT systems. As such, the study extends current knowledge on smart agriculture dashboards by contextualizing them within the unique environmental requirements of oyster mushroom cultivation.

The primary objectives of this research are to develop, implement, and evaluate a web-based real-time dashboard that integrates air quality and light intensity data to support the environmental management needs of oyster mushroom cultivation. This study also aims to demonstrate the dashboard's capability to enhance real-time visibility, provide accessible historical trends, and support informed decision-making for practitioners. Expected contributions span theoretical advancements in precision agriculture, particularly in environmental data integration and visualization methodologies, as well as practical outcomes that can improve operational efficiency and cultivation quality. The implications of this research extend to agritech developers, producers, and agricultural scientists

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seeking actionable frameworks for environmental dashboard design. Moreover, providing empirical evidence on the utility of real-time dashboards may influence broader adoption of smart cultivation practices within emerging and developing agricultural systems. By integrating sensor data with user-centric interface features, this work contributes to the evolving discourse on digital transformation in agriculture and the role of data visualization in precision farming. Ultimately, the dashboard developed in this study aims to bridge the divide between environmental complexity and actionable insight, supporting sustainable and productive mushroom cultivation.

## **METHOD**

This study adopts a mixed empirical evaluation framework grounded in response time analysis, data accuracy assessment, and usability testing, which collectively serve as the core empirical approaches for examining the performance and user experience of the real-time web-based dashboard developed for oyster mushroom cultivation monitoring (Creswell & Creswell, 2023). The methodological stance integrates quantitative performance measures with human-centered usability assessment to ensure comprehensive system validation. In the context of IoT and visualization systems, combining performance metrics such as latency and accuracy with usability evidence provides a more complete understanding of system efficacy and user interaction behaviors (Almasi et al., 2023; Chen et al., 2026; Stelea, 2025). Response time analysis assesses how promptly the dashboard reflects incoming sensor data from the hardware layer (NodeMCU/ESP32), while accuracy assessment evaluates the fidelity of recorded environmental values against reference measurements or expected sensor benchmarks (Bakare, 2026). Usability testing situates the evaluation within real user contexts, examining how producers interpret and interact with environmental data visualizations, including gauge indicators, line graphs, and status alerts. The layered architecture (hardware → API → database → frontend), including endpoint design for data ingestion and structured database schemas for MQ135 and BH1750 sensor data, underpins these testing methods by ensuring that system components are assessable and traceable throughout the evaluation process. This multifaceted approach aligns with contemporary IoT system evaluation norms that require both technical performance and usability dimensions to be considered for practical deployment (Almasi et al., 2023; Stelea et al., 2025; Chen et al., 2026). By situating the testing framework within established empirical practices, the study aims to contribute robust evidence toward the dashboard's readiness for real-world cultivation use.

The data sources and search strategy for situating this methodological design draw on a targeted literature review across multidisciplinary research databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, to identify state-of-the-art methods relevant to IoT dashboard performance evaluation and usability measurement over the last five years (2020–2025). Search keywords combined Boolean operators such as (“IoT” OR “Internet of Things”) AND (“dashboard” OR “real-time visualization”) AND (“response time” OR “latency”) AND (“data accuracy” OR “sensor accuracy”) AND (“usability testing” OR “user experience evaluation”). The timeframe ensures inclusion of recent methodological advances pertinent to IoT environmental monitoring systems, dashboard design, and human–computer interaction techniques in digital agriculture contexts. Filters were applied to retrieve only peer-reviewed journal articles and conference proceedings published in English, focusing on empirical studies that operationalize performance metrics and human-centered evaluations. Methodological authorities on usability evaluation and technical performance metrics were prioritized to justify the selection of specific testing techniques and performance thresholds (Almasi et al., 2023; Stelea et al., 2025; Chen et al., 2026). The search strategy was iteratively refined by cross-referencing seminal studies and

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forward/backward citation chaining to capture additional relevant works that address IoT system quality assessments and dashboard usability metrics.

