Sinkron : Jurnal dan Penelitian Teknik Informatika
Volume 10, Number 2, April 2026
DOI : https://doi.org/10.33395/sinkron.v10i2.15962
e-ISSN : 2541-2019
p-ISSN : 2541-044X

Field Evaluation of an IoT-VFD Smart Ventilation System for Energy-Efficient Rice Seed Storage

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Submitted :04 March 2026 | **Accepted** : March 22, 2026 | **Published** : April 2, 2026

Abstract: Stable storage conditions are required in Rice Seed Storage to preserve seed quality and suppress fungal contamination, yet many warehouse ventilation systems still rely on inefficient on-off operation with limited responsiveness to changing temperature and humidity conditions. This study addresses the lack of integrated IoT-VFD control with field-validated energy and microclimate performance in seed warehouses. It proposes an IoT-based Ventilation Control architecture that combines ESP32, MQTT communication, and a Variable Frequency Drive to regulate a three-phase exhaust fan in both offline and online operating modes. The novelty of this work lies in integrating variable-speed control, real-time supervision, and field-based performance validation within a single seed warehouse deployment. The prototype was implemented in a 900 m^3 warehouse at Politeknik Negeri Jember and evaluated through a 7-day field trial with continuous monitoring of temperature, humidity, and motor speed. The controlled system brought warehouse conditions closer to the intended storage setpoints and produced statistically significant improvements in both temperature and humidity ($p < 0.001$). Control performance was stable, with high target-hit accuracy and low RMSE, while energy testing showed lower electricity consumption than conventional non-VFD operation. Over an equivalent 2-hour operating period, energy use was reduced by 30.4%. The system also maintained 99.64% MQTT uptime, and no mold incidence was observed during controlled operation. These findings indicate that the proposed IoT-VFD architecture is a practical approach for improving microclimate stability, reducing energy use, and supporting fungus-preventive seed warehouse management.

Keywords: Energy Efficiency, Internet of Things, MQTT, Rice Seed Storage, Variable Frequency Drive, Ventilation Control

INTRODUCTION

Rice seed warehousing is a critical phase in the agricultural supply chain because storage conditions directly affect seed viability, germination quality, and market consistency. At the Teaching Factory (TeFa) Seed Center of Politeknik Negeri Jember, where annual production reaches around 300 tons, post-harvest handling quality determines whether seed products can be delivered with stable standards to farmers and distributors (Kusuma, Harlianingtyas, Irawan, & Pratiwi, 2024; Priyantono & Khaliq, 2021). The urgency of improving storage management is also visible at the global level. FAO reports that 13.3% of food is lost worldwide between post-harvest stages and retail, while cereals and pulses still account for 8.4% loss in 2023 (Food and Agriculture Organization of the United Nations [FAO], 2025). In practical operation, one warehouse unit with 900 m^3 volume experiences high humidity and uneven temperature distribution due to limited air circulation. Such conditions increase the risk of mold growth and quality degradation, making reliable air management a high-priority operational problem.

Recent studies in smart agriculture and grain storage indicate that IoT-based monitoring can improve visibility of storage conditions and enable faster operator response (Lutz & Coradi, 2022; Coradi et al., 2022; Leal et al.,

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2023; Wardihani et al., 2024; Steidle Neto et al., 2021). At the implementation level, local and motor-side studies also show that IoT can supervise three-phase loads and VFD-based drives in practical settings (Sahar et al., 2024; Pradhana, Prasetyo, & Syukriyah, 2023; Biswal & Satpathy, 2021). However, many implementations still rely on binary on-off fan control, which tends to run motors at full speed, causes higher inrush stress, and reduces energy efficiency in variable-load conditions (Jaishree et al., 2021; Noyjeen et al., 2021). This matters because seed deterioration rises sharply under humid storage. Rice seed studies show that quality deterioration accelerates when seed moisture exceeds 12%, and that seed paddy stored at 11% moisture in polythene can maintain high germination for about 8-11 months, whereas high air humidity and elevated storage temperature markedly shorten seed longevity and increase the risk of mold-related deterioration (Alahakoon et al., 2021; Zhou et al., 2024). For seed warehouse applications, this means high humidity is not only a comfort problem but a direct quality-risk factor. In addition, practical deployments need robust connectivity behavior: remote monitoring is desirable, but local control must remain active during internet interruption to avoid control gaps.

The research gap addressed in this study is therefore more specific than generic IoT monitoring. Prior local work has demonstrated IoT air-quality control and operational feasibility, but mainly with on-off actuation mechanisms and without integrated validation of energy reduction, microclimate improvement, communication continuity, and storage safety outcomes in a real seed warehouse (Riskiawan et al., 2025). This study differentiates itself by combining an ESP32-based controller, MQTT-based supervision, and a Variable Frequency Drive (VFD) that enables single-phase to controllable three-phase fan operation with PWM frequency regulation. This architecture is designed to support dual operation modes: offline local control for continuity and online mode for supervision, logging, and remote setpoint adjustment (Marzuki, Muzakkir, & Arief, 2024).

