OPEN ACCESS
Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) | ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Review Article

Greenhouse Monitoring and Control Systems: A Review of Internet of Things and Wireless Sensor Network Technologies

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DOI: https://doi.org/10.36348/sjet.2026.v11i08.004 | **Received:** 23.06.2026 | **Accepted:** 15.08.2026 | **Published:** 18.08.2026

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Abstract

The convergence of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) has strengthened smart greenhouse management by enabling continuous environmental monitoring, automated control, and more informed use of agricultural resources. This review examines and synthesises research on IoT- and WSN-enabled greenhouse systems published between 2015 and 2026. Peer-reviewed studies retrieved mainly from IEEE Xplore and Google Scholar were analysed across sensing technologies, system architecture, communication methods, network topology, control approaches, cloud–edge computing, energy management, and performance assessment. The reviewed studies show that achieving strong performance in one area often requires compromises elsewhere, particularly among communication range, energy demand, reliability, scalability, latency, computational capacity, and cost. ZigBee is particularly suitable for low-power, short-range mesh networks, whereas LoRa better supports wider-area deployments. Clustered and hybrid network structures offer favourable scalability and reliability, while cloud–edge architectures combine scalable analytics with rapid local processing. Intelligent control improves prediction, adaptability, and resource use, whereas renewable energy and intelligent energy management can reduce reliance on conventional power sources. Practical deployment, however, remains constrained by sensor reliability, energy limitations, communication instability, interoperability, cybersecurity risks, and limited long-term validation. Future studies should place greater emphasis on energy-autonomous systems, edge intelligence, secure and interoperable architectures, digital twins, adaptive autonomous control, and realistic evaluation of emerging communication technologies for greenhouse applications. Overall, future smart greenhouses are likely to depend increasingly on integrated architectures that combine energy efficiency, adaptive control, reliable connectivity, and security to support sustainable operation.

Keywords: smart greenhouse, Internet of Things, wireless sensor networks, environmental monitoring, intelligent control, precision agriculture.

1. INTRODUCTION

Greenhouse cultivation is an important form of controlled-environment agriculture because it protects crops from climatic variability while allowing growing conditions to be managed more precisely than in open-field production. Regulation of temperature, relative humidity, light intensity, carbon dioxide concentration, and root-zone conditions can support year-round cultivation and improve the yield and quality of high-value crops (Shamshiri *et al.*, 2018a; Farhaoui *et al.*, 2025). Nevertheless, simply providing a controlled structure does not guarantee efficient or sustainable production. Greenhouse performance also depends on structural design, local climate, crop requirements, control accuracy, and resource availability. Conventional practices based on periodic measurements, fixed schedules, and manual intervention may respond poorly to rapidly changing conditions, resulting in inefficient irrigation, excessive energy use, unstable microclimates, and inconsistent crop performance (Gurban and Andreescu, 2018; Maraveas *et al.*, 2023; Argento *et al.*, 2024; Bicamumakuba *et al.*, 2025). More responsive monitoring and control are therefore required to realise the full environmental-management potential of greenhouse cultivation.

The integration of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs) offers a practical means of improving greenhouse responsiveness through continuous sensing, wireless communication, automated actuation, and data-driven decision-making (Shaikh *et al.*, 2022; Mowla *et al.*, 2023; Farooq *et al.*, 2022). Distributed sensor networks capture spatial and temporal variations in greenhouse conditions, while communication networks, computing platforms, and actuators convert these measurements into appropriate management actions. Compared with intermittent manual intervention, such systems support more timely and increasingly automated environmental regulation (Farooq *et al.*, 2022; Bicamumakuba *et al.*, 2025), and low-cost implementations have demonstrated their feasibility for smaller greenhouse facilities (Sumalan *et al.*, 2020; Iyaomolere *et al.*, 2025). More recent systems combine cloud and edge computing with artificial intelligence and machine learning to support remote management, prediction, adaptive decision-making, and resource optimisation (Ficili *et al.*, 2025; Bouarroudj *et al.*, 2025). These capabilities, however, introduce additional demands for computation, connectivity, integration, and cost. Their usefulness therefore depends on how effectively sensing, communication, processing, and control are coordinated within the greenhouse environment.

Despite considerable technological progress, moving from prototype systems to reliable and scalable smart-greenhouse infrastructure remains difficult. Continuous sensing and wireless communication consume energy and can shorten the operating life of resource-constrained sensor nodes (Liu *et al.*, 2022), while larger or more complex greenhouses require greater communication coverage, reliability, and network-management capacity (Farooq *et al.*, 2022; Singh *et al.*, 2024). Long-term performance is also affected by sensor degradation, heterogeneous devices and communication standards, and cybersecurity risks associated with interconnected monitoring and control systems (Yazdinejad *et al.*, 2021; Adam *et al.*, 2024). These challenges are closely linked. Improving communication reliability or cybersecurity, for example, may increase energy consumption, processing requirements, or implementation complexity. Smart greenhouse development must therefore be approached as an integrated design problem in which technical performance, resource limitations, and operational requirements are considered together.

Against this background, this review examines developments in IoT- and WSN-enabled smart greenhouse monitoring and control reported between 2015 and 2026. Unlike previous reviews that primarily focus on individual technological domains, this study considers environmental requirements, digital infrastructure, intelligent control, and sustainability considerations within a unified smart greenhouse framework. Particular attention is given to how alternative approaches balance communication range, latency, energy consumption, reliability, scalability, computational requirements, implementation complexity, and cost. The review also identifies the limitations that continue to hinder practical deployment and examines emerging directions towards more reliable, adaptive, resource-efficient, and sustainable greenhouse systems. By linking technological choices with their operational consequences, the review provides an integrated perspective on the transition from experimental smart-greenhouse implementations towards robust and practically deployable systems.

2. REVIEW METHODOLOGY

This review adopted a structured literature-review approach to examine developments in IoT- and WSN-enabled greenhouse monitoring and control. The review process involved literature identification, relevance-based selection, structured extraction of technological characteristics, and thematic synthesis. Particular attention was given to the relationships among sensing, communication, computing, control, and energy-management technologies so that the literature could be interpreted as an integrated system rather than as a collection of independent technological developments.