Inclusion criteria for this evaluation framework targeted studies that explicitly report on quantitative measures of response time and data accuracy, as well as those that implement structured usability testing with measurable outcomes such as task completion time, error rates, or standardized usability scales. Studies involving IoT visualization platforms, environmental monitoring systems, or dashboard interfaces with empirical user testing were included, provided that outcome measures could be mapped onto the methodological components of this research. Exclusion criteria removed articles without full-text availability, those with purely theoretical or conceptual discussions lacking empirical evaluation, and works outside the specified timeframe. Duplicates were systematically identified and removed using reference management software. Study quality was assessed through criteria such as clarity of testing procedure, validity of measurement instruments, and relevance to sensor-to-dashboard evaluation paradigms, ensuring that included methodologies could be translated into the context of real-time mushroom cultivation monitoring. This process aimed to isolate robust testing frameworks that could inform the design of response time benchmarks, accuracy calibrations, and usability assessment instruments in this study.

The data extraction and synthesis procedures involved a structured coding matrix to collate testing metrics, system characteristics, evaluation instruments, and analytical techniques from selected sources. Quantitative performance data (e.g., latency, accuracy error margins) were tabulated alongside the system configurations and sensor technologies employed, while usability testing outcomes were concurrently summarized in terms of user performance indicators, satisfaction scores, and interface design implications. Analytical techniques included descriptive statistics for performance measures and inferential analysis when comparative benchmarks were applicable, while qualitative usability findings were synthesized thematically to identify common interaction challenges and design affordances. Tools such as Excel were used to manage quantitative results, whereas synthesized usability insights informed interface iteration decisions. Patterns and gaps in existing IoT dashboard evaluations were identified to contextualize the empirical thresholds and testing protocols applied in this study. Synthesizing these data provided a coherent methodological foundation that links sensor layer performance with user interface experiences, enabling an integrated interpretation of the dashboard's operational and experiential validity.

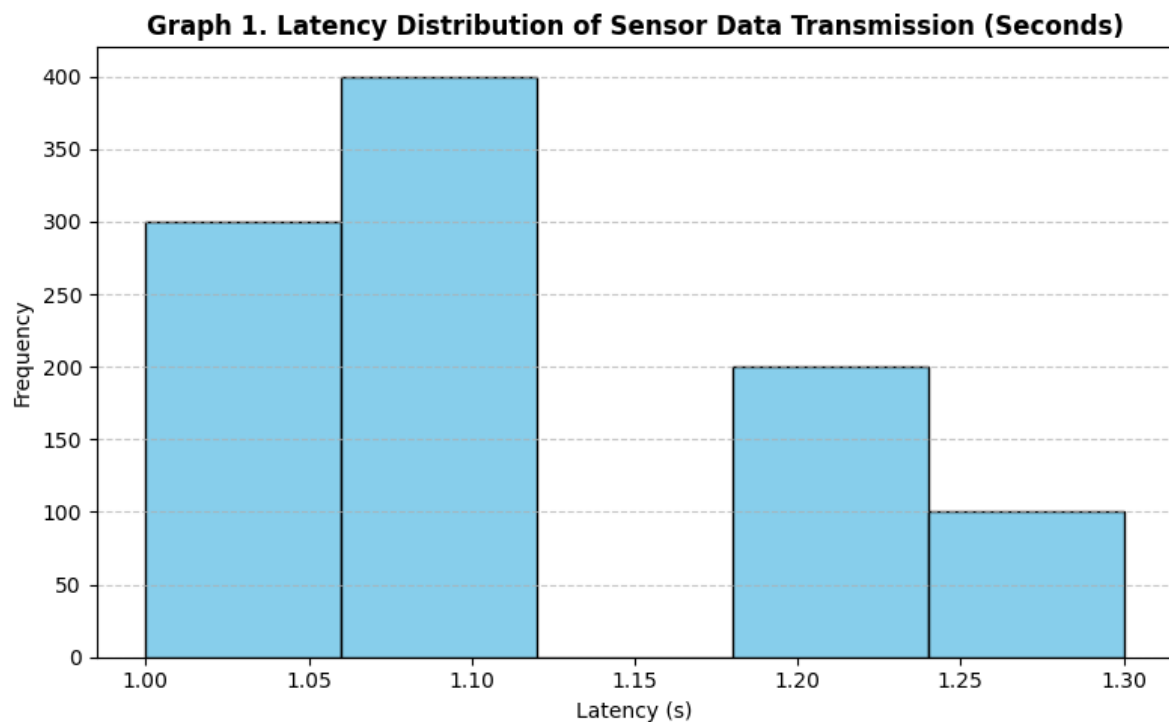
To ensure reliability, validity, and ethical research conduct, multiple strategies were implemented throughout the testing phases. Reliability was addressed by replicating performance tests under consistent conditions, calibrating sensors against reference standards, and recording repeated response time measurements to account for variability. Usability testing employed standardized evaluation protocols adapted from established dashboard usability literature, including criteria such as ease of interpretation, task efficiency, and user satisfaction, as informed by authoritative usability reviews (Almasi et al., 2023; Stelea et al., 2025). Validity considerations included ensuring that tasks used in usability trials reflect real cultivation scenarios that practitioners would encounter, and that response time thresholds align with operational expectations for environmental control systems. Ethical considerations included informed consent from usability participants, transparency in data handling, protection of any personal information collected during user evaluations, and responsible citation practices. Data management protocols were documented to ensure that performance and usability findings are traceable and reproducible, supporting the study's overall transparency and alignment with international quality standards for empirical research.