The objective of this research is to design, implement, and evaluate an IoT-VFD smart air-control system for rice seed warehousing that is energy-efficient, operationally reliable, and effective in reducing fungal risk. The contributions are fourfold. First, the study presents an applied integration of ESP32, MQTT, and VFD for three-phase ventilation control in a real seed warehouse context. Second, it provides quantified performance evidence using a 7-day field dataset and statistical validation (paired pre-post tests) for temperature and humidity control. Third, it compares energy performance between VFD variable-speed control and conventional non-VFD operation. Fourth, it reports practical reliability indicators, including MQTT uptime and mold incidence under controlled operation.

By focusing on real deployment constraints and measurable field outcomes, this study aims to provide a practical reference model for energy-aware and fungus-preventive air management in rice seed storage facilities. To ground these objectives in prior evidence, the next section reviews closely related studies and positions the specific contribution of this manuscript.

LITERATURE REVIEW

Because the Introduction cannot fully detail the technical landscape, this section organizes previous studies into three closely related themes: storage monitoring, VFD-based motor control, and MQTT-based supervisory communication. Table 1 summarizes representative recent studies and maps their contributions and limitations relative to the present work.

Table 1 Comparison of Related Studies

Author	Method	Contribution	Limitation
Coradi et al. (2022)	Wireless real-time monitoring for grain storage	Demonstrated IoT-based quality monitoring in storage environments	Focused more on monitoring than integrated actuation and energy validation
Leal et al. (2023)	Review of post-harvest monitoring technologies	Clarified the role of continuous sensing in grain quality preservation	Did not propose or validate a field control architecture
Jaishree et al. (2021)	IoT-assisted closed-loop VFD control	Showed the feasibility of remote VFD regulation	Not specific to seed warehousing and lacked warehouse microclimate results
Noyjeen et al. (2021)	Web-based remote control of a three-phase induction motor	Confirmed practical remote motor control through the internet/web system	Did not evaluate storage quality, energy saving, or offline fallback
Marzuki et al. (2024)	ESP32-VFD monitoring and control for induction motor	Provided a relevant hardware-control integration model	Industrial motor context, not validated for agricultural warehouse climate control

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Wardihani et al. (2024)	MQTT-based greenhouse monitoring and control	Demonstrated lightweight publish-subscribe communication for environmental control	Greenhouse context; no VFD-driven warehouse ventilation validation
Riskiawan et al. (2025)	IoT air-quality control in a storage warehouse	Showed the local practical feasibility of warehouse air control	Mainly on-off actuation; no integrated energy and microclimate validation
Mateen et al. (2025)	Microcontroller-based silo environment control	Verified automated environmental control in grain storage	Did not combine MQTT resilience, VFD control, and field energy comparison

Recent storage studies consistently show that IoT monitoring improves visibility of environmental conditions and supports faster operator response (Coradi et al., 2022; Leal et al., 2023; Mateen et al., 2025). However, the control dimension remains fragmented. Some studies focus on sensing and quality monitoring, while others focus on VFD or motor control in non-storage contexts (Jaishree et al., 2021; Noyjeen et al., 2021; Marzuki et al., 2024; Biswal & Satpathy, 2021). MQTT-based supervision is also well established for environmental systems, but usually without explicit validation of offline fallback behavior in warehouse operation (Wardihani et al., 2024). More advanced drive-control studies, such as Khadar et al. (2021) and Kalel and Raja Singh (2024) improve motor-control robustness and diagnosis, yet they remain focused on drive-level performance rather than agricultural microclimate outcomes. Likewise, generic IoT control studies such as Kamalapur and Aspalli (2023), Sahar et al. (2024), and Pradhana et al. (2023) confirm implementation feasibility, but not field-validated warehouse storage benefits.

The critical synthesis from these studies is that previous work tends to validate only one or two components at a time: monitoring, actuation, or communication. What is still missing is a field-validated seed warehouse study that integrates all three in one architecture and evaluates them using operational metrics. Specifically, prior studies do not systematically combine variable-speed VFD control for energy-aware airflow modulation, MQTT online supervision with offline continuity, and quantitative warehouse outcomes such as paired statistical improvement of temperature-humidity conditions, energy savings, and mold-related operational observations.

This study addresses that mapped gap by implementing an IoT-VFD architecture in a real rice seed warehouse and validating it through a single field trial that links sensing, communication, actuation, and performance measurement. Based on this synthesis, the following Method section explains how the proposed architecture was implemented and evaluated in the field.