2.1 Literature Search and Selection Strategy

The literature search focused on peer-reviewed scholarly publications published between 2015 and 2026, a period that has seen substantial development in IoT- and WSN-based greenhouse technologies. Relevant studies were identified primarily through IEEE Xplore and Google Scholar using combinations of search terms such as smart greenhouse systems, IoT-enabled agriculture, wireless sensor networks, greenhouse automation, intelligent environmental control, machine learning for greenhouse management, and cloud–edge computing in agriculture. Boolean operators (AND, OR, and NOT) were used where appropriate to combine or refine the search terms. The search was broadened across greenhouse sensing, communication, networking, computing, automation, and intelligent control to reflect the multidisciplinary nature of smart greenhouse research. This approach was intended to capture studies directly relevant to IoT- and WSN-enabled controlled-environment agriculture while maintaining adequate coverage of the major technological themes considered in the review.

2.2 Inclusion, Exclusion and Data Extraction

Studies were selected according to their relevance to the technological and operational scope of smart greenhouse monitoring and control. Eligible publications addressed greenhouse environmental monitoring, automated control, intelligent decision-making, or the application of IoT, WSNs, and computational intelligence within controlled cultivation environments. Studies dealing exclusively with conventional or open-field agriculture, without a relevant digital monitoring or automation component, were excluded. Publications that provided insufficient technical information for meaningful interpretation were also omitted. For the retained studies, information was organised around greenhouse configuration and environmental requirements, sensing technologies, system architecture, communication protocols, network topologies, control strategies, computing frameworks, energy-management approaches, and reported performance outcomes. These common themes allowed the literature to be compared while recognising differences in greenhouse scale, crop requirements, environmental conditions, technological configuration, and application objectives.

2.3 Thematic Synthesis and Review Framework

The selected literature was synthesised thematically to examine how the major technological components interact within a smart greenhouse system. Rather than simply grouping studies by technology, the analysis focused on the relationships and trade-offs among environmental requirements, sensing infrastructure, communication networks, computing resources, control mechanisms, energy management, and overall system performance. Communication technologies and network topologies were compared in terms of transmission range, reliability, latency, scalability, and energy demand, while sensing and control approaches were considered in relation to measurement quality, responsiveness, computational requirements, and deployment feasibility. Cloud–edge computing and intelligent decision-making were assessed according to their ability to improve processing and control while introducing additional demands for connectivity, computation, integration, and security. This framework provided a basis for interpreting the strengths and limitations of different approaches within their operating contexts and for identifying recurring deployment challenges and emerging research priorities.

2.4 Positioning of the Present Review

The contribution of the present review was further examined in relation to five closely related reviews by Gurban and Andreescu (2018), Bersani *et al.* (2022), Ghiasi *et al.* (2023), Singh *et al.* (2024), and Bicamumakuba *et al.* (2025). For consistency, a thematic area was regarded as covered only when it formed a substantive part of the review rather than being mentioned briefly or incidentally. As shown in Table 1, previous reviews provide important insights into greenhouse monitoring, networking, control, energy management, and computing, but the breadth of coverage differs considerably. The present review brings these areas together by linking greenhouse design and environmental requirements with sensing and monitoring, IoT and wireless networking, control strategies, cloud–edge computing, energy management, security, interoperability, and performance evaluation. This integrated scope allows the technological choices and their associated trade-offs to be examined within a common framework and helps clarify the requirements for reliable, scalable, resource-efficient, and sustainable smart greenhouse systems.

Table 1: Scope comparison of related smart-greenhouse reviews

Scope area	Gurban and Andreescu (2018)	Bersani *et al.* (2022)	Ghiasi *et al.* (2023)	Singh *et al.* (2024)	Bicamumakuba *et al.* (2025)	Present review
Greenhouse design	—	—	✓	—	—	✓
Sensors and monitoring	✓	✓	—	✓	✓	✓
Internet of Things and wireless sensor networking	✓	✓	—	✓	✓	✓
Control strategies	✓	✓	✓	✓	✓	✓
Cloud–edge computing	—	—	—	—	✓	✓
Energy management	—	✓	✓	—	—	✓
Security and interoperability	—	—	—	—	✓	✓

Note: ✓ = covered; — = not substantially covered.

3. GREENHOUSE ENVIRONMENT AND MONITORING REQUIREMENTS

Greenhouse performance depends on the interaction between structural design, crop requirements, and climate-regulation processes (Ghiasi *et al.*, 2023). Characteristics such as greenhouse geometry, orientation, covering materials, and ventilation openings influence solar radiation, airflow, temperature, and humidity distribution within the cultivation environment (Lakhiar *et al.*, 2024). These physical conditions determine how temperature, relative humidity, light, CO_2, and soil moisture should be monitored and controlled for effective crop production (Soussi *et al.*, 2022). For this reason, IoT- and WSN-based monitoring should be designed with the greenhouse structure and environmental demands in mind, since both directly affect sensor placement, control requirements, and overall system performance.

3.1 Greenhouse Design and Environmental Interactions

Greenhouse configuration and orientation influence the internal microclimate by affecting solar interception, airflow, temperature distribution, and humidity uniformity. Ghani *et al.* (2019) showed that geometry, roof form, and dimensional proportions influence environmental uniformity through their effects on solar exposure and prevailing wind, while Rodríguez-Peña *et al.* (2025) identified common configurations such as Quonset, arch-tunnel, even-span, uneven-span, gothic, saw-tooth, and hoop-house structures. No single configuration is universally superior. Designs that increase solar gain may improve light availability but can also increase the cooling burden. Ashok and Sujitha (2021) similarly noted that greenhouse orientation should account for both solar access and prevailing wind conditions. Structural form and orientation should therefore be selected according to local climate, crop requirements, and the intended control strategy rather than by geometry alone.

