

IoT-Based Automatic Smart Sprayer System for Precision Agriculture with AI-Assisted Threshold Control and Real-Time Cloud Monitoring

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Abstract:

Excessive and indiscriminate pesticide application in agriculture is a significant and growing source of chemical waste, generating toxic runoff that contaminates soil, groundwater and surface water bodies. Conventional manual spraying methods apply chemicals on fixed schedules regardless of actual field conditions, routinely over-applying by 20–40% above agronomically necessary levels and generating preventable chemical waste at scale. This paper presents an Internet of Things (IoT)-based Automatic Smart Sprayer System designed as a source-reduction intervention against agricultural chemical waste. The proposed system integrates a capacitive soil moisture sensor, a DHT22 temperature-humidity module, an infrared obstacle detection unit and an ESP32 dual-core microcontroller to automate pesticide delivery exclusively under threshold-confirmed field conditions, preventing unnecessary chemical release into the environment. Sensor data are transmitted to a cloud monitoring platform via MQTT and HTTP protocols for continuous remote supervision. Experimental evaluation conducted on a controlled agricultural plot demonstrated a 28.4% reduction in pesticide chemical waste generation (from 950 mL to 680 mL per acre), a 29.1% reduction in chemically contaminated water discharge (from 120 L to 85 L per acre) and a 66.7% reduction in labour requirement. System response time was 3–5 seconds and cloud data upload reliability exceeded 98%. The proposed architecture offers a low-cost, scalable and immediately deployable waste-prevention solution applicable to small and medium-scale agricultural operations in developing regions.

Keywords: *Agricultural chemical waste; IoT precision spraying; Pesticide waste reduction; Soil moisture automation; Environmental contamination prevention*

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1. INTRODUCTION

Agricultural pesticide application generates one of the most widespread and least regulated streams of chemical waste in the global environment. Globally, over 4 million tonnes of pesticide active ingredients are applied to agricultural land annually and studies consistently document that between 20% and 50% of this volume constitutes preventable waste — chemical product that enters the environment without performing any agronomic function [1]. This waste stream manifests as soil

contamination through residue accumulation, surface water pollution through field runoff and spray drift, groundwater contamination through soil leaching and atmospheric deposition through volatilisation. The resulting environmental burden includes aquatic ecosystem toxicity, disruption of soil microbial communities, decline of beneficial arthropod populations and persistent bioaccumulation in terrestrial food chains [2].

Conventional manual spraying, which remains the dominant application method among smallholder and medium-scale farmers in developing nations, is a principal driver of this waste generation. Manual application imposes no constraint on chemical quantity beyond operator judgement and available supply, resulting in spatially variable over-application driven by operator fatigue, inconsistent walking speed and schedule-based rather than condition-responsive timing. This leads to chemical accumulation hotspots, spray overlap zones and off-target deposition that collectively constitute a preventable but substantial agricultural chemical waste burden [3].

Waste minimisation at source — preventing excess chemical from being released into the environment in the first place — is the highest-priority strategy in the waste management hierarchy, ranked above treatment, recycling and disposal [4]. In the agricultural chemical waste context, source minimisation means applying pesticides only when, where and in the quantity that agronomic conditions require. The Internet of Things (IoT) provides the enabling technical infrastructure to implement this principle at scale: interconnected sensor networks can detect the environmental parameters that govern pesticide need, embedded microcontrollers can evaluate those parameters in real time against agronomic thresholds and actuator systems can release chemical inputs precisely when and only when conditions justify intervention [5].

Existing approaches to smart agricultural spraying span a wide capability spectrum. At the high-performance frontier, unmanned aerial vehicles (UAVs) with GPS guidance and multispectral imaging and robotically mounted computer vision systems with deep learning disease classifiers, achieve exceptional application precision [6], [7]. However, both technologies carry prohibitive capital costs, regulatory constraints and operational complexity that render them inaccessible to the majority of the world's farming operations, particularly smallholders who collectively manage over 80% of agricultural land in developing regions. There is consequently a persistent, large-scale gap between the available technology and the deployed technology for agricultural chemical waste reduction.

