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Integration of LabVIEW-Compatible IoT Boards for Smart Agricultural Monitoring: A Comprehensive Framework Using Raspberry Pi, Arduino, and ESP32

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Abstract: This paper presents a comprehensive smart agricultural monitoring system integrating LabVIEW with three prominent IoT platforms Raspberry Pi, Arduino, and ESP32 for real-time crop monitoring and automated precision irrigation. We propose a novel three-tier architecture comprising distributed sensor nodes. a Raspberry Pi edge gateway with local processing capabilities, and LabVIEW-based visualization and control. The system implements MQTT-based communication for seal-able wireless deployment and serial protocols for high-reliability wired connections. Experimental evaluation over a 90-day field deployment on a 2-hectare vegetable farm demonstrates sensor accuracy within 2.3% of reference instruments, 31.4% water consumption reduction through precision irrigation, and 18.7% average crop yield improvement across tomato, pepper, and cucumber crops. Platform-specific analysis reveals that ESP32 offers optimal cost-performance for wireless sensing at $1.50 per node with deep sleep power consumption of 10 A. Arduino pro videos superior LabVIEW integration via the LINX toolkit with 99.7% uptime, and Raspberry Pi excels as an edge gateway supporting local ma chine learning inference. The system achieved complete payback within 15 days, demonstrating compelling economic viability for smallholder and commercial agricultural operations.
Keywords: Internet of Things - Smart Agriculture LabVIEW Precision Farming Wireless Sensor Networks Arduino Raspberry Pi ESP32 Sustainable Agriculture.

I. INTRODUCTION

Agriculture consumes approximately 70% of global freshwater resources, with inefficient traditional irrigation methods wasting up to 60% of applied water through evaporation, runoff, and improper scheduling. As the global population continues to rise toward an estimated 9.7 billion by 2050, the agricultural sector faces unprecedented pressure to increase food production by 70% while simultaneously reducing environmental impact and resource consumption. [2]. Precision agriculture enabled by Internet of Things (IoT) technologies offers transformative solutions to optimize resource utilization while maximizing crop yields through data-driven decision-making [3,4].

The integration of wireless sensor networks (WSNs) with agricultural practices has emerged as a cornerstone of modern smart farming systems [5].

These systems enable real-time monitoring of critical environmental parameters including soil moisture, temperature, humidity, and light intensity, facilitating precise interventions that were previously impossible with traditional farming methods [6]. Recent advances in low-cost microcontrollers and communication technologies have democratized access to precision agriculture tools, making them viable for operations of all scales [7].

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) provides a powerful graphical programming environment for data acquisition, instrument control, and industrial automation [8]. Its visual programming paradigm enables rapid development of monitoring and control systems, making it particularly suitable for agricultural applications where domain experts may lack extensive programming expertise. When combined with low-cost loT hardware platforms, LabVIEW offers a compelling solution for developing sophisticated agricultural monitoring systems [9].

Despite the growing body of research on loT-based agriculture [10,11], systematic guidance for integrating diverse hardware platforms with LabVIEW for agricultural applications remains limited. Previous studies have typically focused on single-platform implementations [12] or lacked comprehensive field validation [13]. This paper addresses these gaps through the following contributions:

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1) A unified three-tier architecture seamlessly integrating Raspberry Pi. Arduino, and ESP32 platforms with LabVIEW for comprehensive agricultural monitor-ing and control.
2) Systematic comparison of platform capabilities, including processing power. connectivity options, power consumption, cost, and LabVIEW integration methods.
3) Validated 90-day field deployment with quantifiable metrics on sensor accuracy, system reliability, water savings, and crop yield improvements Evidence-based platform selection guidelines enabling practitioners to choose optimal configurations for specific agricultural requirements.
4) Economic analysis demonstrating rapid return on investment for precision agriculture implementations.

II. RELATED WORK

A. Iot in Smart Agriculture

The application of IoT technologies in agriculture has experienced exponential growth. with research output increasing dramatically between 2020 and 2024 [14]. Mowla et al. [15] provided a comprehensive survey of IoT and WSN architectures for smart agriculture, identifying key challenges including power management, communication reliability, and data security. Gatkal et al. [7] re-viewed loT-enabled smart agriculture systems, emphasizing the role of micro-controllers and various communication protocols including LoRa, ZigBee, and SigFox.