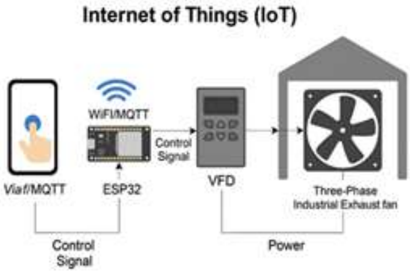

Fig. 1 Design Smart IoT

METHOD

This section describes the experimental design, data collection process, analytical model, and evaluation criteria used to test the proposed IoT-VFD system.

1. Research Design

This study applied a prototype-based field experiment in a real rice seed warehouse. The method was selected based on prior evidence that IoT monitoring is effective for agricultural environment supervision (Lutz & Coradi, 2022; Coradi et al., 2022; Wardihani et al., 2024), while VFD-based closed-loop motor control improves controllability and efficiency compared with fixed-speed or on-off operation (Jaishree et al., 2021; Marzuki et al., 2024). The overall design combines engineering implementation and quantitative evaluation.

2. System configuration and Instruments

The prototype was installed in a 900 m3 warehouse and consisted of:

a. ESP32 controller for local logic and communication.

*name of corresponding author

b. Three-phase exhaust fan driven by a Variable Frequency Drive (VFD) with operating frequency 20-50 Hz.
c. Temperature-humidity sensing nodes for environmental feedback.
d. MQTT broker and web dashboard for online telemetry, logging, and remote setpoint input.
e. Electrical protection components (MCB and overload).

The control target was set at 30 °C and 65% RH. Local control remained active when the internet was unavailable (offline mode), while online mode enabled remote supervision through MQTT topics.

The overall system architecture is presented in Fig. 2b. Sensor readings are acquired by the ESP32, transmitted through MQTT for supervision and logging, and translated into control actions at the VFD to regulate three-phase fan speed according to warehouse conditions.

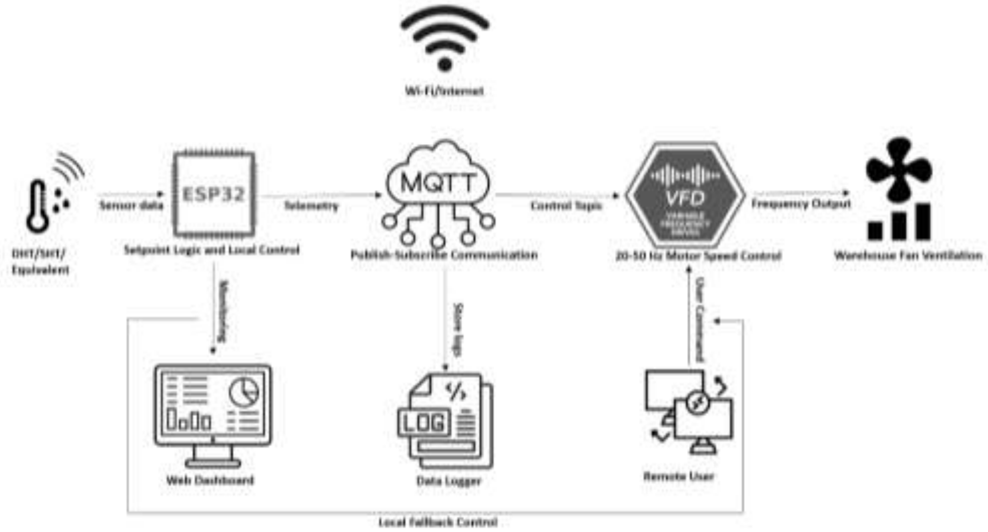

Fig. 2 IoT Architecture Diagram

3. Data Acquisition

Data were obtained from continuous operational logging during a 7-day field trial. Sensor and actuator variables were recorded every 1 hour, resulting in 168 timestamped records. Logged variables included:

a. Temperature (°C)
b. Relative humidity (%RH)
c. Motor speed (RPM)
d. Operating mode (baseline on-off or VFD-IoT control)
e. Communication status (MQTT connection events)

Energy data were obtained from kWh meter readings under equal 2-hour operating windows for two scenarios: non-VFD (on-off) and VFD control.

4. Chronological Procedure

The experimental procedure was conducted chronologically as follows:

a. Baseline assessment: warehouse operated with existing non-VFD on-off behavior to capture initial environmental and energy conditions.
b. Hardware-software integration: ESP32, sensors, VFD, and MQTT dashboard were installed and functionally verified.
c. Offline commissioning: local closed-loop control (without internet dependency) was tested for fan response and setpoint tracking.
d. Online commissioning: MQTT publish-subscribe communication, remote monitoring, and command pathways were validated.
e. Field trial operation: system ran continuously for 7 days with real-time logging.
f. Post-trial extraction: dataset and meter values were exported for statistical and performance analysis.