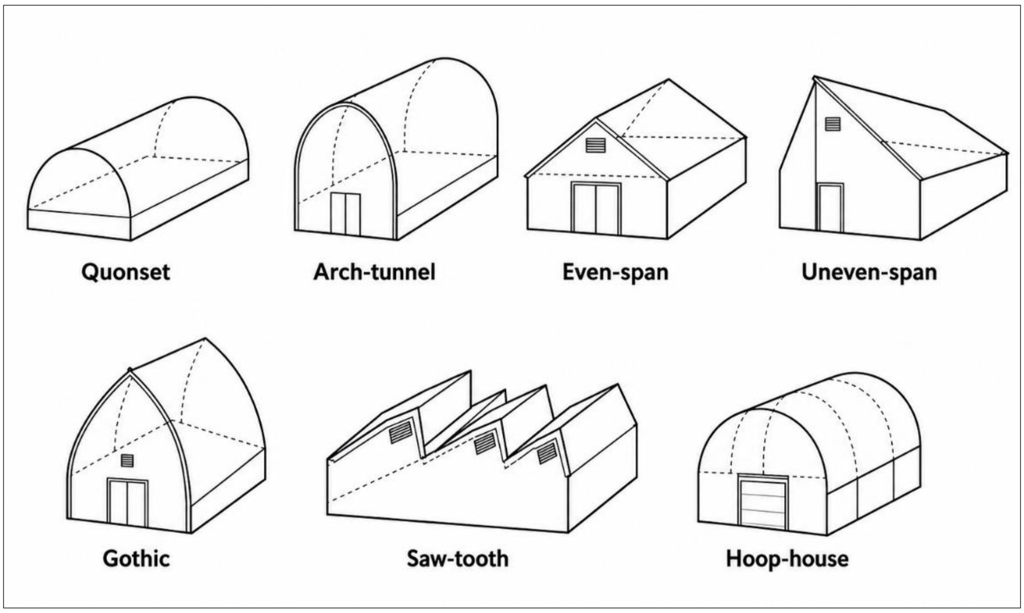

Figure 1: Common greenhouse configurations (Chimankare *et al.*, 2023)

Greenhouse covering materials also influence thermal and optical performance. They determine the transmission and diffusion of solar radiation, heat exchange, and the amount of light reaching the crop canopy (Ghani *et al.*, 2019). Common materials include glass, polyethylene, polycarbonate, acrylic, Polyvinyl Chloride (PVC), and ultraviolet-stabilised plastics, each differing in durability, insulation, optical properties, and cost. Dalai *et al.* (2020) identified glass and polyethylene as widely used greenhouse coverings, while Nawalany *et al.* (2024) showed that material and construction choices can also affect energy consumption and greenhouse-gas emissions. Material selection must therefore consider not only durability and cost but also thermal performance, energy demand, and compatibility with sensing and automation systems.

Taken together, greenhouse geometry, orientation, materials, ventilation, and local climatic conditions define the microclimate that the monitoring and control system must manage. Luna and Ruiz (2019) and Blanco *et al.* (2022) associated greenhouse performance with structural design, wind interaction, solar exposure, and climate-control methods, while Chen *et al.* (2025a) identified temperature, humidity, light intensity, and CO_2 as important variables requiring regulation. Vatistas *et al.* (2022) further emphasised the roles of airflow, humidity, and CO_2 in crop productivity. These relationships have direct implications for smart-greenhouse design: structural characteristics influence where sensors should be placed, how much actuator capacity is required, the reliability of wireless communication, and the energy needed for environmental control. IoT- and WSN-based systems should therefore be configured in relation to the greenhouse itself rather than added as an independent technological layer.

3.2 Environmental Parameters and Monitoring Requirements

Greenhouse productivity depends on maintaining a coordinated microclimate in which temperature, relative humidity, light, carbon dioxide (CO_2), and soil moisture remain within crop-appropriate ranges. Together, these variables influence photosynthesis, respiration, transpiration, nutrient uptake, and crop development (Kumar *et al.*, 2022). Their effects are interrelated, so managing each variable independently can lead to conflicting control actions. Islam *et al.* (2025) likewise highlighted the importance of integrated environmental monitoring in controlled cultivation. Continuous, distributed sensing is therefore particularly valuable in greenhouses because it captures both spatial and temporal variations that may be missed by isolated measurements.

Temperature and relative humidity are especially closely linked. Changes in temperature alter evapotranspiration and atmospheric moisture conditions, while humidity affects transpiration, nutrient transport, condensation, and disease development. Subahi and Bouazza (2020) identified temperature control as fundamental to maintaining favourable greenhouse conditions, and Nicolosi *et al.* (2017) similarly treated temperature as a key continuously monitored variable. Vatistas *et al.* (2022) showed that unsuitable humidity levels can impair crop performance, while Asane *et al.* (2025) highlighted humidity sensing as an important element of greenhouse environmental control. Because ventilation, cooling, and fogging can alter temperature and humidity simultaneously, these variables should be monitored and regulated together. Distributed sensor placement and regular calibration are also important because a single measurement point may not adequately represent microclimatic variation across the greenhouse.

Light, CO_2, and soil moisture create additional interactions between crop requirements and environmental regulation. Solar radiation drives photosynthesis but also increases internal heat load, so shading, covering materials, and supplemental lighting must balance crop light demand with thermal and energy requirements (He *et al.*, 2021; Evola *et al.*, 2017). CO_2 availability presents a similar control problem: enrichment can promote photosynthesis and biomass accumulation, but ventilation used for cooling and humidity control can reduce internal CO_2 concentrations (Soares *et al.*, 2022; Jiang *et al.*, 2015). At the root zone, soil-moisture monitoring supports more efficient irrigation and reduces the risks of water stress and over-irrigation (Bersani *et al.*, 2022), while automated irrigation can improve water-use efficiency and reduce dependence on manual intervention (Gurban and Andreescu, 2018). These interactions reinforce the need for multi-parameter monitoring in which environmental variables are interpreted together and in relation to crop-specific requirements.

3.3 Climate-Regulation and Automation Requirements

Greenhouse climate regulation combines passive and active methods for controlling temperature, humidity, airflow, and solar radiation (Chen *et al.*, 2025a). Natural ventilation provides low-cost cooling through wind- and buoyancy-driven air exchange, and studies by Ikechukwu-Edeh *et al.* (2021), Zhang *et al.* (2022), and Nikolaou *et al.* (2019) demonstrate its value for heat removal, moisture regulation, and air circulation. Its effectiveness, however, depends strongly on external wind conditions, greenhouse geometry, and vent configuration. Forced ventilation offers more predictable airflow when natural ventilation is insufficient. Singh *et al.* (2022) reported improved thermal regulation through enhanced air movement, while Syed and Hachem (2019) and Akrami *et al.* (2021) showed its suitability under high-temperature conditions. The main distinction is therefore one of controllability and energy demand: natural ventilation is inexpensive and energy-efficient but climate-dependent, whereas forced ventilation provides greater control at the cost of additional power and maintenance.