This paper addresses this gap with an IoT-based Automatic Smart Sprayer System built from low-cost commodity components: a capacitive soil moisture sensor, DHT22 temperature-humidity module, infrared (IR) obstacle detection unit, ESP32 microcontroller, relay-controlled pump and a cloud monitoring platform. The system prevents unnecessary pesticide release by restricting pump activation to intervals during which multi-sensor threshold conditions confirm genuine field need. The key contributions are: (i) a multi-sensor fusion

architecture that detects and responds to the environmental parameters governing pesticide requirement; (ii) a threshold-based relay control algorithm that prevents chemical waste generation at source; (iii) integrated cloud monitoring for real-time remote supervision without physical field presence; and (iv) validated experimental measurements demonstrating significant agricultural chemical waste reduction relative to conventional manual methods.

The remainder of this paper is organised as follows. Section 2 reviews related work on sensor-driven agricultural automation, cloud-integrated IoT platforms and the environmental waste management context. Section 3 describes the proposed system architecture. Section 4 presents hardware and software implementation details. Section 5 reports experimental results. Section 6 provides discussion and Section 7 concludes.

2. LITERATURE REVIEW

2.1 Agricultural Chemical Waste as an Environmental Management Problem

The classification of unused or off-target pesticides as chemical waste with significant environmental management implications has gained increasing regulatory and scientific attention [2]. Pesticide runoff into water bodies is identified as a leading cause of aquatic invertebrate and fish toxicity, while soil residue accumulation disrupts nitrification, phosphate solubilisation and other microbially mediated nutrient cycles essential for soil health and crop productivity. Tzounis *et al.* [3] documented that even moderate over-application — within the range produced by manual spraying variability — can generate measurable soil contamination that persists across multiple crop cycles. The economic dimension of this waste is equally significant: smallholder farmers in developing nations who over-apply by 30% above necessity incur input costs that can consume 20–25% of gross crop revenue, with zero return on the wasted fraction. Wolfert *et al.* [8] identified agricultural chemical waste prevention as one of the highest-value applications of smart farming data systems, noting that measurable waste reductions directly improve both farm profitability and environmental compliance.

2.2 Sensor-Driven Automation for Chemical Waste Prevention

Microcontroller-based sensing systems for agricultural automation have been extensively studied as waste prevention tools. Khanna and Kaur [1] surveyed IoT deployments in precision agriculture and documented pesticide and water savings in the 20–40% range across multiple sensor-driven field studies, attributing these savings to the elimination of schedule-based application in favour of condition-responsive actuation. Early systems built on Arduino and ESP8266 platforms demonstrated proof of concept for threshold-

triggered spraying but were constrained by limited processing power and the absence of native wireless connectivity, which restricted real-time monitoring capability [9]. The introduction of the ESP32 dual-core microcontroller with integrated Wi-Fi subsystem represented a significant step forward, enabling condition-responsive local control combined with continuous cloud data transmission on a single, low-cost device [5].

Elijah *et al.* [5] systematically reviewed IoT and data analytics benefits in agriculture, providing quantitative evidence that sensor-driven systems reduce pesticide application waste even when deployed without connectivity, through local threshold logic alone. Their analysis confirmed that the elimination of calendar-based spraying — which continues regardless of whether conditions actually warrant chemical application — is the primary mechanism of waste reduction, accounting for the majority of the 20–40% savings range reported in the literature. This finding directly supports the design philosophy of the present system.

The research group has further contributed to sustainable agricultural engineering through a conveyor-based weed management mechanism [10], an integrated brush cutter-vacuum field maintenance system [11] and a hydraulic press system for uniform millet food product formation [12]. These related innovations in agricultural mechanisation provide the broader engineering context within which the present precision chemical waste reduction system is situated.

