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Operational Monitoring Stability Framework for IoT-Enabled Aeroponic Farming Systems

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Abstract—The integration of Internet of Things (IoT) technologies within controlled-environment agriculture has improved environmental monitoring, automation efficiency. This study evaluated the operational reliability, environmental responsiveness, and monitoring stability of an IoT-enabled aeroponic farming system utilizing Engineering Management principles. A developmental-descriptive research design was employed involving subsystem validation, operational testing, and comparative operational analysis. The developed system integrated environmental sensing technologies, automated nutrient circulation, pH regulation mechanisms, RTC-controlled lighting systems, and IoT-based monitoring infrastructures. Results demonstrated high operational reliability, with 100% operational accuracy achieved by the nutrient circulation, pH regulation, and temperature-responsive exhaust ventilation systems, while the lighting automation subsystem achieved 96.67% operational accuracy. Environmental monitoring results also indicated stable operational conditions throughout repeated testing procedures. The study introduces the Operational Monitoring Stability (OMS) framework as an Engineering Management-oriented operational model emphasizing monitoring reliability, automation responsiveness, environmental stability, and operational coordination within intelligent agricultural systems. Findings suggest that IoT-enabled aeroponic infrastructures can support operational consistency, environmental regulation, sustainability-oriented management, and decision-support capability within smart agriculture environments.

Index Terms—Decision Support Systems, Aeroponics, Smart Agriculture, Internet of Things, Engineering Management, Operational Monitoring Stability.

I. INTRODUCTION

Modern agricultural systems continue to encounter operational challenges associated with climate variability, declining agricultural land availability, water scarcity, labor shortages, inefficient resource utilization, and sustainability pressures. Existing studies demonstrate that smart agricultural systems improve operational efficiency, environmental monitoring capability, and sustainability performance within precision farming environments [1], [2]. The increasing adoption of controlled-environment agriculture further supports the integration of technological monitoring systems and resource-efficient agricultural methods [3].

Aeroponic farming is a soilless cultivation approach in which plant roots are suspended in air and supplied with nutrient-rich mist solutions. Previous studies indicate that aeroponic cultivation improves environmental regulation, resource utilization efficiency, crop management capability, and nutrient absorption performance under controlled agricultural conditions [4], [5].

IoT-enabled agricultural monitoring systems strengthen environmental responsiveness and operational coordination within smart farming environments [6], [7]. Intelligent monitoring infrastructures allow continuous sensing, automated subsystem synchronization, remote monitoring capability, and operational decision-support integration.

Despite the increasing adoption of IoT-enabled agricultural monitoring systems, many existing studies remain primarily focused on isolated automation functions without sufficiently addressing operational coordination, monitoring stability, environmental synchronization, and Engineering Management-oriented decision support. This study evaluates a previously developed IoT-enabled aeroponic farming system from an operational management perspective by examining automation reliability, environmental responsiveness, subsystem synchronization, and monitoring stability under controlled agricultural conditions. The study further introduces the Operational Monitoring Stability (OMS) framework as an Engineering Management-oriented operational model for intelligent agricultural systems.

The current study was derived from a previously developed academic aeroponic farming prototype designed for high-value crop cultivation under controlled environmental conditions. The prototype integrated Arduino Uno, NodeMCU ESP8266, DHT22 sensors, pH sensors, relay modules, RTC automation, and mobile-assisted monitoring systems.

Unlike existing IoT-based smart agriculture studies primarily focused on isolated automation functions, the present study contributes an Engineering Management-oriented operational framework integrating monitoring stability, environmental responsiveness, subsystem synchronization, and decision-support capability within controlled agricultural systems.

1. Objective of the Study

1.1 General Objective

To evaluate the operational efficiency and decision-support capability of an IoT-enabled aeroponic farming system utilizing Engineering Management principles under controlled smart agriculture environments.

1.2 Specific Objectives:

1.2.1 To examine the operational reliability of the automated environmental monitoring and control systems integrated within the aeroponic farming infrastructure.
1.2.2 To assess the environmental responsiveness and monitoring capability of the IoT-enabled agricultural monitoring system.
1.2.3 To compare operational characteristics between traditional farming and aeroponic cultivation environments.
1.2.4 To evaluate the contribution of integrated monitoring systems toward operational efficiency, sustainability performance, and decision-support quality.
1.2.5 To propose an Operational Monitoring Stability (OMS) operational assessment framework for intelligent agricultural systems.

