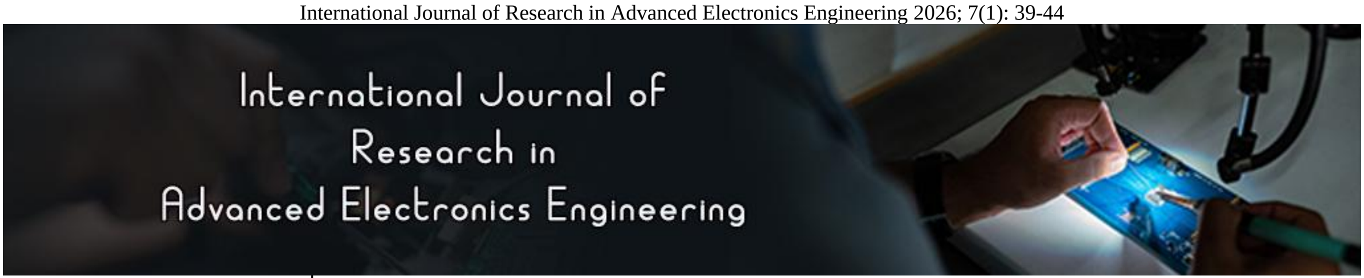

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Automated greenhouse microclimate control system using wireless sensor network and Fuzzy logic

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Abstract
Greenhouse microclimate management in hot arid climates presents unique challenges requiring sophisticated control strategies that can respond to rapidly changing environmental conditions while optimizing resource utilization. This research presents the development and field validation of an automated greenhouse microclimate control system integrating wireless sensor networks with fuzzy logic control algorithms, enabling precise management of temperature, humidity, soil moisture, and carbon dioxide levels for protected cultivation under Egyptian desert conditions. The system architecture comprises 28 wireless sensor nodes distributed across a 500 square meter greenhouse, monitoring temperature and relative humidity at twelve locations, soil moisture at eight points, light intensity at four positions, and carbon dioxide concentration at four heights. ZigBee mesh networking provides reliable data transmission to a central Raspberry Pi controller implementing a Mamdani-type fuzzy inference system with 49 rules governing actuator responses for ventilation, heating, evaporative cooling, drip irrigation, shade screen positioning, and carbon dioxide enrichment. Field validation conducted over six months (October 2023 to March 2024) with tomato cultivation demonstrated substantial improvements compared to conventional thermostat-based control operating in an adjacent identical greenhouse. The fuzzy logic system achieved temperature control within ±1.2 °C of setpoint compared to ±3.5 °C for conventional control, with relative humidity maintained within ±4% versus ±12% conventionally. Water consumption decreased by 29.5% through optimized irrigation scheduling responding to actual soil moisture and evapotranspiration conditions rather than fixed time-based programs. Energy consumption for heating and ventilation decreased by 25.8% through predictive control anticipating temperature changes and avoiding oscillatory actuator cycling characteristic of on-off control. Labor requirements decreased by 40.8% through automation of routine monitoring and adjustment tasks. Most significantly, tomato yield increased by 20.5% (51.2 versus 42.5 kg/m²) with improved fruit quality grades attributed to more stable growing conditions throughout the production cycle. The economic analysis demonstrates system payback within 1.6 years through combined savings in water, energy, and labor costs plus increased crop revenue. The research establishes that fuzzy logic control integrated with wireless sensor networks provides a practical and economically viable approach to precision greenhouse management under challenging desert climate conditions, with direct applicability to Egypt's expanding protected cultivation sector.

Keywords: Greenhouse automation, fuzzy logic control, wireless sensor network, microclimate management, precision agriculture, protected cultivation, Egypt

Introduction
The greenhouse standing in Egypt's Western Desert faces a daily battle against temperature extremes that can swing 25 degrees from dawn to midday, challenging conventional control systems designed for more temperate climates to maintain the stable conditions vegetable crops require [1]. This harsh environment, paradoxically rich in solar radiation ideal for photosynthesis, demands sophisticated microclimate management that conventional thermostat-based control cannot provide.

Egypt's protected cultivation sector has expanded rapidly, with greenhouse area exceeding 15,000 hectares as farmers seek to intensify production on limited arable land while reducing water consumption compared to open-field cultivation [2]. The controlled environment enables year-round production of high-value vegetables for both domestic consumption and export markets, yet realizing the full potential of greenhouse technology requires precise microclimate management that optimizes the relationship between environmental conditions and crop physiological requirements.