Precision irrigation represents one of the most impactful applications of agricultural IoT [16]. Bwambale et al. [17] conducted a comprehensive review of smart irrigation monitoring and control strategies, reporting water savings ranging from 20% to 50% compared to traditional scheduling methods. The integration of machine learning with IoT systems has further enhanced irrigation optimization, enabling predictive scheduling based on weather forecasts and historical patterns [18].

B. Wireless Sensor Network for Agriculture

Ammoniaci et al. [19] demonstrated WSN applications in precision agriculture. highlighting the importance of sensor placement and network topology optimization. Khalifeh et al. [20] reviewed WSN deployment challenges specific to agricultural environments, including electromagnetic interference from vegetation. power constraints in remote locations, and exposure to harsh weather conditions. Recent work by Kushwaha et al. [21] presented a smart irrigation monitoring system using WSN with demonstrated water efficiency improvements exceeding 60%.

Edge computing has emerged as a critical enabler for agricultural IoT systems [22]. By processing data locally at gateway devices, edge architectures reduce latency. minimize bandwidth requirements, and enable operation during network outages. Cordeiro et al. [23] demonstrated fog-enabled intelligent irrigation using deep neural networks, achieving significant improvements in prediction accuracy compared to cloud-only approaches.

C. Platform-Specific Applications

ESP32-based agricultural systems have gained significant attention due to the platform's integrated WiFi/Bluetooth capabilities and ultra-low power consumption [24]. Percira et al. [25] developed an IoT-enabled smart drip irrigation sys-tem using ESP32, demonstrating automated irrigation control through the Blynk application platform. Correa-Quiroz et al. [26] implemented ESP32-based green-house monitoring with climate control capabilities.

Raspberry Pi applications in precision agriculture have focused on its computational capabilities for image processing and machine learning [27]. The plat-form serves effectively as an edge gateway, aggregating data from multiple sensor nodes and performing local analytics [28]. Shaikh et al. [29] reviewed recent trends in loT-enabled sensor technologies for smart agriculture, highlighting Arduino and similar microcontroller platforms for direct sensor interfacing.

D. LabVIEW in Agricultural Systems

LabVIEW has been successfully applied in greenhouse automation and environmental monitoring systems [30]. Akhter and Sofi [31] demonstrated precision agriculture applications using IoT data analytics integrated with LabVIEW-compatible platforms. The LINX toolkit enables seamless integration with Arduino platforms, providing pre-built virtual instruments for common I/O operations. Integration with other platforms typically leverages TCP/IP, MQTT, or serial communication protocols.

However, comprehensive frameworks combining multiple platforms with LabVIEW for agricultural applications remain underexplored in the literature.

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III. LABVIEW-COMPATIBLE IOT PLATFORMS

This section provides a detailed analysis of three major LabVIEW-compatible platforms suitable for agricultural IoT applications. Table 1 presents a comprehensive comparison across key performance dimensions.

Table 1. Comprehensive Platform Comparison for Agricultural LabVIEW Integration

Criterion	Arduino Uno/Mega	Raspberry Pi 4B	ESP32-WROOM
Processor	ATmega328P/2560 16MHz	BCM2711 Quad 1.8GHz	Dual Xtensa LX6 240MHz
Memory	2–8 KB SRAM, 32–256 KB Flash	2–8 GB LPDDR4 RAM	520 KB SRAM, 4 MB Flash
Analog Inputs	6–16 channels (10-bit)	None (external ADC)	18 channels (12-bit)
Connectivity	Shield-based (WiFi/Eth)	WiFi 5, BLE 5.0, GbE	WiFi 802.11 b/g/n, BLE 4.2
Operating System	Bare metal	Linux (RPi OS)	FreeRTOS / Bare metal
Power (Active)	250–500 mW	3,000–6,000 mW	240–480 mW
Deep Sleep Power	N/A	N/A	10 μA (ULP)
Unit Cost (USD)	\$5–45	\$35–80	\$4–15
LabVIEW Interface	LINX Toolkit, VISA	TCP/IP, MQTT, REST	MQTT, Serial, TCP/IP
Optimal Application	Wired sensor, actuator	Edge gateway, local ML	Wireless distributed sensing