1.3. Significance of the Study

This study contributes to smart agriculture and Engineering Management by evaluating how IoT-enabled monitoring systems improve operational efficiency, environmental stability, and sustainability within controlled agricultural environments.

The study contributes an Engineering Management-oriented operational framework through the proposed Operational Monitoring Stability (OMS) model, which integrates monitoring reliability, automation responsiveness, environmental stability, and operational coordination within intelligent agricultural systems.

The findings may benefit agricultural researchers, smart farming practitioners, Engineering Management researchers, and developers of intelligent agricultural infrastructures by providing operational insights regarding integrated monitoring systems, environmental responsiveness, and sustainability-oriented agricultural management.

II. METHODOLOGY

1. Research Design

The study employed a developmental-descriptive research design grounded in Engineering Management and smart agricultural systems analysis. The research focused on the operational evaluation of a previously developed aeroponic farming prototype utilizing IoT-enabled monitoring systems, automated environmental regulation, and operational control mechanisms.

2. Population and Sample of the Study

The study focused on the operational performance of the developed aeroponic farming prototype and its integrated environmental monitoring components. Purposive testing was conducted on the automated subsystems, including nutrient delivery mechanisms, pH regulation systems, temperature monitoring sensors, lighting automation controls, and IoT communication modules. Pechay crops cultivated within the aeroponic environment served as the primary agricultural test subject for comparative operational observation.

3. Research Instruments

The study utilized Arduino Uno microcontrollers, NodeMCU ESP8266 communication modules, DHT22 sensors, pH sensors, relay modules, RTC modules, automated pumps, and IoT-based monitoring applications for environmental sensing, automated regulation, subsystem synchronization, and operational monitoring within the aeroponic infrastructure.

Table 1. Integrated Monitoring Components

Component	Technical Function	Operational Role
DHT22 Sensor	Environmental sensing	Environmental Monitoring
pH Sensor	Nutrient monitoring	Nutrient Monitoring
NodeMCU ESP8266	IoT communication	Remote Monitoring
Relay Module	Automation control	Automation Management
RTC Module	Scheduling control	Automation Management
Submersible Pump	Nutrient circulation	Nutrient Delivery
Peristaltic Pump	pH Regulation	Nutrient Regulation

4. Data Collection Procedure

Operational testing and validation procedures were conducted to evaluate subsystem responsiveness and monitoring reliability. Environmental parameters monitored included temperature, humidity, nutrient delivery, pH level, and lighting automation.

Automated operational responses were recorded according to predefined operational thresholds. Expert consultation involving agricultural practitioners, agricultural engineers, electronics engineering specialists, and controlled-environment farming evaluators was conducted to validate subsystem adequacy and implementation feasibility.

Three domain experts specializing in agriculture, electronics engineering, and smart farming systems participated in the validation process using operational adequacy criteria.

4.1 Operational Validation Procedure

The developed aeroponic farming system underwent repeated operational validation involving nutrient circulation, pH regulation, exhaust ventilation, and RTC-controlled lighting automation. Automated responses were triggered according to predefined environmental thresholds, including temperature regulation at 29°C and pH regulation within the 5.5–6.5 range. Each subsystem underwent thirty repeated activation trials over a seven-day testing period to evaluate operational consistency and monitoring reliability.

5. Statistical Treatment

The study utilized descriptive statistical analysis, operational success ratios, mean operational response analysis, standard deviation measurements, and repeated subsystem validation procedures.

Subsystems achieving at least 95% successful activation were considered operationally reliable.

The OMS operational score was computed using the following operational relationship:

$$OMS = (MR+AR+ES+OC)/4$$

Where:

MR – Monitoring Reliability
AR – Automation Responsiveness
ES – Environmental Stability
OC – Operational Coordination

The OMS operational relationship was conceptually derived from integrated systems reliability and operational coordination principles within Engineering Management and cyber-physical systems literature.

OMS values approaching 1.0 indicate higher integrated monitoring stability and operational synchronization.

Inferential statistical analysis was not applied due to the developmental and prototype-oriented nature of the study.

III. RESULTS AND DISCUSSION

This section presents the operational evaluation, subsystem validation, environmental monitoring performance, and comparative operational analysis of the developed IoT-enabled aeroponic farming system under controlled agricultural conditions. The findings focus on automation reliability, environmental responsiveness, operational stability, and subsystem coordination within the integrated monitoring infrastructure.

1. Validation and Field Performance

Operational testing demonstrated stable automation performance and consistent environmental responsiveness within the developed aeroponic farming system. Repeated response testing procedures evaluated subsystem consistency according to predefined environmental parameters programmed within the monitoring infrastructure.