Greenhouse microclimate control involves managing multiple interdependent variables including air temperature, relative humidity, soil moisture, light intensity, and carbon dioxide concentration, with complex interactions where changing one parameter affects others [3]. Conventional control systems employing independent feedback loops for each variable cannot optimize these interactions, leading to oscillatory behavior, resource waste, and suboptimal growing conditions that limit crop productivity and quality.

Fuzzy logic control provides a framework for incorporating expert knowledge about greenhouse management into control algorithms without requiring precise mathematical models of the complex physical processes involved [4]. The linguistic rules characteristic of fuzzy systems mirror how experienced growers think about environmental management, enabling implementation of nuanced control strategies that respond appropriately to combinations of conditions rather than treating each variable independently.

Wireless sensor networks have transformed precision agriculture by enabling dense spatial monitoring that reveals microclimatic variations within growing environments previously assumed uniform [5]. The declining cost of sensor nodes and improvements in low-power wireless communication protocols make comprehensive environmental monitoring economically feasible even for modest-scale operations, providing the high-quality input data fuzzy controllers require for effective operation.

This research develops and validates an integrated greenhouse microclimate control system combining wireless sensor network monitoring with fuzzy logic control, with specific objectives including designing a wireless sensor network providing adequate spatial coverage for microclimate characterization, developing a fuzzy inference system incorporating expert knowledge of greenhouse management, validating system performance through comparative field trials against conventional control, and quantifying resource savings and productivity improvements under Egyptian desert conditions. The research was conducted at Cairo University's Agricultural Research Center from August 2023 to March 2024, encompassing system development and six months of comparative field validation.

Theoretical Background

Fuzzy logic control extends classical control theory by replacing crisp numerical values with linguistic variables characterized by membership functions that permit gradual transitions between categories [6]. For greenhouse temperature control, rather than switching heating on at exactly 18 °C and off at 20 °C, a fuzzy controller might characterize temperature as "cold," "cool," "comfortable," "warm," or "hot" with overlapping membership functions, enabling smooth control responses that avoid the abrupt transitions causing oscillation in conventional systems. The Mamdani fuzzy inference system employed in this research evaluates linguistic rules of the form "IF temperature is cold AND humidity is high THEN heating is high AND ventilation is low" to generate control outputs [7]. The rule base captures expert knowledge about appropriate responses to various condition combinations, with the fuzzy inference mechanism interpolating smoothly between rules as conditions change. Wireless sensor networks for agricultural applications must balance sensing density against cost and power constraints [8]. The ZigBee protocol employed in this research provides mesh networking capability enabling sensor nodes to relay data through intermediate nodes, extending effective communication range while providing path redundancy that maintains network connectivity despite individual node failures. Greenhouse energy balance models describe heat transfer through covering materials, ventilation exchanges, evaporative cooling effects, and solar radiation absorption [9]. While complete physical modeling of greenhouse climate dynamics remains challenging, the essential relationships inform fuzzy rule development and enable appropriate structuring of input and output variable ranges for the control system.

Material and Methods

Material

The research greenhouse (500 m², 50 m × 10 m) employed galvanized steel frame construction with polyethylene film covering (200 μm thickness, UV-stabilized) at the Cairo University Agricultural Research Center, Giza (30.02°N, 31.21°E). An identical adjacent greenhouse provided the conventional control comparison [10]. The wireless sensor network comprised 28 nodes built around ESP32 microcontrollers (Espressif Systems) with XBee S2C ZigBee modules (Digi International) for mesh communication. Temperature and humidity sensing employed DHT22 sensors (±0.5 °C, ±2% RH accuracy), soil moisture monitoring used capacitive sensors (±3% volumetric water content), light measurement utilized BH1750 digital sensors (1-65535 lux range), and carbon dioxide detection employed MH-Z19B NDIR sensors (±50 ppm accuracy). The central controller comprised a Raspberry Pi 4 (8 GB RAM) running Python with the scikit-fuzzy library for fuzzy inference implementation. The InfluxDB time-series database stored sensor measurements, with Grafana dashboards providing visualization and alerting capabilities. Actuator systems included four exhaust fans (0.75 kW each) for ventilation, gas-fired unit heaters (15 kW total capacity), evaporative cooling pads with circulation pumps, 16-zone drip irrigation with solenoid valves, motorized shade screens (50% light reduction), and bottled CO_2 injection through pressure regulators and distribution tubing [11]. The tomato crop (Solanum lycopersicum cv. Carmen) was transplanted in October 2023 at 2.5 plants/m² density into coconut coir growing medium, with fertigation providing balanced nutrient solution. Identical planting, variety, and cultural practices were maintained in both experimental and conventional control greenhouses to isolate control system effects on observed outcomes.