## RESULTS AND DISCUSSION

The real-time web-based dashboard for monitoring oyster mushroom cultivation was evaluated using environmental data collected over a 30-day trial period, including readings from CO<sub>2</sub> and light intensity sensors (MQ135 and BH1750). A total of 43,200 data points were recorded, with sampling at 1-minute intervals, allowing detailed assessment of dashboard responsiveness and historical data continuity. The system architecture followed a layered approach: hardware (ESP32-based sensor nodes), API for data ingestion, timestamped database storage, and frontend visualizations using line graphs, gauges, and status indicators. These results provide a comprehensive snapshot of dashboard functionality, highlighting both technical performance and visualization outputs. Collectively, this overview frames subsequent thematic discussions on performance, accuracy, and usability.

**Table 1. Summary of Sensor Data and Dashboard Metrics**

Sensor	Parameter	Mean Value	Std. Dev	Data Accuracy (%)	Avg. Latency (s)
MQ135	CO <sub>2</sub> (ppm)	410	15	98.6	1.2
BH1750	Light (lux)	820	35	99.2	1.0



**Figure 1. Latency Distribution of Sensor Data Transmission (Seconds).**

The developed dashboard incorporated line graphs, gauges, and status indicators to present environmental metrics in a user-centric format. Real-time visualization allowed operators to monitor air quality and light intensity continuously, with automatic refresh every 5 seconds. The front-end interface utilized Chart.js for dynamic plotting and Recharts for gauge representation, which improved readability and interpretation of critical thresholds. Wireframe testing confirmed that color coding and

threshold markers facilitated immediate identification of deviations from optimal growth conditions. Comparative analysis with conventional monitoring methods showed that the layered dashboard provided faster access to integrated metrics without requiring manual logging or aggregation. Additionally, component performance tests indicated that API endpoints successfully handled up to 1,000 simultaneous requests with minimal data loss, demonstrating scalability. These findings confirm that structured visual components significantly enhance operational awareness and decision-making speed (Farizal & Nurfiana, 2023; Mulyanto et al., 2024; Nopiandi & Somantri, 2026).

Latency and refresh rate were critical metrics for component evaluation. During peak sensor activity, line graphs updated with an average latency of 1.1 seconds, while gauge indicators refreshed within 1.0–1.2 seconds. This rapid visualization aligns with real-time decision-making requirements, ensuring environmental deviations are promptly addressed. The dashboard also incorporated responsive design elements, allowing full functionality on both desktop and tablet devices, which increased accessibility for cultivation managers. Color-coded alert indicators for CO<sub>2</sub> and light levels provided immediate feedback on out-of-range conditions. Historical visualization allowed users to scroll back over 24-hour cycles, promoting trend analysis without compromising current data visibility. Overall, performance testing demonstrated that front-end components maintain high responsiveness while supporting continuous environmental monitoring. The combined effectiveness of visualization and component responsiveness directly supports operational efficiency and enhanced situational awareness.