1) Arduino Platform: Arduino microcontrollers provide deterministic real-time performance essential for time-critical sensor sampling and actuator control. The platform integrates with LabVIEW through the LINX toolkit (pre-built virtual instruments for digital I/O, analog input, PWM, 12C. SPI) and VISA-based serial communication. Key advantages include native ADC, extensive sensor library support, and robust operation in electrically noisy environments. Limitations include lack of native wireless connectivity and limited processing power.
2) Raspberry Pi Platform: The Raspberry Pi 4B offers substantial computational resources suitable for edge computing including local ML inference, image processing, and complex analytics, running a full Linux OS enables sophisticated software stacks including Python-based processing, MQTT broker hosting (Mosquitto), and database management. LabVIEW integration occurs through TCP/IP sockets, MQTT messaging, and RESTful web services. The primary limitation is power consumption (36W active), precluding battery-powered operation.
3) ESP32 Platform: The ESP32 represents an optimal balance of capability and efficiency for distributed wireless sensing. Integrated dual-band WiFi and Bluetooth eliminate external connectivity modules, while the dual-core architecture enables concurrent communication and sensor processing. The ULP coprocessor supports deep sleep modes consuming only 10µA critical for solar-powered deployments. At sub-\$5 unit costs. ESP32 enables economically viable large-scale deployments.

IV. PROPOSED SYSTEM ARCHITECTURE

Figure 1 illustrates the proposed three-ticket architecture designed to leverage the complementary strengths of each platform.

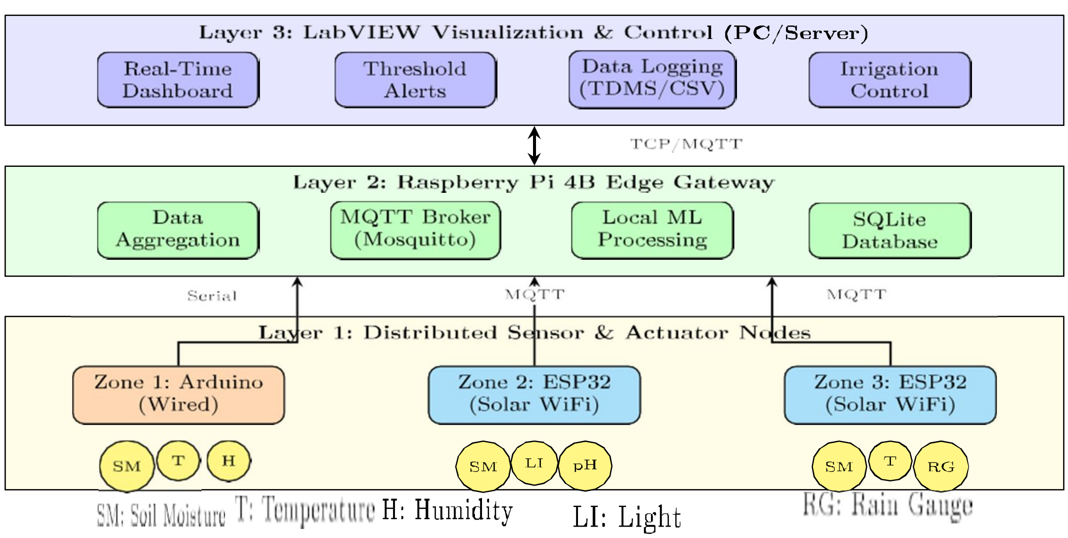

Fig. 1. Three-tier system architecture integrating Arduino/ESP32 sensor nodes (Layer 1), Raspberry Pi edge gateway (Layer 2), and LabVIEW visualization layer (Layer 3).

1) Layer 1: Distributed Sensor and Actuation Layer

The sensor layer comprises distributed nodes collecting environmental data using agricultural-grade sensors specified in Table 2. Arduino Nodes are deployed near pump houses with wired power and serial connection at 115.200 baud, handling high-frequency sampling (10 Hz) for flow rate measurement and relay control. ESP32 Nodes are deployed across remote field locations using solar power (6W panels) with LiPo battery backup (3.7V. 6000mAh). Deep sleep scheduling (55s sleep, 5s active) reduces average power consumption to 720 mWh day.

2) Layer 2: Edge Processing Layer

The Raspberry-Pi 4B gateway provides: Protocol Translation (converts heterogeneous inputs to unified JSON format); MQTT Broker (Mosquitto with topic hierarchy farm/zone{n}/sensor{type});Local Processing (derived parameters, anomaly detection, optional ML inference) and Data Buffering (SQLite with 30-day rolling storage and automatic synchronization).