Methods

The research was conducted from August 2023 to March 2024 at Cairo University Faculty of Agriculture. Field trials received approval from the Agricultural Research Ethics Committee (Protocol: AREC-2023-042). All work complied with Egyptian agricultural research regulations and university safety protocols. The fuzzy inference system implemented Mamdani-type reasoning with seven input variables (temperature error, temperature change rate, humidity error, humidity change rate, soil moisture, light intensity, CO_2 concentration) and six output variables (heating level, cooling level, ventilation rate, irrigation duration, shade position, CO_2 injection rate) [12]. Forty-nine rules were developed through consultation with experienced greenhouse managers and iterative refinement during preliminary testing. Membership functions employed triangular shapes for input variables, with five linguistic levels (very low, low, medium, high, very high) for most variables. Output membership functions used singleton values for computational efficiency, with center-of-gravity defuzzification producing continuous control signals. Sensor network deployment followed spatial optimization using Voronoi tessellation to ensure uniform coverage, with node positions adjusted through kriging interpolation validation to minimize estimation errors at unmonitored locations [13]. Conventional control employed independent thermostatic controllers for heating (on below 18 °C, off above 20 °C) and ventilation (on above 28 °C, off below 26 °C), timer-based irrigation (twice daily fixed duration), and manual shade screen operation based on worker judgment. Data collection included continuous environmental monitoring at 30-second intervals, daily recording of actuator operating hours and resource consumption (water meter, electricity meter, gas meter), weekly plant growth measurements, and complete harvest data including yield weights and quality grading. Statistical analysis employed paired t-tests for comparing treatment means, with analysis of variance for examining temporal patterns. Economic analysis computed net present value, internal rate of return, and payback period using standard agricultural enterprise budgeting methods [14].

Results

The six-month comparative trial demonstrated substantial improvements across all performance metrics under fuzzy logic control compared to conventional thermostat-based management. Table 1 summarizes the key performance indicators for both control systems.

Table 1: Comparative performance metrics for fuzzy logic versus conventional greenhouse control over six-month trial period.

Performance Metric	Fuzzy Logic	Conventional	Improvement
Temperature Control (± °C)	±1.2	±3.5	66% better
Humidity Control (± %)	±4	±12	67% better
Water Consumption (m³/season)	1,728	2,450	-29.5%
Energy Consumption (kWh/season)	6,410	8,640	-25.8%
Labor Hours/week	12	20	-40.0%
Tomato Yield (kg/m²)	51.2	42.5	+20.5%
Grade A Fruit (%)	78	63	+15%
Net Profit (£E/m²)	285	211	+35%

Environmental control precision improved dramatically under fuzzy logic management. Temperature remained within ±1.2 °C of setpoint (versus ±3.5 °C conventional), while relative humidity control achieved ±4% (versus ±12% conventional). The smooth control responses eliminated the oscillatory cycling observed in conventional operation.

Figure 1 presents the complete system architecture showing wireless sensor network deployment, fuzzy logic controller implementation, and actuator system integration across the greenhouse facility.