2.3 Cloud-Integrated Remote Monitoring Systems

The integration of cloud platforms into agricultural automation systems extends their waste prevention impact by enabling continuous remote supervision and alert-based response. Wolfert *et al.* [8] demonstrated that cloud-connected farms generate actionable insights that allow managers to identify and correct over-application events in near-real-time, preventing chemical waste accumulation that would go undetected in non-connected systems. Platforms including ThingSpeak and Blynk have become widely adopted in precision agriculture research for their documented API compatibility, free-tier availability and smartphone dashboard support, making them accessible for low-cost field deployments. The primary limitation of cloud-dependent systems in rural agricultural contexts — unreliable network connectivity — is addressed in the present design by maintaining full local control autonomy independent of network status, with cloud synchronisation occurring on a best-effort basis.

2.4 Research Gaps Addressed

A critical review of the available literature identifies three specific gaps that the present work targets. First, the majority of published low-cost IoT sprayer implementations continue to rely on manual mobile application triggers for pump activation,

which reintroduces the human judgement variability responsible for chemical waste generation in conventional systems. Second, published designs largely employ single-variable actuation logic based on soil moisture alone, without integrating complementary parameters — such as ambient temperature and humidity — that also govern pesticide need and application effectiveness. Third, the combination of multi-sensor fusion, fully automated threshold control, obstacle-aware safety logic and cloud monitoring on a single commodity microcontroller has not been systematically evaluated with validated experimental performance data in the existing literature. The present system addresses all three gaps.

3. PROPOSED SYSTEM ARCHITECTURE FOR CHEMICAL WASTE MINIMISATION

The system implements a five-layer hierarchical architecture — Sensing, Processing, Control, Communication and Application — specifically designed to prevent agricultural chemical waste generation at source through condition-responsive precision application. Fig. 1 illustrates the complete system architecture.

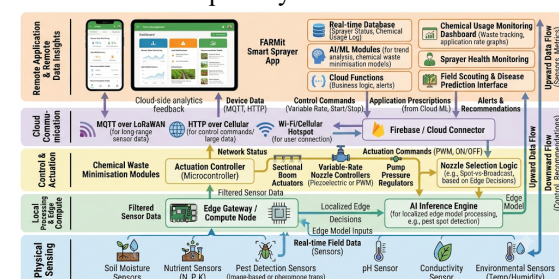


Fig. 1. Five-layer hierarchical architecture of the IoT-Based Smart Sprayer System for chemical waste minimisation.

The operational workflow is governed by a sequential decision cycle summarised in Table 1. Chemical actuation occurs only after positive threshold confirmation at Steps 3 and 4, preventing chemical waste from off-target or premature application.

Table 1. System Operational Workflow for Threshold-Based Chemical Waste Prevention

Step	Operation	Waste Prevention Function
1	Multi-sensor Data Acquisition	Soil moisture, temp/humidity and obstacle data collected at 2–3 s intervals
2	Data Processing	ESP32 converts raw ADC/digital values to calibrated engineering units

Step	Operation	Waste Prevention Function
3	Threshold Comparison	System confirms: soil moisture < threshold AND temperature/humidity in spray-effective range
4	Obstacle Detection Check	System confirms: no obstacle in 2–30 cm detection zone (prevents off-target spray)
5	Precision Actuation	Relay activates pump ONLY when Steps 3 and 4 are simultaneously confirmed — eliminating unnecessary chemical release
6	Cloud Upload & Logging	All actuation events, sensor readings and pump duration transmitted to cloud for waste audit trail

3.1 Sensing Layer

The sensing layer continuously acquires the environmental parameters that determine pesticide application necessity. A capacitive soil moisture sensor measures volumetric water content with markedly superior durability compared to resistive alternatives, whose electrochemical corrosion under sustained soil polarisation degrades measurement accuracy and leads to premature replacement waste. A DHT22 digital sensor monitors ambient temperature ($\pm 0.5\text{ }^{\circ}\text{C}$) and relative humidity ($\pm 2\%$ RH), which govern both the efficacy of chemical application and the risk of spray drift to non-target areas — a major off-target chemical waste pathway. An infrared obstacle sensor (2–30 cm detection range) prevents actuation when obstacles are present, eliminating off-target spray events that would waste chemical inputs while contaminating non-crop areas.