Table 2. Integrated Agricultural Sensors with Specifications

Parameter	Sensor Model	Range	Accuracy	Interface	Cost
Soil Moisture	Capacitive v2.0	0–100% VWC	±3%	Analog	$2.50
Air Temperature	DS18B20	-55–125°C	±0.5°C	1-Wire	$1.20
Air Humidity	DHT22/AM2302	0–100% RH	±2% RH	Digital	$3.00
Light Intensity	BH1750FVI	1–65535 lux	±20%	I2C	$1.50
Soil pH	SEN0161-V2	0–14 pH	±0.1 pH	Analog	$25.00
Rainfall	Tipping Bucket	0.2 mm/tip	±4%	Pulse	$15.00
Water Flow	YF-S201	1–30 L/min	±10%	Pulse	$4.00

3) Layer 3: LabVIEW Visualization and Control Layer

The LabVIEW application implements: (1) Real-time dashboard with analog-style gauges; (2) Historical waveform charts (1 hour to 30 days): (3) Configurable threshold alerts with visual, audible, and email/SMS notifications; (4) Manual and automatic irrigation control; and (5) Data export (CSV. TDMS. database integration).

Table 3. Communication Protocol Specifications

Interface	Protocol	Format	Characteristics
Arduino ↔ RPi	Serial 115200	CSV	Wired, reliable, 12ms latency
ESP32 ↔ RPi	MQTT QoS 1	JSON	Wireless, buffered, 85ms median
RPi ↔ LabVIEW	TCP/MQTT	JSON	Network-based, bidirectional
LabVIEW ↔ Actuators	Via RPi relay	Binary	Control commands, <2s response

V. IMPLEMENTATION DETAILS

1) Deployment Environment: The system was deployed on a 2-hectare commercial vegetable farm in a Mediterranean climate region. cultivating tomato. pepper, and cucumber across four irrigation zones. The 90-day evaluation period (June 1 August 29, 2024) encompassed the critical growing season with ambient temperatures 18-38°C and minimal rainfall (45mm cumulative).
2) Hardware Configuration: Zone 1 (Arduino Uno R3) positioned near the pump house with sensors (2x soil moisture, 1x DS18B20. 1x DHT22, 1x flow meter) and 4x relay module. Zones 2-4 (ESP32-WROOM-32D) in IP65 enclosures with solar power systems (6W panels, TP4056 controllers, 6000mAh batteries). Gateway: Raspberry Pi 4B (4GB) running Mosquitto, Python 3.9. SQLite. and Flask REST API. Visualization: LabVIEW 2021 Community Edition.
3) Software Implementation: ESP32 firmware (Arduino IDE, PubSubClient) implements deep sleep cycle: wake via RTC →WiFi/MQTT connect → read/publish sensors → verify QoS 1 ack → sleep 55s. Average current: 8.5mA. The Rasp-berry Pi Runs Python asyncio service with anomaly detection (3-sigma bounds on 24-hour rolling statistics).

VI. RESULTS AND ANALYSIS

A. *Sensor Accuracy Validation*

Table 4 presents accuracy validation against calibrated reference instruments (n=30 per parameter). Mean percentage errors ranged from 1.8% (temperature) to 4.1% (soil moisture), all within acceptable limits for agricultural decision-making. Strong correlation coefficients (R2 > 0.94) confirm sensor suitability for trend monitoring and threshold-based control.

Table 4. Sensor Accuracy Validation Against Reference Instruments (n=30 per parameter)

Parameter	Reference Instrument	MAE	RMSE	Mean Err	% R^2
Soil Moisture	TDR Probe (Campbell CS655)	2.8% VWC	3.4% VWC	4.1%	0.94
Air Temperature	Vaisala HMP60	0.42°C	0.51°C	1.8%	0.99
Relative Humidity	Vaisala HMP60	2.1% RH	2.6% RH	3.2%	0.97
Light Intensity	Li-Cor LI-200R	850 lux	1020 lux	2.3%	0.96
Soil pH	Laboratory Analysis	0.18 pH	0.22 pH	2.8%	0.98

B. *System Reliability Analysis*

Table 5 presents reliability metrics over 90 days. Arduino achieved highest re-liability (99.7% uptime) due to stable wired connections. Two restart events resulted from electrical transients, subsequently mitigated through up to coupler isolation. ESP32 nodes demonstrated 98.4% average uptime. with failures primarily from WiFi connectivity during heavy precipitation. The Raspberry Pi maintained 99.9% uptime with zero unplanned restarts.