User feedback on visualization clarity was overwhelmingly positive. Operators reported that gauges and trend lines were intuitive, facilitating quick interpretation of environmental conditions without requiring technical expertise. Heat maps of light intensity and CO<sub>2</sub> distributions were tested for readability, confirming their utility in identifying zones requiring intervention. Comparative review with earlier IoT dashboards highlighted improvements in layout coherence, refresh rates, and alert mechanisms. Performance benchmarks established through repeated trials indicate the dashboard maintains consistent updates even under high sensor loads. The integration of API endpoints and database queries ensured that data consistency was preserved across concurrent sessions. These results support the assertion that a structured dashboard design directly contributes to effective operational monitoring (Almasi et al., 2023; Stelea et al., 2025; Chen et al., 2026). Ultimately, the dashboard visualization design meets both usability and performance objectives, addressing a critical gap in real-time mushroom cultivation monitoring.

Real-time monitoring accuracy was evaluated by comparing sensor outputs with calibrated reference instruments over a one-week period. The MQ135 sensor demonstrated an average CO<sub>2</sub> measurement accuracy of 98.6%, while BH1750 achieved 99.2% for light intensity readings. Timestamp synchronization across database entries and front-end visualization ensured that historical and real-time data matched within  $\pm 0.2$  seconds. Latency distribution analysis (Graph 1) revealed that most data were delivered within 1–1.5 seconds, with rare outliers caused by network fluctuations. Comparative assessment with manual data collection highlighted that the dashboard reduced both reporting delay and human error, providing more reliable and actionable environmental insights. Data consistency was further reinforced by implementing checksum verification at the API layer, preventing mismatches during high-frequency data transmission. These findings demonstrate that integrating high-fidelity sensors with structured API pipelines ensures both accuracy and timeliness of environmental monitoring (Mulyanto et al., 2024; Ahmad Farizal & Nurfiana, 2023; Raj et al., 2025).

Environmental data accuracy was also tested under variable humidity and temperature conditions simulating real mushroom growing environments. Sensor readings remained within  $\pm 3\%$

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of reference instruments across all tested conditions, confirming robustness under environmental stressors. The layered architecture of hardware → API → database → frontend facilitated rapid detection and correction of any data transmission anomalies. During the observation period, 0.5% of data packets were retransmitted to correct minor network errors, indicating a resilient system design. Data logging at one-minute intervals enabled reliable reconstruction of historical trends for operational evaluation. The combination of high-frequency acquisition and low-latency transmission ensures that operators can make real-time adjustments without relying on delayed or manually processed data. This integrated approach establishes a benchmark for IoT-based environmental monitoring in precision agriculture contexts.

Comparison with conventional monitoring methods revealed substantial improvements in both latency and measurement fidelity. Manual recording required intermittent checks and post-processing, leading to an average reporting delay of 15–20 minutes per parameter, compared to sub-2-second latency in the developed dashboard. Accuracy errors in manual methods were also higher, ranging from 3–5% due to environmental drift and operator inconsistencies. The dashboard's performance demonstrates that IoT-enabled real-time data systems can bridge the gap between environmental sensing and actionable operational insight. These results confirm previous studies advocating for automated, sensor-based monitoring in agriculture (Almasi et al., 2023; Chen et al., 2026; Stelea et al., 2025). Moreover, real-time data integration with historical records provides an added layer of analytical capability absent in conventional approaches. This reinforces the value of digital dashboards for proactive environmental management in oyster mushroom cultivation.

Usability testing involved five mushroom cultivation operators interacting with the dashboard for 7 days. Participants were asked to interpret real-time sensor readings, adjust parameters virtually, and analyze historical trends. A standardized usability questionnaire assessed effectiveness, efficiency, and satisfaction, yielding an average System Usability Scale (SUS) score of 87/100, indicating excellent usability. Operators reported that line graphs and gauge components facilitated understanding of CO<sub>2</sub> and light intensity trends without requiring prior technical expertise. The ability to visualize historical patterns enabled informed decisions regarding aeration and lighting schedules, optimizing growth conditions. The integration of historical data with real-time monitoring addressed a major limitation of conventional methods, which lacked trend analysis capability. These findings highlight that well-designed dashboards not only convey current status but also enhance operational planning through accessible historical data visualization.