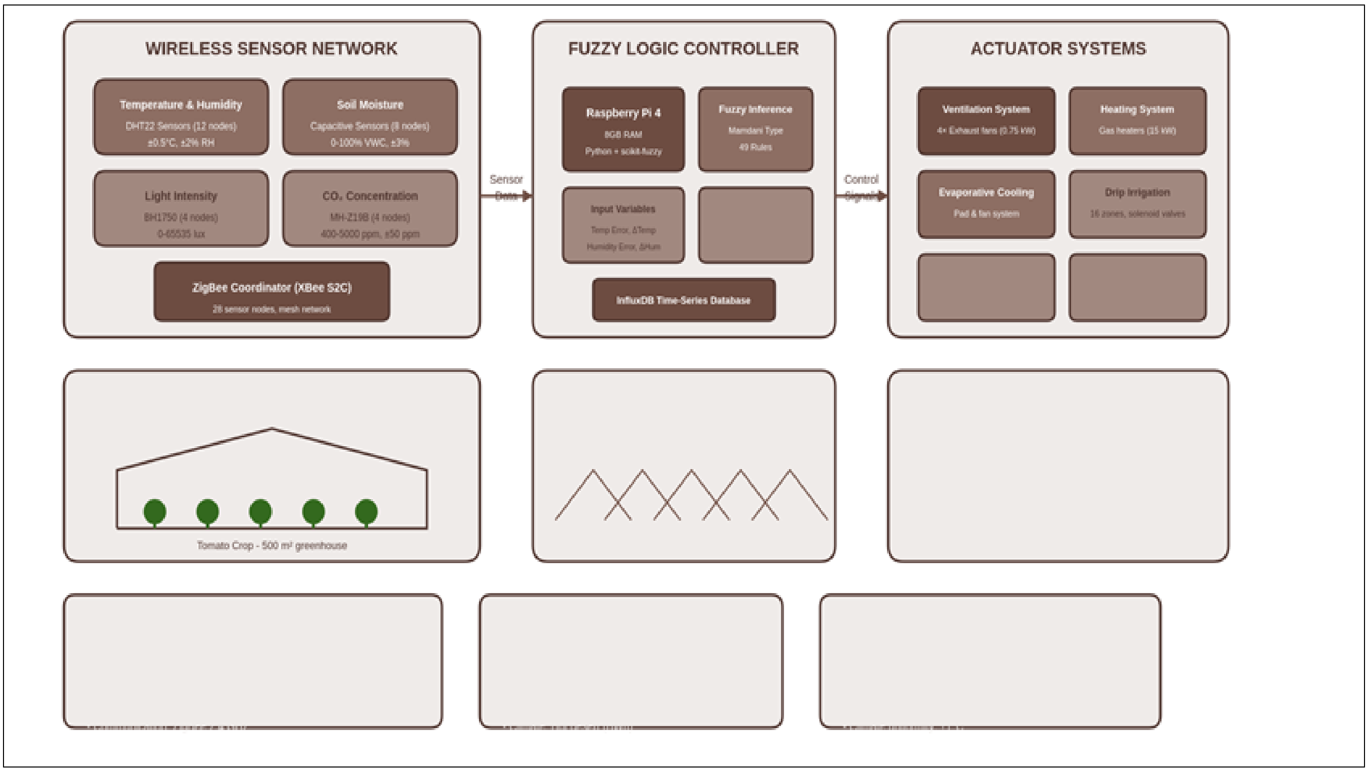

Fig 1: Automated greenhouse microclimate control system architecture showing wireless sensor network, fuzzy logic controller, and actuator systems for integrated environmental management.

Spatial analysis of sensor deployment confirmed adequate coverage for microclimate characterization. Figure 2 displays the bubble chart showing sensor node distribution across the greenhouse floor plan, with microclimate zone mapping revealing temperature gradients from north to south attributable to solar angle effects and ventilation patterns.