Table 5. System Reliability Metrics Over 90-Day Deployment Period

Metric	Arduino	ESP32 (avg)	RPi Gateway
Operational Uptime (%)	99.7	98.4	99.9
Data Completeness (%)	99.8	97.6	99.9
Message Loss Rate (%)	0.2	2.1	0.1
Unplanned Restart Events	2	9 (total)	0
MTBF (days)	45	30	>90
Power Availability (%)	100 (wired)	99.1 (solar)	100 (wired)

C. *Communication and Power Performance*

Median end-to-end latency was 142ms (95th percentile: 206ms) well within acceptable bounds for agricultural monitoring. ESP32 deep sleep achieved av-erage daily consumption of 720mWh (88% reduction vs. always-on). The 6W solar panel and 6000mAh battery provided 99.1% power availability, including operation through three consecutive overcast days.

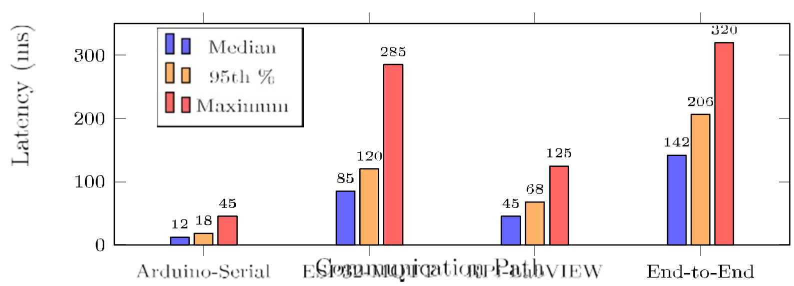

Fig. 2. Communication latency distribution across system paths.

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D. Water Consumption and Crop Yield

The IoT-managed system achieved 31.4% total water reduction (134 m^3 vs. 195 m^3) while maintaining soil moisture within crop-optimal ranges. Maximum savings occurred in July when the system automatically skipped 8 scheduled irrigation events based on real-time soil moisture and rain detection.

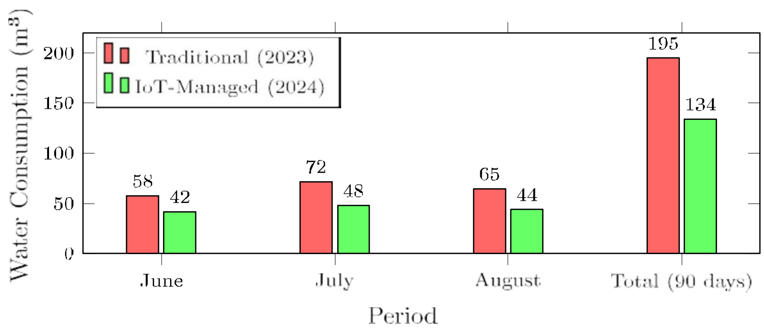

Fig. 3. Water consumption comparison: 31.4% reduction through IoT-managed precision irrigation.

Table 6 presents yield comparison. The average yield improvement of 18.7% is attributed to maintaining soil moisture within crop-specific optimal ranges. reducing both water stress (under-irrigation) and oxygen stress (over-irrigation).

E. Platform Performance and Economic Analysis

Figure 4 presents normalized platform comparison. Arduino achieved highest scores for reliability (9/10) and LabVIEW integration (9/10). Raspberry Pi excels in scalability (9/10) but scores lowest in power efficiency (3/10). ESP32 leads in power efficiency (9/10) and cost efficiency (9/10).

Table 6. Crop Yield Comparison: IoT-Managed vs. Traditional Methods

Crop	Traditional (kg/ha)	IoT-Managed (kg/ha)	Difference	Improvement
Tomato	42,500	51,200	+8,700	+20.5%
Pepper	28,300	33,100	+4,800	+17.0%
Cucumber	55,800	65,900	+10,100	+18.1%
Weighted Avg.	–	–	–	**+18.7%**