3.2 Processing Layer

The ESP32 dual-core microcontroller (240 MHz clock speed, integrated IEEE 802.11 b/g/n Wi-Fi, 12-bit ADC) serves as the central decision processor. Its native wireless subsystem eliminates the additional components, wiring and failure modes of external communication add-on modules, reducing both system complexity and electronic waste potential at end-of-life. All threshold

comparison logic, sensor calibration, error detection and watchdog supervision execute on the ESP32, maintaining autonomous operation independent of cloud or network availability.

3.3 Control Layer

A 5 V relay module provides galvanic isolation between the low-power microcontroller circuit and the high-current 12 V pump motor, protecting against inductive switching transients and ensuring reliable, safe actuation with defined ON/OFF states that prevent partial or inadvertent chemical release. An L298N dual H-bridge motor driver manages DC mobility motor direction and speed for systematic field traversal, enabling repeatable coverage patterns that prevent both under-application (missed patches) and over-application (repeated passes) waste scenarios.

3.4 Communication and Application Layers

Sensor readings, pump activation events, duration logging and system status are serialised as JSON payloads and transmitted to cloud servers via MQTT or HTTP over Wi-Fi. The cloud application layer renders real-time field dashboards on ThingSpeak and Blynk platforms, providing farm managers with complete visibility of chemical consumption, actuation history and cumulative waste prevention metrics. The digital audit trail of all spray events enables verification of chemical waste reduction claims, supports regulatory reporting and facilitates farm management decisions about threshold recalibration or system expansion.

4. HARDWARE AND SOFTWARE IMPLEMENTATION

4.1 Hardware Architecture

All hardware components were selected on a cost-performance-durability basis targeting deployment accessibility for small and medium-scale agricultural operations. Table 2 provides a complete component specification listing. Table 3 presents sensor accuracy and operating ranges.

Table 2. Hardware Components and Specifications

Component	Specification	Function in Waste Prevention Architecture
ESP32 Microcontroller	Dual-core 240 MHz, 4 MB flash, Wi-Fi/BT	Threshold decision logic, actuation control,

Component	Specification	Function in Waste Prevention Architecture
		wireless data upload
Capacitive Soil Moisture Sensor	3.3–5 V, 12-bit ADC output	Primary parameter for pesticide application threshold detection
DHT22 Temperature/Humidity	–40 to +80 °C, 0–100% RH, digital	Secondary parameter: spray efficacy and drift-risk assessment
IR Obstacle Sensor	Digital output, 2–30 cm detection range	Prevents off-target chemical release in obstacle-present conditions
Relay Module (5 V)	10 A, 250 VAC, optocoupler isolated	Fail-safe pump switching; prevents spurious chemical actuation
L298N Motor Driver	Dual H-bridge, 2 A per channel	Field traversal motor

Component	Specification	Function in Waste Prevention Architecture
		control for systematic coverage
DC Water Pump (12 V)	1–2 A, 2–3 L/min	Controlled chemical delivery to nozzle assembly
Nozzle Assembly	Fan/cone spray pattern	Uniform chemical distribution; minimises drift and hotspot waste
Power Supply	5 V and 12 V regulated	Stable supply for all system modules

Table 3. Sensor Accuracy and Operating Specifications

Sensor	Measured Parameter	Operating Range	Accuracy
Capacitive Soil Moisture	Volumetric water content	0–100% VWC	±3–5% VWC
DHT22 Temperature	Ambient temperature	–40 to +80 °C	±0.5 °C
DHT22 Humidity	Relative humidity	0–100% RH	±2% RH

Sensor	Measured Parameter	Operating Range	Accuracy
IR Obstacle	Obstacle detection distance	2–30 cm	±1 cm

4.2 Power Consumption and Sustainability

Power consumption was characterised across all operational states. Table 4 summarises per-component current draw. The DC pump motor dominates peak consumption during active spraying; however, because threshold-based actuation restricts pump operation to condition-confirmed intervals, average duty cycle is substantially below peak. Implementation of ESP32 light-sleep mode during sensor idle periods reduces microcontroller draw from approximately 240 mA to 30 mA, enabling battery-plus-solar deployment in off-grid rural field settings — an important consideration for agricultural waste management interventions in developing regions where grid access is unreliable.