The operational control sequence is summarized in Fig. 2c. The algorithm continuously reads environmental variables, checks connectivity status, compares measured values with setpoints, and either maintains or adjusts VFD frequency while preserving offline fallback capability.

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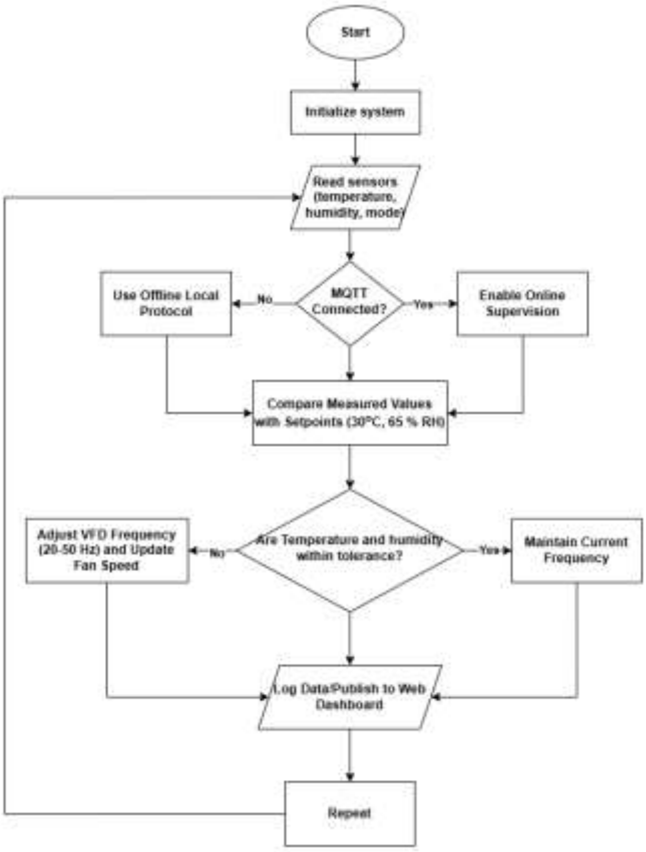

Fig. 3 Flowchart of Control Algorithm

5. Analytical and Statistical Methods

To interpret ventilation dynamics, the indoor temperature transient was modeled using a well-mixed approach:

$$T(t) = T_{out} + (T_0 - T_{out})e^{-ACH\,t} \qquad (1)$$

Where $T(t)$ Is the indoor temperature at time t, $T_{out}$is the outdoor (asymptotic) temperature, $T_0$is the initial indoor temperature, and $ACH$is the air change rate per hour. The air change rate is defined as:

$$ACH = \frac{Q}{V} \qquad (2)$$

Where Q is the fan airflow capacity and $V$is the room volume. In this study, $Q = 32{,}000\ \mathrm{m}^3/\mathrm{h}$and $V = 3{,}600\ \mathrm{m}^3$, resulting in $ACH = 8.89\ \mathrm{h}^{-1}$. The time required to reach a target tolerance Δ Above ambient temperature is expressed as:

$$t = -\frac{1}{ACH}\ln\left(\frac{\Delta}{T_0 - T_{out}}\right) \qquad (3)$$

For hypothesis testing, paired t-tests were used to compare pre- and post-control conditions for temperature and humidity using matched 48-hour windows (baseline period versus the first 48-hour controlled period). The same analysis was repeated for offline and online subsets to verify consistency across operating modes.

6. Measurement, Testing, and Evaluation Criteria

System performance was measured and evaluated using:

a. Microclimate effectiveness:
    1. Mean ± SD comparison (before vs after control)
    2. Paired t-test significance (alpha = 0.05)
b. Control quality:

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    1. Target-hit accuracy (% of records within tolerance band)
    2. RMSE for temperature and humidity against setpoints
c. Energy performance:
    1. kWh comparison in matched 2-hour operating windows
    2. Percentage energy saving relative to non-VFD mode
d. Reliability: MQTT uptime percentage and total downtime duration
e. Storage safety outcome: Mold incidence observation during controlled operation

With these procedures and metrics defined, the next section reports the observed field results.

RESULT

Results are presented sequentially from system-level operation, model-based cooling behavior, and statistical performance to energy, reliability, and monitoring outcomes.

1. Prototype Field Test Outcome

The IoT-VFD prototype was deployed and operated in real warehouse conditions. Target control around 30 °C and 65% RH was reached and maintained with stable operation. During the controlled operation period, no fungus was observed (mold incidence 0%).

From a control perspective, this result indicates that the ESP32-VFD loop was able to continuously translate environmental feedback into practical ventilation action under field conditions rather than only in bench testing.