Shading and evaporative cooling provide complementary ways of reducing greenhouse heat loads, although they operate through different mechanisms. Shading limits solar gain and can reduce cooling demand, but excessive shading may reduce the radiation available for photosynthesis (Ashok and Sujitha, 2021; Maraveas *et al.*, 2021; Rabbi *et al.*, 2019). Evaporative cooling and fogging remove sensible heat through water evaporation and are particularly effective in hot, dry climates (Misra and Ghosh, 2018). Fogging can simultaneously lower temperature and increase humidity (Ikechukwu-Edeh *et al.*, 2021), but its effectiveness declines as ambient humidity rises and excessive use may increase water consumption or condensation. Automated operation should therefore account for solar radiation, temperature, humidity, and crop requirements rather than rely on fixed schedules.

Heating remains necessary where low external temperatures or limited solar radiation threaten crop development. Common options include hot-water, steam, unit, radiant, and solar-assisted systems (Fu *et al.*, 2021). Castro *et al.* (2024) and Cepolina *et al.* (2023) identified heating as essential for maintaining thermal stability under cold conditions, while Nawalany *et al.* (2024) showed that heating demand is strongly influenced by greenhouse materials, insulation, and the energy source used. Compared with passive regulation, heating, forced ventilation, and mechanical cooling generally provide greater environmental precision but also increase operating cost and energy demand. Effective greenhouse automation must therefore coordinate ventilation, shading, cooling, fogging, and heating according to local climate, greenhouse design, crop requirements, and available energy. IoT- and WSN-based sensing provides the continuous information required to make these control actions more responsive and resource-efficient.

4. IOT AND WSN TECHNOLOGIES FOR SMART GREENHOUSES

The integration of IoT and WSN technologies has shifted greenhouse management from isolated monitoring towards connected, data-driven, and increasingly automated operation. IoT platforms support sensing, processing, remote access, and control, while WSNs enable distributed acquisition and transmission of environmental data (Rayhana *et al.*, 2020). Their growing use in smart agriculture reflects the need for reliable connectivity between sensors, gateways, computing platforms, and actuators (Abdollahi *et al.*, 2021). In practice, however, the effectiveness of these systems depends on how well sensing accuracy, communication reliability, interoperability, energy use, and processing requirements are coordinated. IoT–WSN integration should therefore be understood as an enabling architecture rather than as a standalone technology.

4.1 Integrated IoT–WSN Architecture and Sensing Infrastructure

IoT–WSN integration links greenhouse sensing directly with communication, processing, and control. IoT frameworks coordinate sensors, networks, computing resources, analytics, and actuators for continuous monitoring and management (Shaheen, 2024; Ficili *et al.*, 2025), while WSNs provide distributed sensor nodes equipped with sensing, processing, communication, and power units (Nurlan *et al.*, 2021; Trigka and Dritsas, 2025). Compared with single-point monitoring, distributed sensing provides a better representation of spatial variation in temperature, relative humidity, soil moisture, CO_2, and light across the greenhouse (Ferentinos *et al.*, 2017). Data typically move from the sensing layer through communication technologies such as ZigBee, Wi-Fi, BLE, and LoRa, to cloud, edge, or AI-enabled processing platforms, before reaching user interfaces and control devices. Single-hop communication offers lower latency and simpler routing, whereas multi-hop networking can extend coverage but introduces additional routing and energy overhead. Consequently, architecture design should reflect greenhouse size, node density, communication range, latency requirements, and available energy rather than follow a single fixed model (Jondhale *et al.*, 2021; Kumari and Tyagi, 2024). The overall interaction among sensing, processing, communication, and actuation is illustrated in Figure 2.