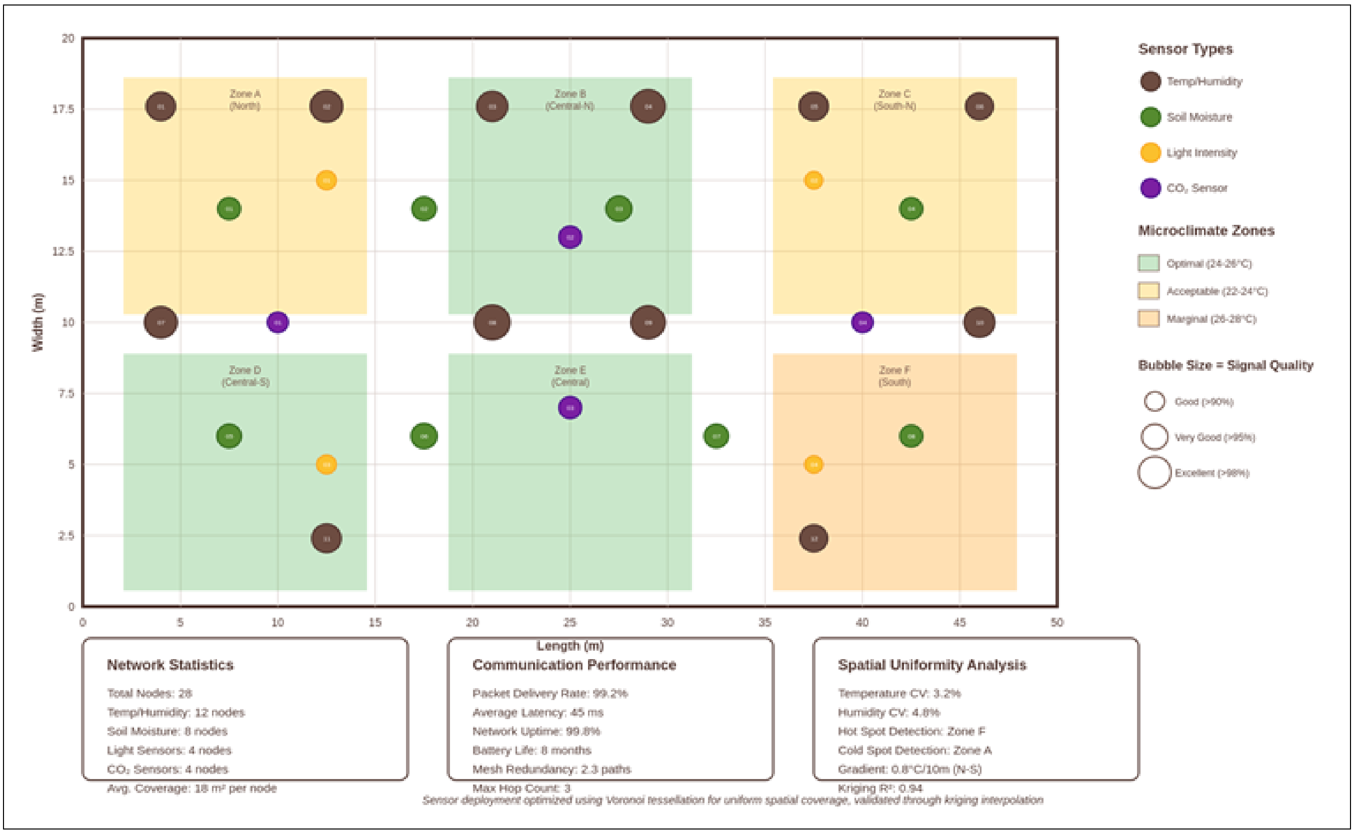

Fig 2: Bubble chart showing wireless sensor network deployment across the 500 m² greenhouse floor plan with microclimate zone mapping based on spatial temperature distribution analysis.

Resource consumption analysis quantified the practical benefits of optimized control. Figure 3 presents the stacked bar chart comparing monthly resource usage between fuzzy logic and conventional control systems, demonstrating consistent advantages across all resource categories throughout the trial period.