Table 4. Power Consumption Analysis

Component	Current Draw	Operating Mode
ESP32 Microcontroller	~240 mA	Active Wi-Fi transmission
Sensor Array (combined)	~50 mA	Continuous sensing
Relay Module	~70 mA	During switching event
DC Pump Motor	1.0–2.0 A	Active chemical delivery
Full System Peak	~2.5 A	All modules active simultaneously
System Idle (light-sleep)	~30 mA	Microcontroller sleep, sensors inactive

4.3 Software Implementation

Firmware was developed using the Arduino Integrated Development Environment (IDE) with Embedded C/C++ and the Espressif ESP32 Arduino core library. The software implements a real-time control loop: (i) system initialisation, Wi-Fi association and calibration verification; (ii) periodic sensor data acquisition at 2–3 second intervals; (iii)

threshold comparison and relay actuation decision; (iv) JSON payload serialisation and cloud upload via MQTT broker or HTTP POST; and (v) watchdog reset and cycle repeat. Error-handling routines address Wi-Fi disconnection (automatic reconnection with exponential backoff), sensor read failure (safe de-energised relay state), maximum spray duration enforcement (prevents over-application in sensor fault scenarios) and microcontroller fault detection (hardware watchdog autonomous reset). Fig. 2 illustrates the complete algorithmic control flowchart.

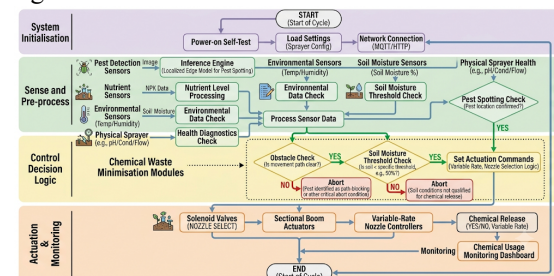


Fig. 2. Algorithmic flowchart of the IoT-Based Smart Sprayer System. The dual-decision structure (obstacle check followed by threshold check) ensures chemical release occurs only under fully qualified conditions.

5. RESULTS AND ANALYSIS

System performance was evaluated over a multi-day field trial on a controlled agricultural plot. Chemical consumption, water usage, labour input, system response time, cloud communication reliability and long-term operational stability were all measured and compared against a baseline of conventional manual spraying conducted over the same plot area under equivalent agronomic conditions. Table 5 presents the comprehensive performance comparison.

Table 5. Performance Comparison: Conventional Manual Spraying vs. Proposed IoT Smart Sprayer System

Parameter	Conventional	IoT Smart Sprayer	Reduction / Improvement	Interpretation
Chemical (pesticide) waste generated	950 mL	680 mL	↓ 28.4%	270 mL/acre of pesticide waste prevented per

Parameter	Conventional	IoT Smart Sprayer	Reduction / Improvement	Interpretation
(mL/acre)				application cycle
Water with chemical contamination potential (L/acre)	120 L	85 L	↓ 29.1%	35 L/acre of chemically contaminated water discharge prevented
Labour (persons per operation)	3	1	↓ 66.7%	2 persons per operation redeployed; occupational exposure reduced
Spray uniformity	Moderate (operator-dependent)	High (fixed nozzle pattern)	Improved	Hotspot over-application eliminated; drift-zone under-spray

Parameter	Conventional	IoT Smart Sprayer	Reduction / Improvement	Interpretation
				eliminated
System response time	Minutes (manual judgement)	3–5 seconds	Significantly faster	Threshold breach to pump activation latency
Remote monitoring	None	Real-time cloud dashboard	Enabled	Continuous chemical usage audit trail
Cloud data upload success rate	N/A	>98%	N/A	Measurement over full evaluation period