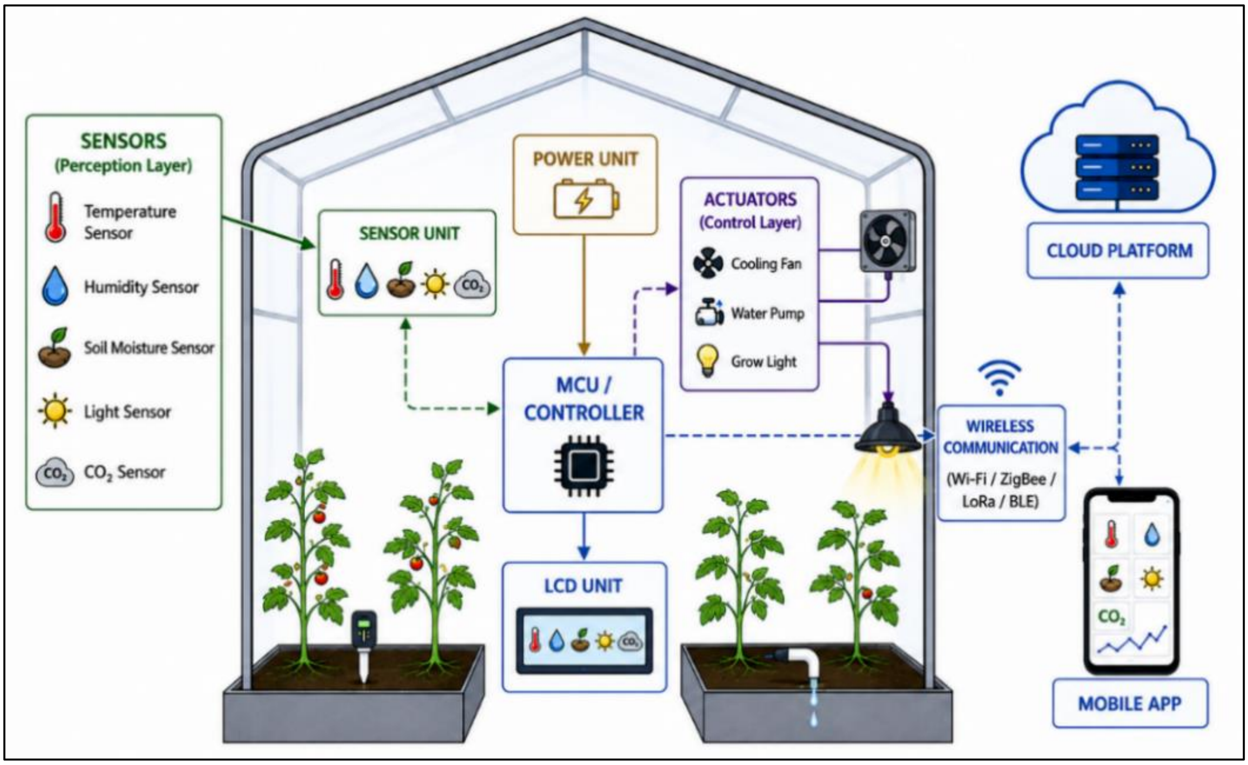

Figure 2: Integrated IoT–WSN architecture for smart greenhouse systems (Iyaomolere *et al.*, 2025)

The performance of the overall architecture depends heavily on sensing quality. Sensor accuracy, sensitivity, response time, and reliability directly affect the quality of subsequent monitoring and control decisions (Jawad *et al.*, 2017; Sagheer *et al.*, 2020; Abdulhussain *et al.*, 2025), while Manono *et al.* (2026) similarly identified reliable sensing as a prerequisite for intelligent agricultural management. Different sensor types, however, involve different balances of cost, accuracy, durability, and operating range. Thermistors and digital devices such as the DS18B20 provide economical temperature measurement, whereas Resistance Temperature Detectors (RTDs) and thermocouples generally offer greater stability or wider operating ranges at higher cost (Abdinoor *et al.*, 2025). Humidity sensors may suffer from drift under prolonged high-moisture or condensation conditions (Shamshiri *et al.*, 2018b; Vatistas *et al.*, 2022), while inexpensive resistive soil-moisture sensors are more prone to corrosion than capacitive or Time Domain Reflectometry (TDR) alternatives (Abdelmoneim *et al.*, 2025; Gurban and Andreescu, 2018). Sensor selection should therefore be guided by the measurement task, greenhouse environment, required accuracy, expected service life, and available budget.

Similar considerations apply to light, CO_2, and nutrient sensing. Photodiodes and light-dependent resistors provide relatively simple measurements of illumination, while photosynthetically active radiation (PAR) sensors more directly quantify the radiation available for photosynthesis (Proietti *et al.*, 2022), making them more suitable for shading and supplemental-lighting decisions (Ashok and Sujitha, 2021). For CO_2 monitoring, non-dispersive infrared (NDIR) sensors generally offer better selectivity and stability than lower-cost alternatives, which is important because photosynthetic activity can substantially alter CO_2 concentration in enclosed greenhouses (Sapounas *et al.*, 2020; Ghani *et al.*, 2019). Monitoring pH and nutrient conditions can also support more precise irrigation and fertiliser management (Lakhiar *et al.*, 2018; Nakachew *et al.*, 2024), while dynamic nutrient monitoring and precision fertilisation have also been supported through integrated sensing, UAV remote sensing, and GIS-based approaches (Chen *et al.*, 2025b). Despite these advances, sensor contamination, measurement drift, and calibration requirements remain practical limitations. Poor sensing can therefore weaken the performance of an otherwise reliable communication and control architecture, reinforcing the need to treat sensing, networking, processing, and actuation as closely connected stages of the same control chain.

4.2 Communication Technologies and Protocols

Wireless communication determines how reliably and efficiently greenhouse data can move between sensor nodes, gateways, processing platforms, and control devices. Important selection criteria include transmission range, data rate, energy demand, network scalability, and coverage (Nourildean *et al.*, 2022), with communication often accounting for a substantial share of sensor-node energy consumption (Mowla *et al.*, 2023). ZigBee is well suited to low-power, short-range sensor networks and supports mesh communication that can extend coverage and improve resilience (Tang *et al.*, 2023; Hudda and Haribabu, 2025). Wi-Fi, in contrast, provides higher throughput and direct Internet connectivity, making it useful for gateways and data-intensive applications, but its greater power demand can limit use in battery-operated nodes (Bersani *et al.*, 2022; Chicaiza *et al.*, 2024). Figure 3 illustrates the relative characteristics of these and other wireless technologies.

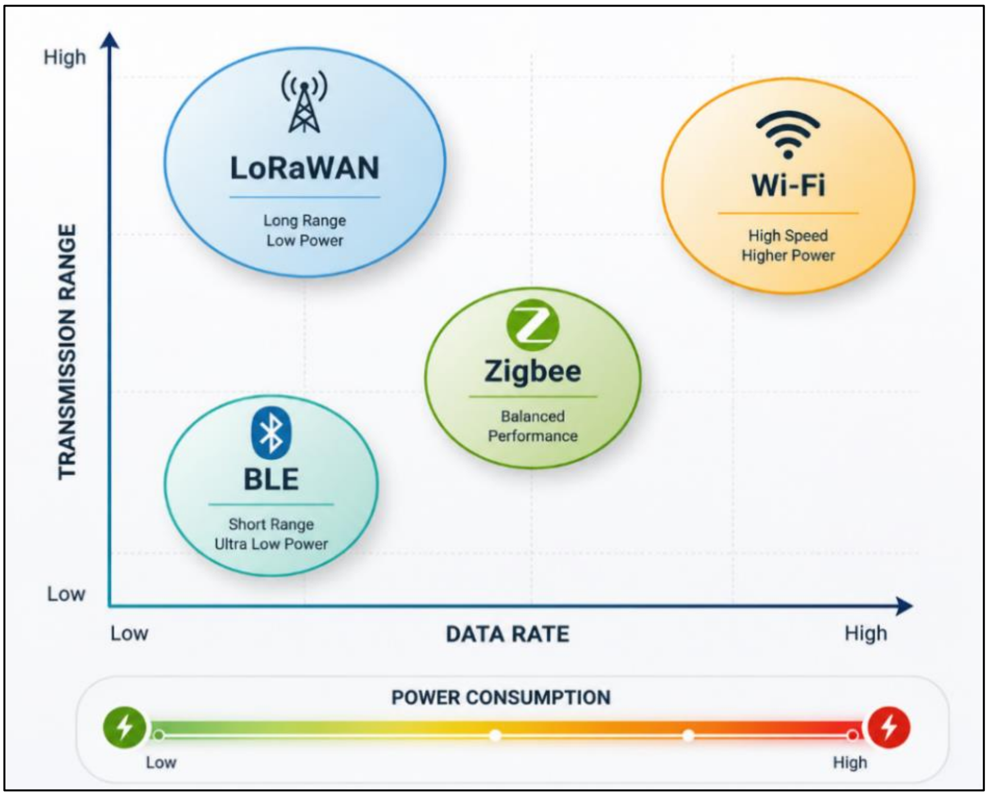

Figure 3: Comparison of wireless communication technologies (Zakaria *et al.*, 2025)