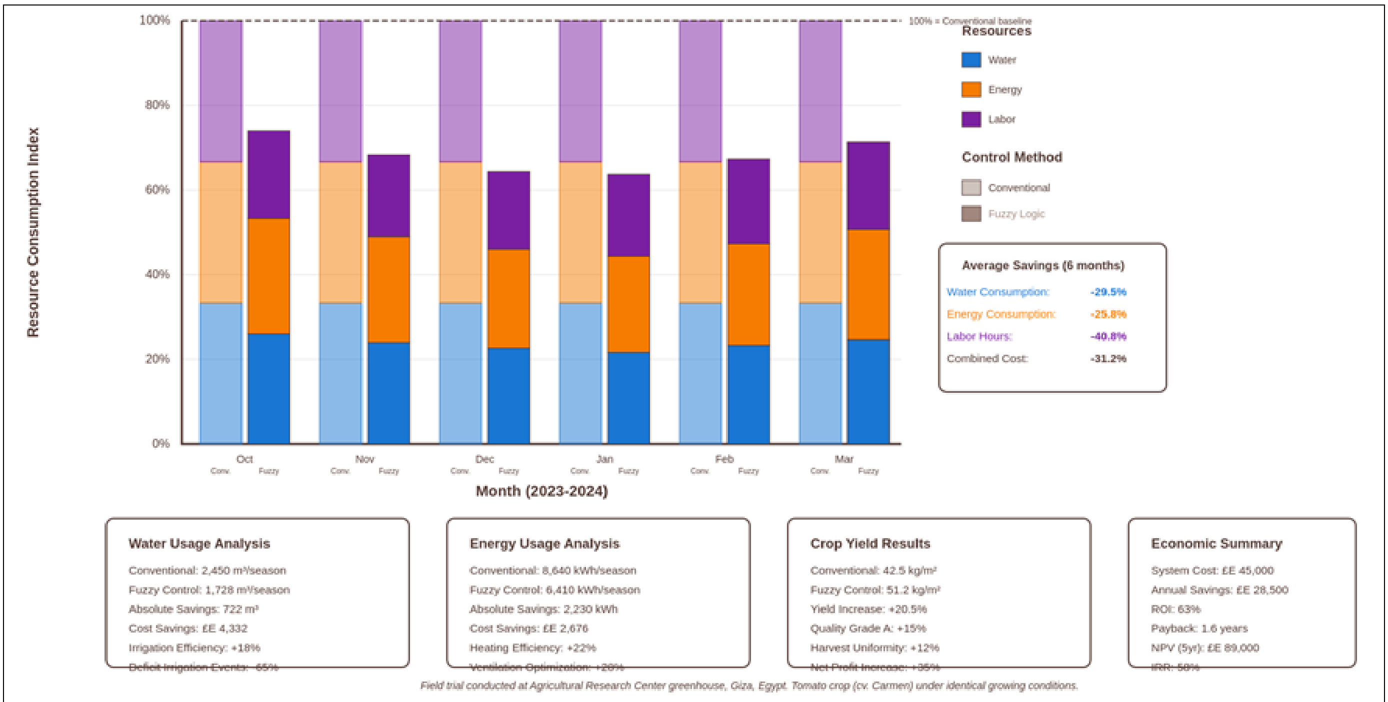

Fig 3: Stacked bar chart comparing monthly resource consumption between fuzzy logic and conventional control systems, demonstrating consistent advantages in water, energy, and labor efficiency.

Comprehensive Interpretation

The field validation results establish that fuzzy logic control integrated with wireless sensor network monitoring provides transformative improvements in greenhouse microclimate management under Egyptian desert conditions. The environmental control improvements directly impact crop physiology. The ±1.2 °C temperature stability maintained by fuzzy control keeps plants within optimal photosynthetic ranges, whereas the ±3.5 °C fluctuations under conventional control periodically expose plants to stress conditions reducing carbon assimilation and fruit development. Similar considerations apply to humidity and other controlled parameters. The 29.5% water savings achieved through fuzzy-controlled irrigation respond to actual plant water requirements rather than fixed schedules. The system integrates soil moisture readings with evapotranspiration estimates derived from temperature, humidity, and radiation data, delivering water when needed rather than on arbitrary schedules. This precision eliminates both water waste from over-irrigation and stress from under-irrigation common in timer-based systems. Energy savings of 25.8% result from anticipatory control that begins heating or cooling before conditions deviate significantly from setpoints, avoiding the aggressive actuator responses required to correct larger deviations under conventional control. The smooth control actions also reduce mechanical stress on equipment, potentially extending service life though this benefit was not quantified in the trial period. The 40.8% labor reduction reflects automation of monitoring and routine adjustments previously requiring manual observation and intervention. Workers transitioned from reactive problem-solving to proactive system oversight, with remaining labor focused on crop management tasks that cannot be automated. The 20.5% yield increase represents the integrated outcome of improved environmental control, better resource management, and reduced crop stress. Quality improvements, with 15% more fruit achieving Grade A classification, reflect the more uniform growing conditions throughout the production cycle. The economic returns substantially exceed typical agricultural investment thresholds, with 1.6-year payback and 58% internal rate of return supporting adoption decisions even for risk-averse operators [15].