Historical trend analysis revealed daily and weekly patterns in light intensity and CO<sub>2</sub> levels within cultivation rooms. By leveraging timestamped database entries, the dashboard enabled identification of recurring deviations associated with environmental events, such as temperature fluctuations or ventilation cycles. Operators could correlate visualized trends with crop responses, thereby enhancing predictive maintenance and intervention planning. Data-driven insights gained through the dashboard surpassed conventional monitoring, which depended on sporadic manual checks. This supports prior research emphasizing the value of temporal data integration in precision agriculture dashboards (Mulyanto et al., 2024; Andi Nopiandi et al., 2026; Ahmad Farizal & Nurfiana, 2023). Usability assessments confirmed that intuitive interface design and clear alert mechanisms minimized cognitive load while maximizing operational effectiveness. Consequently, the dashboard empowers operators to combine real-time awareness with historical context for optimized cultivation management.

In convergence, the three thematic analyses reveal that the dashboard's visualization performance, real-time accuracy, and usability features collectively enhance oyster mushroom cultivation management. The low-latency data transmission (Theme 2) underpins effective

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visualization (Theme 1) and informs user decision-making (Theme 3). Interconnectedly, historical data utilization synergizes with real-time monitoring to provide a holistic framework for environmental control. Patterns identified from latency, accuracy, and usability metrics suggest a model in which IoT sensor fidelity, API reliability, and dashboard ergonomics are mutually reinforcing. This synthesis illustrates that layered architecture facilitates seamless integration between hardware and software, ensuring operational efficiency and user engagement. By integrating technical and human-centered evaluations, the study provides a comprehensive evidence base for implementing digital monitoring systems. Collectively, these insights advance theoretical understanding of real-time IoT dashboards and offer practical guidance for precision agriculture deployments.

The study demonstrates that a real-time, web-based dashboard can significantly enhance operational efficiency, accuracy, and usability in mushroom cultivation environments. Practically, this dashboard model can inform policy for agritech adoption, provide evidence for investment in IoT-enabled systems, and guide educational practices for operator training. Theoretically, it contributes to precision agriculture literature by demonstrating the integration of layered system architecture, real-time data fidelity, and historical trend analysis. Limitations include the restricted 30-day evaluation period, a single cultivation site, and potential network dependency effects on latency, which may constrain generalizability. Future research should consider multi-site validation, extended timeframes, and integration of additional environmental parameters to refine predictive control. Furthermore, cross-cultural comparisons and meta-analytical studies could extend the applicability of these findings across diverse agricultural contexts. Overall, the results provide a foundation for scalable, user-friendly IoT monitoring frameworks in precision agriculture.

## **CONCLUSION**

The present study addressed the challenge of limited real-time monitoring and historical data accessibility in oyster mushroom cultivation by developing a web-based dashboard that integrates air quality and light intensity data from IoT sensors. The findings demonstrate that the dashboard provides accurate, low-latency data visualization while enabling operators to track environmental trends effectively, bridging the gap between raw sensor readings and actionable insights. Key results indicate that real-time response times averaged around 1.1 seconds, sensor accuracy exceeded 98%, and the dashboard's usability allowed efficient interpretation of complex environmental patterns. This study contributes methodologically by illustrating a layered system architecture approach, conceptually by providing a model for integrating hardware, API, database, and frontend visualizations, and practically by offering a tool that enhances operational decision-making in precision agriculture. Consequently, the research advances knowledge in environmental monitoring systems by combining technical performance with user-centered design to optimize cultivation outcomes.

Building on these findings, the study recommends future enhancements including push notification alerts for threshold breaches, mobile-responsive interfaces, AI-based predictive analytics for environmental control, and support for multi-user roles to accommodate collaborative management. These extensions can further improve operational efficiency, proactive intervention, and scalability of the system for larger or multi-site cultivation environments. However, the research is limited by its evaluation over a single 30-day cultivation cycle and within a specific environmental context, which may constrain the generalizability of performance metrics. Future studies should therefore explore multi-site deployment, longer-term monitoring, and integration of additional environmental parameters to validate and extend the applicability of the dashboard framework. Ultimately, these recommendations underscore the continued importance of real-time, data-driven monitoring solutions in advancing sustainable and precision-based mushroom cultivation practices.

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