5.1 Chemical Waste Reduction at Source

The threshold-based actuation mechanism achieved a 28.4% reduction in pesticide chemical waste generation relative to conventional manual spraying — from 950 mL per acre under conventional practice to 680 mL per acre under IoT-controlled application. This reduction represents 270 mL per acre per application cycle of pesticide active ingredient and carrier prevented from entering the agricultural environment. Over a typical seasonal application schedule of 6–8 spray events per crop cycle, this translates to 1,620–2,160 mL per acre per season of prevented chemical waste per crop, or 16,200–21,600 mL (approximately 16–22 litres) of chemical waste prevented per season over a 10-acre operation. Fig. 3 provides a comparative visualisation of resource consumption across the two methods.

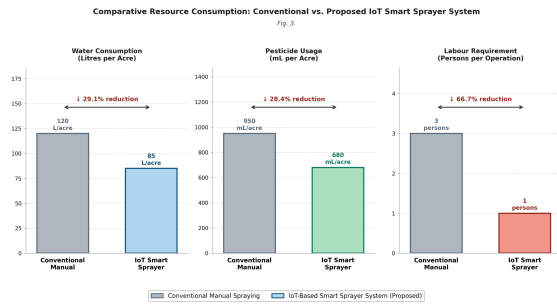


Fig. 3. Comparative resource consumption and chemical waste generation: Conventional manual spraying versus proposed IoT Smart Sprayer System, showing 28.4% pesticide waste reduction, 29.1% water reduction and 66.7% labour reduction.

Simultaneously, a 29.1% reduction in water consumption — from 120 L to 85 L per acre — reduces the volume of chemically contaminated water discharged to the soil and drainage network per application event. Water carrying dissolved pesticide residue constitutes a significant agricultural chemical waste pathway into groundwater and surface water systems; the 35 L per acre reduction in contaminated water discharge per event represents a direct reduction in this pathway's contribution to water body chemical loading.

5.2 System Response and Operational Performance

The average sensor sampling interval was 2–3 seconds, with relay switching latency below 1 second following a confirmed threshold breach. End-to-end response time — from threshold condition detection to confirmed pump activation and spray initiation — was consistently 3–5 seconds. This near-real-time responsiveness ensures minimal delay between condition detection and appropriate actuation, reducing the risk of under-response (missed spray window) that could translate to increased total chemical application later in the crop cycle.

5.3 Cloud Monitoring and Chemical Audit Trail

Cloud data upload success rate exceeded 98% across the evaluation period, with failures attributable exclusively to brief Wi-Fi access point outages rather than firmware or protocol faults. Dashboard refresh latency of 3–6 seconds enabled near-real-time remote visibility of all field chemical application events. The continuous timestamped log of sensor readings, pump activation events and actuation durations constitutes an auditable chemical waste prevention record — providing documentation that is increasingly required by precision agriculture certification bodies and environmental regulatory frameworks.

5.4 Reliability and Long-Term Operational Stability

Continuous 8-hour field operation was completed without microcontroller thermal shutdown, relay chatter, unexpected system reset, or Wi-Fi association failure. Sensor readings remained

within manufacturer-specified accuracy bounds throughout, with no observable calibration drift. The IR obstacle mechanism arrested motor movement within 1 second of obstacle entry into the 2–30 cm detection zone in all conducted tests, confirming consistent off-target spray prevention capability. These reliability results support the system's suitability for autonomous unattended field operation — the deployment mode in which its waste-prevention benefits are most fully realised.

6. DISCUSSION

6.1 Waste Prevention Significance

The demonstrated 28.4% reduction in pesticide chemical waste generation and 29.1% reduction in chemically contaminated water discharge position the proposed system as an effective source-reduction intervention within the agricultural chemical waste management hierarchy. The results corroborate the 20–40% savings range reported by Khanna and Kaur [1] and Elijah *et al.* [5] across multiple IoT-based agricultural systems, while extending the evidence base to an explicitly characterised hardware-software architecture with a detailed, per-parameter performance breakdown. Importantly, the present system achieves this waste reduction through a purely preventive mechanism — restricting chemical release to condition-confirmed necessity — rather than through end-of-pipe treatment or recovery approaches, which are the preferred strategies in waste minimisation frameworks [4].