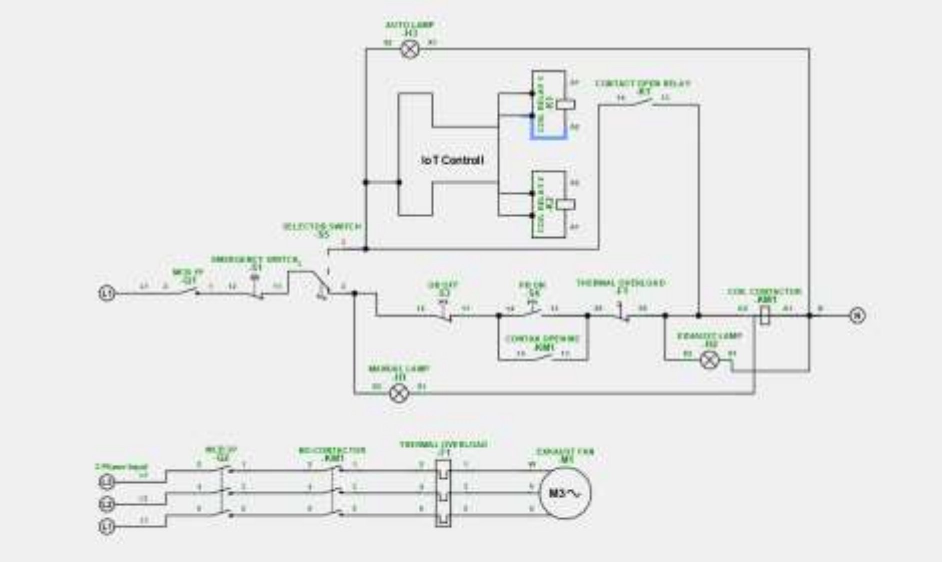

Fig. 4 Design Wiring

2. Ventilation-Only Cooling (Model-Based)

For a cooling transition from 32.0 °C to 30.0 °C under an air change rate of 8.89 h^{-1}, the corresponding tolerance-based settling time is obtained using Equation.

Table 2
Ventilation Cooling

Tolerance above 30 °C (Delta)	**Desired temperature (°C)**	**Theoretical time t (min)**	**Practical estimate x3 (min)**	**Practical estimate x5 (min)**
1.20	31.20	3.4	10.3	17.2
0.80	30.80	6.2	18.6	30.9
0.50	30.50	9.4	28.1	46.8
0.20	30.20	15.5	46.6	77.7

0.10	30.10	20.2	60.7	101.1
0.05	30.05	24.9	74.7	124.5
0.01	30.01	35.8	107.3	178.8

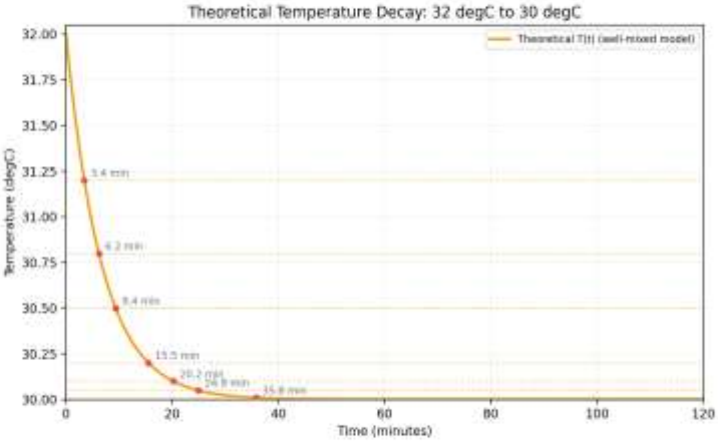

Fig. 5 Theoretical Temperature decay

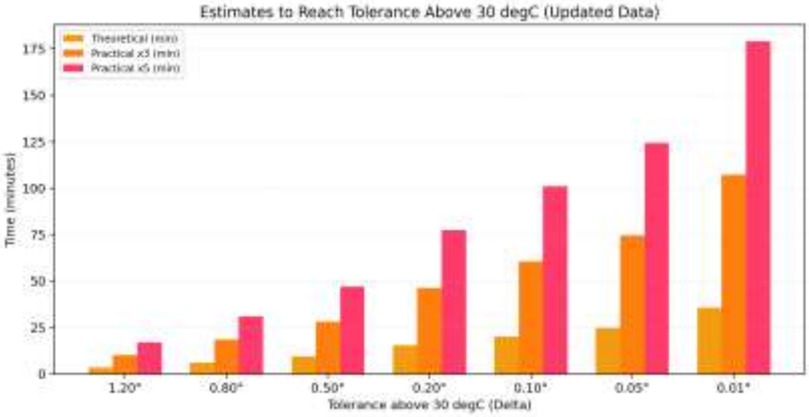

Fig. 6 Estimates to Reach Tolerance

Interpretation: cooling trend is exponential. Ventilation can approach ambient outdoor temperature, but cannot cool below it without active refrigeration.