Table 2. Operational Reliability and Automation Performance

Component	ST	OA	MR	SD
Submersible Pump System	30/30	100%	1.00	0.00
Lighting Automation	29/30	96.67%	0.97	0.18
pH Regulation System	30/30	100%	1.00	0.00
Exhaust Fan Response	30/30	100%	1.00	0.00

ST = Success Trials; OA = Operational Accuracy; MR = Mean Reliability Score; SD = Standard Deviation

The subsystem validation results indicate high operational consistency across automated environmental regulation mechanisms. Three major subsystems achieved complete operational activation reliability during repeated testing procedures, while the RTC-controlled lighting subsystem demonstrated only minimal scheduling inconsistencies equivalent to a 3.33% operational deviation.

The low standard deviation values also indicate operational stability and subsystem synchronization consistency during repeated operational execution.

The findings indicate that integrated monitoring systems improve operational consistency and environmental coordination within controlled agricultural infrastructures. Similar studies have shown that IoT-enabled environmental monitoring systems enhance agricultural responsiveness and operational efficiency within smart farming environments [1], [6].

2. Category-Level Performance

The developed aeroponic farming system exhibited stable environmental monitoring capability and operational responsiveness across multiple automated subsystems.

Environmental monitoring results demonstrated stable operational conditions throughout the validation period. Observed environmental averages remained within predefined operational thresholds, including an average temperature of 27.4 °C, humidity level of 75%, and nutrient pH level of 6.1. The RTC-controlled lighting subsystem maintained 96.67% successful automation execution, indicating stable environmental regulation capability within the controlled aeroponic environment.

Table 3. Environmental Stability Monitoring Results

Parameter	Threshold	Average Response	Stability Result
Temperature	28–29 ºC	27.4 ºC	Stable
Humidity	70–80%	75%	Stable
pH Level	5.5–6.5	6.1	Stable

Lighting Cycle	Scheduled	96.67%	Stable

Automated temperature regulation successfully activated exhaust ventilation mechanisms once predefined environmental thresholds were reached. Automated nutrient circulation and pH correction mechanisms also demonstrated stable operational synchronization with the integrated monitoring infrastructure.

The findings indicate that environmental sensing and automated operational coordination improve monitoring consistency and agricultural management capability within controlled farming environments. Existing studies similarly emphasize that IoT-enabled monitoring systems strengthen environmental responsiveness and automation reliability within smart agricultural infrastructures [1], [4], [6].

Operational Monitoring Stability (OMS) Dimensions

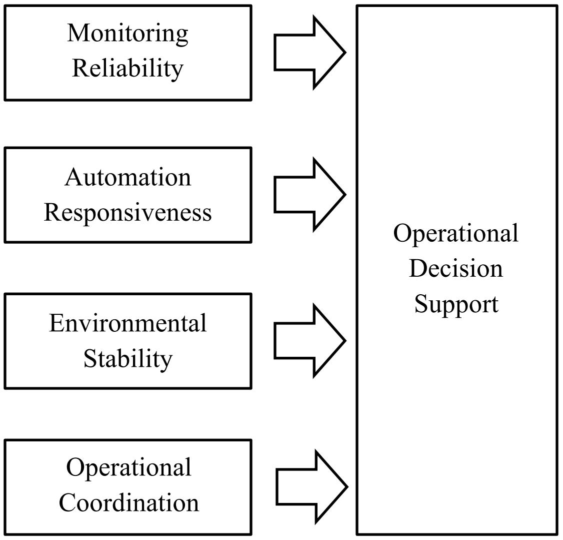

Figure 1. Operational Monitoring Stability (OMS) Framework

The OMS framework integrates four operational dimensions within intelligent agricultural systems: monitoring reliability, automation responsiveness, environmental stability, and operational coordination. These dimensions collectively support adaptive environmental regulation, subsystem synchronization, and sustainability-oriented operational decision support within IoT-enabled agricultural infrastructures.

The OMS framework conceptualizes intelligent agricultural infrastructures as coordinated cyber-physical operational environments integrating environmental sensing reliability, automation responsiveness, environmental regulation capability, and subsystem synchronization.

The framework is conceptually grounded in systems reliability theory, cybernetic control theory, Engineering Management principles, and cyber-physical systems coordination.

The framework positions environmental monitoring as the foundational operational layer supporting adaptive operational regulation and sustainability-oriented decision-support capability within intelligent agricultural systems.