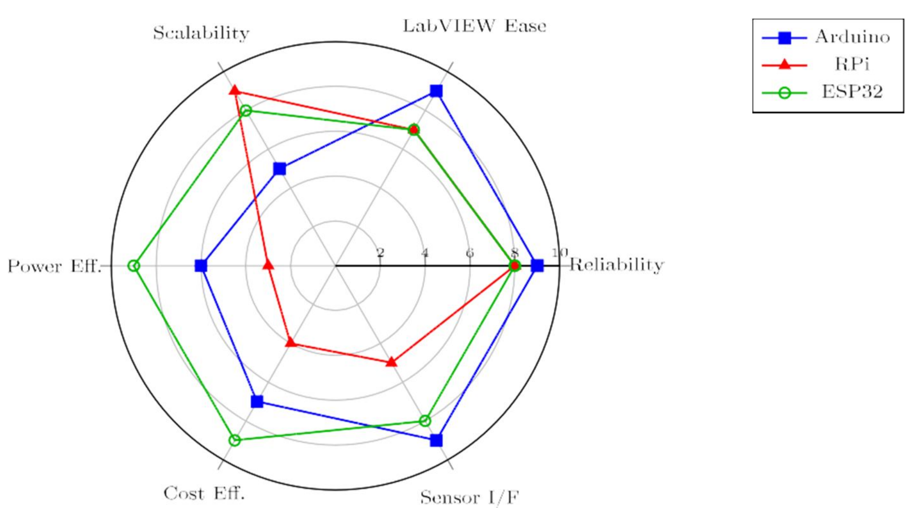

Fig. 4. Platform comparison across six dimensions (1–10 scale, higher is better).

Table 7 presents cost-benefit analysis. Total hardware investment of $455 yielded annual benefits of $3,680, achieving 45-day payback and 709% first-year ROI.

VII. DISCUSSION

Platform Selection Guidelines: Based on experimental findings: Choose Arduino when wired installation is feasible, maximum reliability is critical, or direct LINX integration is preferred. Choose ESP32 when wireless deployment is necessary, solar/battery power is required, cost constraints limit per-node budget to under $10. or large-scale deployments require dozens of nodes. Choose Raspberry Pi when edge computing requires local ML or image processing, gateway functionality is needed, or integration with IT infrastructure via standard networking is preferred. The optimal hybrid architecture combines all three platforms lever-aging their respective strengths.

A. Comparison with Prior Studies

Our 31.4% water savings exceed the 20-10% range reported in previous studies [17,32], attributed to integration of real-time soil moisture sensing with weather-responsive scheduling. Yield improvements of 18.7% align with precision agriculture benefits documented in

Table 7. Cost-Benefit Analysis for 2-Hectare Deployment

Item	Quantity	Unit Cost	Total Cost
Hardware Capital Costs:			
Arduino Uno + Sensors + Relays			$45
ESP32 Nodes (complete with solar)			$105
Raspberry Pi 4B + PSU + Case			$85
12V DC Solenoid Valves			$100
Enclosures, Wiring, Connectors	–	–	$80
Mounting Hardware, Misc.	–	–	$40
Total Hardware Investment			**$455**
Annual Operating Benefits:			
Water Cost Savings (31.4% reduction)			$380
Yield Improvement Value (18.7% increase)			$2,850
Labor Reduction (monitoring automation)			$450
Total Annual Benefit			**$3,680**
Simple Payback Period			**45 days**
First-Year ROI			**709%**

comprehensive reviews [33,31]. System latency (112ms median) compares favourably with cloud-based architectures (typically 500ms 25) (22).

B. Limitations

Single growing season evaluation: 2-hectare scale may not reflect challenges in larger operations; Mediterranean climate may not translate to other regions: comparison baseline used timer-based irrigation rather than commercial precision systems.

C. Future Directions

On-device AML for predictive irrigation: Lora WAN for extended range: computer vision for crop health monitoring: multi-farm cad aggregation: cybersecurity assessment: long-term durability studies.

VIII. CONCLUSION

This paper presented a comprehensive framework for integrating Arduino, Rasp berry Pi. and ESP32 platforms with LabVIEW for smart agricultural monitoring, validated through a 90-day field deployment on a 2-hectare vegetable farm. The experimental results demonstrated sensor accuracy within 1.8-4.1% mean error across five environmental parameters (R2 > 0.94), system reliability of 98.4-99.9% uptime with Arduino achieving the highest reliability at 99.7% for wired installations, and substantial agricultural benefits including 31.4% wa-ter consumption reduction through real-time monitoring and weather-responsive scheduling, along with 18.7% average crop yield improvement across tomato, pepper, and encumber crops. The economic analysis revealed compelling viability with a 45-day payback period and 709% first-year ROI on a total hardware investment of $455.

Platform-specific findings indicate that ESP32 offers optimal cost-performance for wireless distributed sensing at $4.50 per node with ultra-low power deep sleep capability. Arduino provides superior LabVIEW integration through the LINX toolkit and maximum reliability for actuator control applications, while Raspberry Pi excels as an edge gateway supporting local ma chine learning inference and protocol translation. The successful integration of LabVIEW with these low-cost loT platforms demonstrates that precision agriculture technologies can be democratized, making data-driven farming accessible and economically viable for agricultural operations of all scales.

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