This behavior is consistent with the well-mixed first-order model introduced in the Method section, where temperature convergence becomes progressively slower as the indoor condition approaches the asymptotic outdoor state.

3. Dataset Expansion

A 7-day sensor dataset was compiled and summarized in Table 3.

Table 3
Sensor Log Summary and Paired t-test

Parameter	Before (mean ± SD)	After (mean ± SD)	Paired t-test p-value	Decision (alpha=0.05)
Temperature (°C)	31.92 ± 1.00	30.03 ± 0.45	9.00e-15	Significant
Humidity (%RH)	98.75 ± 1.13	65.08 ± 1.45	1.19e-60	Significant

The result confirms great improvement toward the setpoint after VFD-IoT control activation.

Theoretically, this shift toward lower temperature and humidity reflects the effect of feedback-based ventilation, in which fan speed is regulated according to measured deviation from the desired warehouse microclimate.

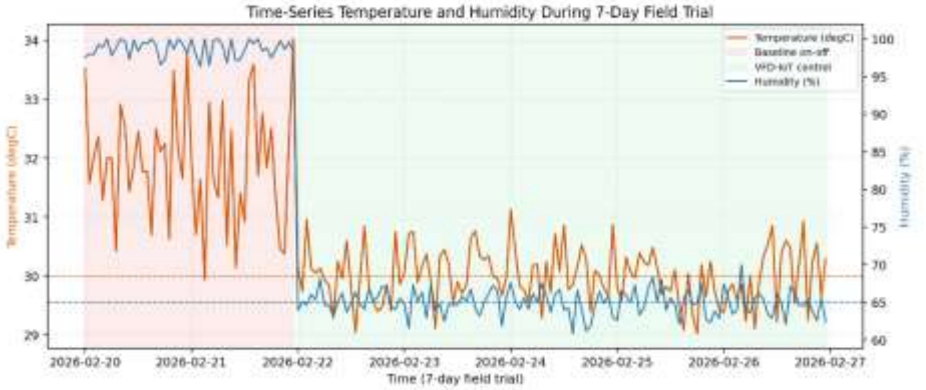

Fig. 7 Time-Series 7-Day Field Trial

4. Line-of-Sight Analysis

Meter data for an equivalent 2-hour operation window:

a. Non-VFD on–off: 2.70 kWh
b. VFD IoT PWM: 1.88 kWh

Energy saving percentage is calculated as:

$$\%Saving = \frac{E_{nonVFD} - E_{VFD}}{E_{nonVFD}} \times 100$$
$$= \frac{2.70 - 1.88}{2.70} \times 100$$
$$= 30.4\%.$$

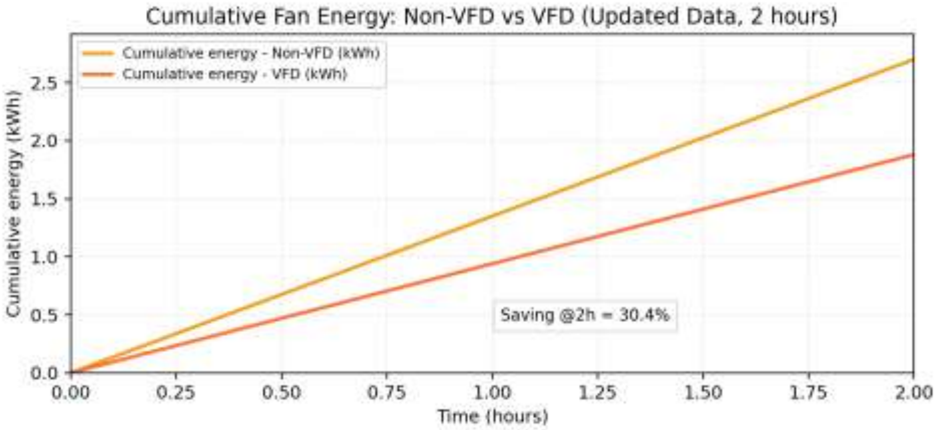

Fig. 8 Cumulative Fan Energy: VFD vs Non-VFD

This indicates substantial energy benefit when replacing binary on-off control with variable-speed VFD control.

This result is theoretically consistent with VFD operation, because motor speed and airflow can be matched to actual load demand rather than forcing repeated full-speed operation as in conventional on-off control.

5. Performance Metrics

To evaluate control quality and efficiency in one view, Table 4 summarizes target-hit accuracy, RMSE, and energy metrics during controlled operation.