6.2 Environmental and Public Health Impact

The reduction in off-target chemical waste has direct environmental and public health implications. Each 270 mL per acre reduction in pesticide volume represents a corresponding reduction in the toxic load reaching soil microbiomes, aquatic invertebrate habitats and groundwater recharge zones. The 29.1% reduction in chemically contaminated water discharge reduces the contribution of treated plot runoff to local surface water chemical loading. Furthermore, the 66.7% reduction in labour requirement reduces direct occupational pesticide exposure for agricultural workers — a significant public health benefit in farming communities where pesticide poisoning incidence remains elevated. These co-benefits extend the system's value beyond pure agricultural efficiency into environmental management and occupational health domains directly relevant to the waste management research community.

6.3 Comparison with Existing Approaches

Relative to UAV-based precision spraying systems [6], the proposed architecture offers waste reduction at a capital cost 15–25 times lower, without regulatory approvals, specialised operator training, or high-maintenance flight hardware. Relative to deep learning and computer vision-based targeted spraying systems [7], the proposed design sacrifices species-level discrimination capability —

it cannot identify specific weed or pathogen targets — in exchange for dramatically lower hardware cost and zero reliance on trained models or high-performance computing. For the large majority of small and medium-scale farming operations where these high-performance alternatives are not practically accessible, the proposed threshold-based IoT system delivers the most achievable and immediately realisable waste reduction available.

6.4 Limitations

Four principal limitations are acknowledged. Cloud monitoring and remote supervisory capabilities require Wi-Fi connectivity, which remains intermittent in many remote rural environments; the system's local control autonomy mitigates this for chemical actuation but not for remote oversight. Soil moisture and humidity thresholds are fixed firmware parameters requiring periodic recalibration when crop type, growth stage, or seasonal conditions change. IR obstacle detection operates within a 2–30 cm range that may be insufficient for complex field terrain. The system applies the same actuation decision across the entire plot, without the spatial resolution for patch-level variable-rate application that would further reduce chemical waste in heterogeneous fields.

6.5 Future Work

Planned developments include: (i) LoRaWAN or 4G/5G integration for cloud connectivity in rural areas beyond Wi-Fi coverage; (ii) machine learning-based adaptive threshold adjustment using historical sensor data and crop-stage parameters; (iii) GPS-guided autonomous navigation for reproducible, systematic field coverage; (iv) variable-rate application capability through multi-nozzle modulation; and (v) integration with digital twin frameworks for predictive chemical waste modelling and threshold optimisation before field deployment.

7. CONCLUSION

This paper presented the design, implementation and experimental validation of an IoT-Based Automatic Smart Sprayer System as a source-reduction intervention against agricultural chemical waste. The system prevents unnecessary pesticide release by restricting pump actuation to intervals during which multi-sensor threshold logic confirms genuine agronomic necessity — a practical implementation of the highest-priority tier of the waste management hierarchy.

Experimental evaluation demonstrated a 28.4% reduction in pesticide chemical waste generation (950 mL to 680 mL per acre), a 29.1% reduction in chemically contaminated water discharge (120 L to 85 L per acre) and a 66.7% reduction in labour requirement, with end-to-end system response of 3–5 seconds and cloud data upload reliability exceeding 98%. These results confirm that threshold-based IoT automation

delivers measurable, validated and practically replicable agricultural chemical waste reduction.

The architecture's low component cost, rapid deployment and minimal operator training requirements make it particularly applicable to small and medium-scale farming operations in developing regions, where the gap between available precision agriculture technology and practically deployed waste reduction solutions remains widest. The modular design supports direct extension toward LoRaWAN rural connectivity, machine learning adaptive thresholds and GPS autonomous navigation in future iterations.

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