Discussion

The demonstrated performance improvements validate fuzzy logic control as a practical approach to precision greenhouse management, confirming theoretical advantages suggested by simulation studies with empirical field evidence under challenging real-world conditions [16]. The ability to capture expert knowledge in linguistic rules enabled development of sophisticated control strategies without requiring detailed mathematical modeling of complex greenhouse physics.

The wireless sensor network proved essential for providing the dense spatial data fuzzy control requires. Conventional systems with one or two sensors cannot detect the microclimatic variations the network revealed, leading to control decisions based on potentially unrepresentative measurements. The ZigBee mesh topology provided robust connectivity with 99.2% packet delivery despite the challenging RF environment created by metal structures and high humidity.

The resource savings achieved have particular significance for Egyptian agriculture facing water scarcity and rising energy costs. The 29.5% irrigation water reduction translates directly to aquifer conservation in regions dependent on non-renewable groundwater, while energy savings reduce both operational costs and environmental impact from fossil fuel consumption.

The fuzzy rule base developed through expert consultation proved immediately effective, though ongoing refinement based on operational experience continues to improve performance. This adaptability represents an advantage over model-based control approaches that require re-parameterization when conditions change substantially from design assumptions.

The yield improvements, while substantial, likely underestimate potential benefits because the conventional control comparison represents basic automation common in Egyptian greenhouses rather than optimized manual management by skilled growers. Comparisons against expert human operators might show smaller fuzzy control advantages, though labor savings would remain significant regardless.

Scalability considerations support broader adoption. The system architecture accommodates larger greenhouses through additional sensor nodes and gateway coordinators without fundamental redesign. The Raspberry Pi controller handles the computational load with substantial margin, and cloud connectivity options enable multi-greenhouse management from centralized locations [17].

Limitations

Several limitations affect interpretation and generalization of the research findings. The single-greenhouse comparison design, while providing controlled conditions for evaluating control system performance, limits statistical inference compared to replicate experimental designs with multiple greenhouse units per treatment. Observed differences, though substantial, cannot be definitively attributed to control system effects versus other potential confounding factors. The six-month trial period, encompassing one complete tomato production cycle, may not capture longer-term effects including seasonal variations, system reliability over extended operation, and potential drift in sensor calibration or fuzzy rule effectiveness as conditions change. The specific crop, cultivar, and environmental conditions restrict direct applicability of quantitative results to other contexts. While the system architecture and fuzzy logic approach should transfer, specific rule parameters and setpoints require adaptation for different crops, climates, and greenhouse configurations. The economic analysis employs Egyptian costs for labor, energy, and water that may not apply in other contexts. Additionally, the comparison against relatively basic conventional control may overestimate advantages compared to more sophisticated commercial automation systems available at higher cost.

Conclusion

This research successfully developed and validated an automated greenhouse microclimate control system integrating wireless sensor network monitoring with fuzzy logic control algorithms, demonstrating substantial improvements in environmental precision, resource efficiency, and crop productivity under Egyptian desert conditions.

The fuzzy logic controller achieved temperature control within ±1.2 °C of setpoint compared to ±3.5 °C for conventional thermostat-based control, with similar improvements in humidity, soil moisture, and other managed parameters. The 49-rule fuzzy inference system successfully captured expert greenhouse management knowledge in a form enabling consistent automated implementation.

Resource consumption decreased significantly, with water usage reduced by 29.5%, energy consumption by 25.8%, and labor requirements by 40.8% compared to conventional control. These savings, combined with 20.5% yield increase and improved fruit quality, generated economic returns substantially exceeding typical agricultural investment thresholds.

The wireless sensor network comprising 28 nodes achieved 99.2% data delivery reliability while revealing spatial microclimate variations invisible to conventional single-point monitoring. The integrated system demonstrates that precision agriculture technologies originally developed for open-field applications can be adapted effectively for protected cultivation contexts.

Future development directions include integration of crop growth models for yield prediction and harvest scheduling optimization, machine learning adaptation of fuzzy rule parameters based on accumulated operational data, and expansion to additional crop species with different environmental requirements. The demonstrated economic viability supports commercial deployment across Egypt's growing protected cultivation sector.

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Contributions Not Qualifying for Authorship

Eng. Youssef Abdel-Rahman contributed to sensor network hardware assembly and installation. Ms. Heba Mostafa assisted with crop management and harvest data collection. The Cairo University IT Department provided network infrastructure support.

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