Table 4
Operational Performance Metrics

Metric	Value	Notes
Target-hit accuracy	97.5%	Criterion: Temp within 30 ± 1 °C and RH within 65 ± 4%
Temperature RMSE	0.47 °C	Against a 30 °C setpoint
Humidity RMSE	1.67% RH	Against 65% RH setpoint
Energy (non-VFD, 2 h)	2.70 kWh	Baseline on-off
Energy (VFD, 2 h)	1.88 kWh	IoT PWM control
Energy saving	30.4%	Relative to non-VFD

Taken together, these aggregate metrics support the underlying closed-loop control theory: small tracking error and high target-hit accuracy indicate that the controller maintained the warehouse state close to the defined equilibrium band, while lower energy use indicates that this regulation was achieved with load-matched actuation rather than excessive fan operation.

6. Statistical Validation

Paired pre-post significance remained valid in both operation modes:

Table 5
Statistical Validation (Offline vs Online)

Mode	p-value Temperature	p-value Humidity	Conclusion
Offline mode	9.32e-10	4.45e-32	Significant
Online MQTT mode	1.58e-06	3.71e-29	Significant

This shows that control effectiveness is maintained even when remote IoT mode is active.

In theoretical terms, the result supports the dual-mode architecture assumption that communication loss should affect supervisory visibility more than the core local control loop, as long as setpoint logic remains embedded at the controller level.

7. Sensitivity Analysis

PWM/VFD frequency was varied from 20 to 50 Hz to observe the cooling response time to 30 °C. Higher frequency shortened response time, with diminishing gain above 45 Hz.

Table 6
Frequency versus Time

Frequency (Hz)	Response time (min)
20	31.5
25	26.2
30	22.0
35	18.8
40	16.4
45	15.1
50	14.7

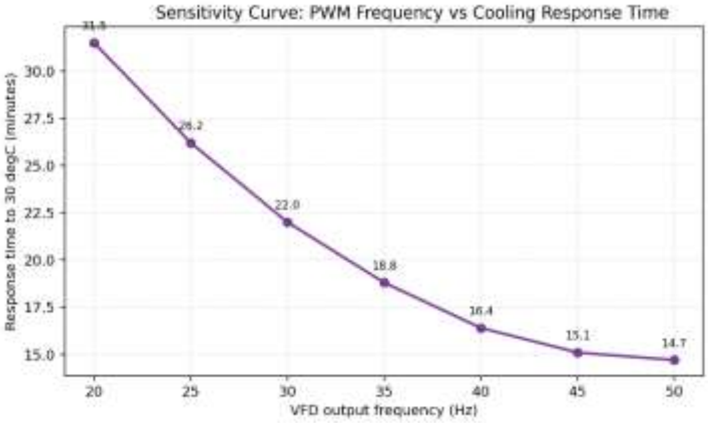

Fig. 9 Sensitivity Curve

Operationally, 40-45 Hz is recommended as an efficiency-response tradeoff region.

This trend also aligns with fan-drive theory, where increasing frequency initially improves response speed, but the marginal benefit decreases as the system approaches a region of diminishing returns relative to added electrical demand.

8. Web Monitoring and Operational Supervision

The system includes a web-based monitoring dashboard connected through MQTT for real-time supervision. The dashboard displays:

a. Current KPI cards (temperature, humidity, motor speed, and MQTT connectivity status).
b. Time-series trend charts for temperature-humidity and fan RPM.
c. Event and alarm logs for operational traceability (setpoint changes, humidity spikes, reconnect events).

Web monitoring provides two practical benefits in warehouse operations. First, operator response time is improved because abnormal trends can be detected before conditions exceed tolerance limits. Second, control transparency is improved because each intervention is recorded in the event log, supporting audit and maintenance decisions.

In online mode, operators can adjust setpoints remotely and observe direct response in telemetry curves. In offline mode, local ESP32-VFD control remains active and monitoring resumes automatically after MQTT reconnection. This architecture keeps control continuity while still enabling remote supervision when the network is available.

Conceptually, this confirms that the monitoring layer functions as a supervisory extension of the control system rather than as its sole dependency, which is an important design requirement for warehouse environments with intermittent connectivity.

Fig. 10 Web Monitoring Dashboard

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9. Discussions

Building on the reported results, this section interprets the findings, relates them to prior studies, and outlines their practical implications.

The results indicate that the IoT-VFD architecture improves both control quality and operational practicality in rice seed warehousing. Numerically, controlled operation reduced mean temperature by 1.89 °C and relative humidity by 33.67 percentage points, while maintaining 97.5% target-hit accuracy, 0.47 °C temperature RMSE, and 1.67% RH humidity RMSE. These values are not only statistically significant but also practically meaningful because they show that the controller kept the warehouse close to the desired operating band under field variability. This behavior is technically consistent with variable-speed control principles, where airflow is adjusted continuously according to error magnitude rather than through full-speed switching. The agreement between the well-mixed model and the observed cooling pattern further strengthens the interpretation that the warehouse behaves as a first-order ventilation-driven system over the tested operating range.