BLE and LoRa/LoRaWAN occupy different positions within the range–energy–data-rate spectrum. BLE provides low-power short-range communication and is therefore useful for localised sensing and portable monitoring applications (Ray, 2017; Nikoukar *et al.*, 2018), but its limited range restricts wider deployments. LoRa and LoRaWAN, by contrast, offer kilometre-scale coverage with relatively low power consumption, making them attractive for large greenhouse complexes or geographically distributed agricultural monitoring (Pitu and Gaitan, 2025; Shaheen, 2024). Their main limitation is the comparatively low data rate, which makes them less suitable for applications requiring frequent data transfer or rapid closed-loop communication. BLE is therefore more appropriate for local low-power links, whereas LoRa/LoRaWAN is better suited to applications where coverage and energy autonomy are more important than data throughput.

The comparison in Table 2 confirms that communication technology should be selected according to application requirements rather than by assuming that one protocol is universally superior. Lorincz *et al.* (2019) showed that range, energy consumption, scalability, deployment cost, and data-rate requirements must be considered together. ZigBee remains attractive for low-power mesh networks within confined greenhouse environments, Wi-Fi for high-throughput and Internet-connected applications, BLE for short-range energy-constrained devices, and LoRa/LoRaWAN for long-range monitoring where lower data rates are acceptable. The most appropriate choice therefore depends on greenhouse scale, node density, traffic volume, latency requirements, energy availability, and deployment cost.

Table 2: Comparison of Wireless Communication Technologies for Smart Greenhouses

Technologies	Typical Range	Data Rate	Power Consumption	Network Topology	Major Advantages	Major Limitations
ZigBee (IEEE 802.15.4)	10–100 m	Up to 250 kbps	Very Low	Star, Mesh, Tree	Low energy consumption, self-healing network, cost-effective	Limited transmission range
Wi-Fi (IEEE 802.11)	50–100 m	Up to several Mbps	High	Star	High data rate, internet connectivity	High power consumption
Bluetooth Low Energy (BLE)	10–50 m	Up to 2 Mbps	Very Low	Star	Energy-efficient, simple implementation	Short communication range
LoRa	2–15 km	0.3–50 kbps	Low	Star-of-Stars	Long-range communication, low power requirement	Lower data transmission rate

4.3 Network Topologies and Communication Organisation

Network topology determines how sensor nodes exchange data and how information reaches gateways and processing platforms, directly affecting energy use, reliability, scalability, and fault tolerance. Wang *et al.* (2020) highlighted the importance of network organisation in distributed greenhouse sensing, while Nguyen and Kim (2021) and Kavra *et al.* (2022) showed that communication activity is a major contributor to WSN energy consumption. Star topology offers simple single-hop communication, low latency, and straightforward management (Lin *et al.*, 2017), making it suitable for small greenhouses with short transmission distances (Khan *et al.*, 2025). Its main weakness is dependence on a central coordinator. Mesh topology provides multiple communication paths and greater resilience to node or link failure (Berto *et al.*, 2021; Chai and Zeng, 2021), but this robustness comes with greater routing complexity and communication overhead. Figure 4 summarises the principal topology options used in smart-greenhouse networks.

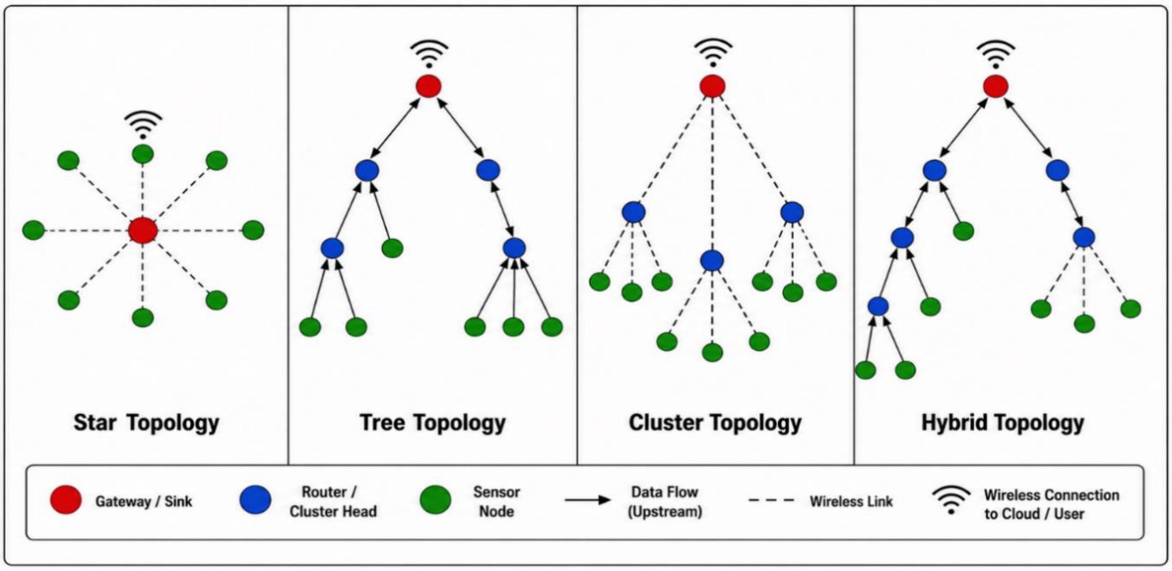

Figure 4: Network topologies for smart greenhouse systems

Tree and clustered topologies provide more structured communication for larger deployments. Tree networks organise nodes hierarchically and support data aggregation through intermediate nodes (Nakas *et al.*, 2020), which can suit row-based or zoned cultivation layouts (Yu *et al.*, 2019). Their main vulnerability is that failure of a parent node may disconnect subordinate nodes. Clustered networks reduce repeated long-distance communication by grouping sensors around cluster heads that aggregate and forward data. Guleria and Verma (2019) showed that this arrangement can lower communication overhead and improve energy utilisation in dense deployments. Its performance, however, depends on effective cluster-head selection and load management because overloaded or failed cluster heads can reduce network reliability.