3. Discussion

The findings demonstrate that IoT-enabled monitoring infrastructures improve operational coordination, environmental responsiveness, and sustainability-oriented agricultural management within controlled farming environments. Compared with traditional agricultural systems, the developed aeroponic infrastructure provided improved environmental regulation, automated operational control, and enhanced monitoring accessibility.

Compared with traditional agricultural environments, the developed aeroponic system provided improved environmental control capability, minimized pest exposure conditions, and enhanced operational monitoring consistency.

Comparative operational benchmarking was conducted to evaluate how integrated monitoring infrastructures influence environmental regulation capability, operational responsiveness, and management coordination relative to conventional agricultural environments.

Table 4. Comparative Operational Characteristics

Indicator	Traditional Farming	IoT-Enabled Aeroponic System
Environmental Monitoring	Manual Observation	Real-Time Sensor Monitoring
Nutrient Delivery	Manual Watering	Automated Nutrient Mist Circulation
Lighting Control	Natural Sunlight Dependency	RTC-Controlled Automation
Environmental Regulation	Limited Control	Threshold-Based Automation
Monitoring Accessibility	On-Site Only	Mobile-Assisted Monitoring
Operational Coordination	Manual Management	Integrated IoT Coordination

The findings suggest that operational stability within intelligent agricultural infrastructures depends not only on sensor accuracy, but also on coordinated subsystem synchronization and environmental feedback responsiveness.

From an Engineering Management perspective, monitoring infrastructures function as operational coordination mechanisms supporting adaptive environmental regulation and sustainability-oriented resource management.

The OMS framework strengthens the Engineering Management contribution of the study by introducing an operational model focused on monitoring stability, automation responsiveness, environmental coordination, and intelligent subsystem integration. The framework demonstrates potential applicability within urban farming infrastructures, controlled-environment agriculture, and sustainability-oriented smart agricultural systems.

3.1 Practical Implications

The OMS framework may assist Engineering Management practitioners and smart agriculture developers in evaluating subsystem coordination, monitoring responsiveness, automation reliability, and sustainability-oriented operational management within intelligent agricultural infrastructures.

IV. LIMITATIONS

This study is limited to the operational evaluation and validation of an IoT-enabled aeroponic farming system conducted under controlled environmental conditions.

The study did not include large-scale agricultural deployment, long-term crop productivity analysis, economic scalability assessment, or commercial implementation evaluation.

External environmental variables such as extreme climate fluctuations, internet instability, and long-term hardware degradation were also not extensively examined during the operational testing period.

Machine learning-based predictive control, cloud-integrated analytics, and energy optimization analysis were beyond the scope of the study.

Despite these limitations, the study provides operational insights regarding the integration of IoT-enabled monitoring systems, automated environmental regulation, and Engineering Management-oriented operational coordination within controlled smart agricultural infrastructures.

V. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. Summary of Findings

This study evaluated the operational efficiency, environmental responsiveness, and monitoring capability of an IoT-enabled aeroponic farming system utilizing Engineering Management principles under controlled smart agriculture environments.

The developed prototype integrated environmental sensing technologies, IoT communication modules, automated nutrient circulation systems, pH regulation mechanisms, and RTC-controlled automation infrastructures.

Operational testing demonstrated stable subsystem responsiveness and reliable automation performance across multiple environmental monitoring components.

The study introduced the Operational Monitoring Stability (OMS) framework as an Engineering Management-oriented operational model emphasizing environmental monitoring, automation responsiveness, operational stability, and subsystem coordination within intelligent agricultural systems.

B. Conclusions

The study demonstrated the operational viability and monitoring reliability of an IoT-enabled aeroponic farming system operating under controlled environmental conditions. Integrated environmental sensing, automated regulation, and IoT-based monitoring improved subsystem synchronization, operational responsiveness, and environmental stability. The proposed OMS framework strengthens the Engineering Management contribution of the study by emphasizing monitoring reliability, automation responsiveness, environmental coordination, and sustainability-oriented operational decision support within intelligent agricultural systems.

C. Recommendations

Future studies may incorporate machine learning-based predictive control, cloud-integrated monitoring infrastructures, database-driven analytics, image-based crop health assessment, energy optimization analysis, and large-scale agricultural implementation.

Future researchers may also evaluate the scalability and long-term sustainability performance of IoT-enabled aeroponic farming systems across larger agricultural environments and multiple crop varieties.

Further validation of the OMS framework across multiple intelligent agricultural infrastructures is likewise recommended.

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