Compared with Coradi et al. (2022) and Leal et al. (2023), which emphasized real-time monitoring and quality visibility in grain storage, this study advances the literature by reporting field control outcomes in directly interpretable operational units: 1.89 °C temperature reduction, 33.67-point RH reduction, and 30.4% fan-energy saving over a matched 2-hour window. Compared with Jaishree et al. (2021), Noyjeen et al. (2021), and Marzuki et al. (2024), who established the feasibility of IoT-assisted motor or VFD control, the present study moves beyond feasibility by linking motor-speed modulation to measurable warehouse microclimate performance, matched energy comparison, and storage-safety observation in one deployment. Compared with Wardihani et al. (2024) and Mateen et al. (2025), which support MQTT-based supervision for agricultural environments, this work contributes a stronger resilience result because the same control objective remained statistically valid in both offline and online modes, while MQTT uptime still reached 99.64%. In this sense, the state-of-the-art contribution is not any single subsystem, but the integrated validation of sensing, communication, actuation, and field performance in one seed-warehouse case.

The communication and storage-safety results also deserve critical interpretation. MQTT uptime of 99.64% with preserved local control in offline mode suggests that supervisory connectivity and control continuity can coexist, but it also shows that cloud-linked monitoring alone is insufficient as the primary control dependency for warehouse environments with unstable internet. This distinction is important because low-power monitoring platforms such as those reported by Ioannides et al. (2023, 2024) are valuable for environmental visibility, yet the present study goes a step further by coupling monitoring with direct VFD actuation and local fallback control. Likewise, zero observed mold incidence is a positive operational outcome, yet it should be interpreted cautiously as a trial-bound indicator rather than proof of universal fungal prevention. The more defensible scientific claim is that sustained reduction of humidity toward 65% RH reduced the environmental favorability for fungal growth during the monitored period. This is a more rigorous position than simply claiming that the prototype eliminates mold.

Threats to validity remain and should be considered when interpreting these results. Internal validity may be influenced by site-specific airflow patterns, sensor placement, and unmodeled external disturbances. External validity is limited because the trial was conducted at a single warehouse, so generalization to other storage geometries or commodities should be made cautiously. Construct validity is also bounded by the selected performance indicators (temperature, humidity, RPM, and kWh) and trial duration. In line with these constraints, several limitations should frame the interpretation of this study. The current prototype focuses on ventilation-based control and has not yet been integrated with active cooling (AC), so thermal regulation remains bounded by ambient conditions. The field validation was conducted in a single warehouse, which limits direct generalization to different building geometries, stocking densities, and climatic contexts. In addition, although the technical benefits are clear, this work has not yet included a full techno-economic assessment covering CAPEX, OPEX, payback period, and lifecycle maintenance cost. Future work should therefore prioritize multi-site deployments, integration of predictive machine learning for humidity forecasting and proactive control, and comprehensive economic analysis to strengthen deployment readiness at scale.

CONCLUSION

Considering the full set of results and discussion points above, the following conclusions summarize the main answers and manuscript contributions. This study answers the main research question by showing that an IoT-VFD architecture can control rice seed warehouse air conditions effectively, reliably, and with lower energy use than conventional on-off operation. The field trial demonstrates significant microclimate improvement from about 31.92 °C and 98.75% RH to 30.03 °C and 65.08% RH, with paired statistical significance ($p < 0.001$) in both offline and online modes. The system also reduced energy consumption by 30.4% in a matched 2-hour operating window (2.70 kWh to 1.88 kWh), achieved 99.64% MQTT uptime, and maintained 0% observed mold incidence during controlled operation.

The manuscript contributes in four explicit ways. First, it provides an applied integration of ESP32, MQTT, and VFD for single-phase to controllable three-phase ventilation in a real rice seed warehouse. Second, it contributes quantitative evidence of control performance using target-hit accuracy, RMSE, and paired inferential statistics. Third, it contributes practical energy evidence through direct non-VFD versus VFD comparison under equivalent operation windows. Fourth, it contributes an implementation framework that combines local offline control continuity with online supervisory monitoring. Overall, these findings support IoT-VFD deployment as a practical approach for energy-aware and fungus-preventive rice seed storage management. Beyond the reported prototype results, the broader impact of this work is that it provides a technically grounded pathway for modernizing seed warehouse operations toward more reliable post-harvest quality protection, lower ventilation energy use, and better digital traceability in agricultural storage management. Future work will integrate predictive control using machine learning and multi-site validation.

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