Hybrid topologies combine elements of star, mesh, tree, or clustered organisation to match changing deployment requirements. Lv *et al.* (2024) noted that such networks can adapt more effectively to variations in sensor density, communication demand, and environmental conditions, although this flexibility increases routing and management complexity. As summarised in Table 3, star networks favour simplicity and low latency, mesh networks favour redundancy, tree networks provide hierarchical organisation, clustered networks improve energy efficiency and scalability, and hybrid designs provide greater adaptability. For large or highly automated greenhouses, clustered and hybrid architectures may offer the most favourable balance, provided that their additional complexity is justified by the scale and reliability requirements of the application.

Table 3: Comparison of network topologies for smart greenhouses

Topology	**Communication Mode**	**Energy Efficiency**	**Scalability**	**Reliability**	**Greenhouse Application**
Star	Single-hop	High (small networks)	Low	Moderate	Small greenhouses and experimental facilities
Mesh	Multi-hop	Moderate	High	Very High	Large greenhouse complexes requiring redundancy
Tree	Hierarchical multi-hop	Moderate	Moderate	Moderate	Structured cultivation zones and row-based layouts
Clustered	Intra-cluster and inter-cluster communication	Very High	Very High	High	Dense sensor deployments and automated greenhouse systems
Hybrid	Adaptive communication	High	Very High	Very High	Advanced IoT-enabled smart greenhouse environments

4.4 Deployment Challenges and System-Level Trade-offs

Reliable greenhouse deployment remains limited by closely related problems in energy consumption, communication reliability, sensing quality, and environmental robustness. Continuous sensing, processing, and wireless transmission can shorten the lifetime of battery-powered nodes (Prauzek *et al.*, 2018), with communication representing a substantial share of WSN energy demand (Liu *et al.*, 2022). Lower sampling rates, reduced transmission frequency, and sleep scheduling can extend operating life, but they may also reduce data availability or increase response time. Communication performance is further affected by greenhouse structures, vegetation, humidity, and electromagnetic interference, which can contribute to attenuation, multipath propagation, packet loss, and delay (Singh *et al.*, 2024). Chai and Zeng (2021) showed that communication disruption can compromise subsequent monitoring and control. Measures such as redundant routes can improve reliability, but they also increase routing overhead and energy consumption (Mowla *et al.*, 2023; Kumari and Tyagi, 2024). The central challenge is therefore to maintain dependable communication without creating excessive energy and network-management costs.

Sensing reliability and scalability become increasingly important as greenhouse systems operate for longer periods and include more devices. Exposure to moisture, contamination, ageing, and calibration drift can gradually reduce measurement quality (Belgacem and Chihi, 2025), making regular calibration and maintenance important for sustained data reliability (Aarif *et al.*, 2025). Sensor fusion, redundancy, fault detection, and self-calibration may reduce these problems, although their long-term effectiveness still requires validation. At the network level, increasing sensor density can improve spatial coverage but also creates more traffic, higher processing demand, and greater management complexity. Interoperability adds another difficulty when devices from different manufacturers use incompatible protocols, interfaces, or data formats. Fischer *et al.* (2020) identified such integration problems as an important challenge in IoT systems. Scaling a smart greenhouse therefore requires not only additional network capacity but also common interfaces, data models, and communication standards.

Cybersecurity and physical durability further affect long-term deployment. Increased connectivity exposes greenhouse IoT systems to unauthorised access, data breaches, malware, denial-of-service attacks, and network intrusion (Yazdinejad *et al.*, 2021), while larger numbers of connected devices expand the potential attack surface (Shaheen, 2024). Encryption and authentication can strengthen protection but may increase processing and energy requirements on resource-constrained nodes. The hardware itself must also withstand humidity, water, temperature fluctuations, dust, chemicals, and biological contaminants that can degrade sensors and communication devices (Batista and Dos Santos, 2024). Protective enclosures, corrosion-resistant materials, maintenance, secure communication, and adaptive operating strategies can reduce these risks, but they also add cost and complexity. Practical smart-greenhouse design therefore requires a balanced treatment of energy efficiency, communication reliability, sensing quality, scalability, interoperability, security, and physical robustness rather than maximising any one attribute in isolation.

5. SMART GREENHOUSE MONITORING AND INTELLIGENT CONTROL

Smart greenhouse systems have progressed from basic environmental monitoring platforms to integrated cyber-physical systems capable of sensing, analysing, and automatically responding to changing cultivation conditions. IoT, WSN, cloud computing, edge processing, and artificial intelligence have expanded the capability of greenhouse systems beyond data collection towards prediction, autonomous decision-making, and resource optimisation (Soheli *et al.*, 2022; Olasehinde *et al.*, 2023; Ficili *et al.*, 2025). Modern smart-greenhouse solutions increasingly combine distributed sensors, communication networks, intelligent algorithms, and automated actuators to maintain suitable growing conditions while reducing labour requirements and improving resource efficiency. However, increasing technological complexity also introduces challenges related to reliability, energy demand, interoperability, cybersecurity, and long-term operational validation.

5.1 Monitoring, Feedback and Actuation

Environmental monitoring and automated control form a continuous feedback loop in smart greenhouse systems, where effective regulation depends on the accurate and timely acquisition, transmission, and interpretation of environmental information. Monitoring infrastructures integrate sensors, communication devices, gateways, computing platforms, and visualisation interfaces to continuously observe key parameters, including temperature, relative humidity, soil moisture, CO_2 concentration, light intensity, pH, and nutrient levels. Bicamumakuba *et al.* (2025) demonstrated that continuous monitoring enables early identification of environmental variations and abnormal conditions, while Bouarroudj *et al.* (2025) highlighted that automation performance is strongly influenced by the quality, accuracy, and timeliness of acquired data. Through IoT-enabled platforms, environmental information can be transmitted using wireless technologies such as ZigBee, Wi-Fi, LoRa, and BLE, with cloud-based services supporting remote visualisation, data analysis, and decision-making (Shaheen, 2024). However, the availability of continuous measurements alone does not guarantee effective greenhouse management; sensor accuracy, spatial representativeness, communication reliability, and processing latency must be sufficient to support appropriate control decisions.

The practical value of monitoring is achieved when environmental information is converted into coordinated control actions through a closed-loop system consisting of sensors, communication networks, controllers, actuators, and feedback mechanisms. Unlike conventional greenhouse management, where adjustments are often based on periodic observations or manual intervention, automated systems continuously compare measured conditions with desired operating targets and initiate appropriate responses through irrigation pumps, ventilation fans, heating and cooling units, fogging systems, shading devices, or artificial lighting. Gurban and Andreescu (2018) associated such automation with improved environmental stability and more efficient utilisation of water, energy, and nutrients, while Batista and Dos Santos (2024) emphasised the role of IoT integration in enabling real-time regulation and remote operation. Similarly, Ficili *et al.* (2025) reported that automated control can reduce human intervention errors and improve production consistency. Nevertheless, achieving reliable control requires effective coordination among sensing accuracy, communication delay, actuator response, and appropriate control set-points. Poorly coordinated actions may result in unnecessary energy consumption, conflicting actuator responses, or unstable environmental conditions. Therefore, smart greenhouse operation depends on the integration of monitoring, feedback, and actuation as a unified control cycle rather than as separate technological components.

5.2 Evolution of Greenhouse Control Strategies

Greenhouse control has progressed from simple reactive methods to adaptive and increasingly intelligent strategies as environmental regulation has become more demanding. Early rule-based systems rely on predefined thresholds to trigger actions, such as activating ventilation when temperature rises above a specified limit (Asane *et al.*, 2025) or initiating irrigation when soil moisture falls below a predetermined value (Jabro *et al.*, 2020). Their simplicity, low computational demand, and relatively low implementation cost make them suitable for greenhouses operating under reasonably predictable conditions (Biswal *et al.*, 2024). However, fixed thresholds respond only to predefined conditions and have limited capacity to accommodate changing system dynamics or interactions among environmental variables. PID control provides more continuous regulation by adjusting control actions according to deviations between measured and desired conditions (Guan, 2025). Although PID controllers can provide stable and reliable regulation (Li *et al.*, 2025), fixed controller parameters may require retuning as greenhouse conditions change or system behaviour becomes nonlinear. Moving from threshold-based rules to continuous feedback therefore improves regulatory precision, but does not fully resolve the uncertainty and dynamic interactions characteristic of greenhouse environments.

The limitations of conventional feedback methods have encouraged greater use of fuzzy and data-driven control. Fuzzy logic is particularly useful where greenhouse behaviour is difficult to describe using precise mathematical models because it represents environmental conditions through linguistic rules and accommodates uncertainty and nonlinear relationships (Tang and Ahmad, 2024). This gives the controller greater flexibility when operating conditions vary (Dudnyk *et al.*, 2025), although its effectiveness depends on the design and tuning of the underlying rule base. Artificial neural networks and other machine-learning methods extend this adaptability by learning relationships from historical and real-time environmental data, supporting applications such as prediction, anomaly detection, irrigation scheduling, and control optimisation (Hemal *et al.*, 2025; Abioye *et al.*, 2022). Ficili *et al.* (2025) similarly identified adaptability and predictive capability as important advantages of data-driven methods over conventional control. These capabilities come with additional requirements for representative training data, computational resources, model generalisation, and integration with existing greenhouse infrastructure. The progression towards intelligent control therefore reflects a broader change in greenhouse management: control systems are increasingly expected not only to respond to measured deviations but also to anticipate environmental changes and crop-management needs.

Hybrid intelligent systems extend this development by combining conventional feedback control, fuzzy logic, neural networks, machine learning, and optimisation methods so that the strengths of one approach can compensate for the limitations of another (Fernández Mareco and Pinto-Roa, 2025). Cevallos *et al.* (2022) and Villagran *et al.* (2025) reported that such combinations can improve environmental regulation and support more autonomous operation under complex greenhouse conditions. These benefits, however, are accompanied by greater computational demand, integration complexity, implementation cost, and requirements for technical expertise. As summarised in Table 4, increasing control intelligence generally improves adaptability, predictive capability, and decision flexibility, but also places greater demands on data, computation, infrastructure, and system integration. The most appropriate control strategy should therefore be determined by greenhouse dynamics, available resources, control objectives, and the required degree of automation rather than by technological sophistication alone (Bhat and Wang, 2025). Integration with IoT and computing platforms further extends these capabilities by linking real-time sensing with predictive and increasingly autonomous decision-making (Shaheen, 2024), marking a continuing shift towards more adaptive and intelligent greenhouse control.

Table 4: Comparative Analysis of Greenhouse Control Strategies

Author(s)/Year	Control Strategy	Advantages	Limitations
Shaheen (2024)	IoT-Based Intelligent Control	Enables remote monitoring and efficient management.	Depends on reliable communication and security.
Biswal *et al.* (2024)	Rule-Based Control	Simple, low-cost, and easy to implement.	Limited adaptability to changing conditions.
Asane *et al.* (2025)	Rule-Based IoT Control	Suitable for low-cost smart greenhouse systems.	Lacks predictive capability.
Jabro *et al.* (2020)	Threshold-Based Irrigation Control	Reduces water wastage and improves efficiency.	Limited optimisation capability.
Guan (2025)	PID Control	Provides stable and accurate regulation.	Requires parameter tuning.
Li *et al.* (2025)	PID-Based Control	Reliable and widely applicable.	Less effective for complex environments.
Tang and Ahmad (2024)	Fuzzy Logic Control	Handles uncertainty and nonlinear conditions.	Requires expert rule development.
Dudnyk *et al.* (2025)	Fuzzy Intelligent Control	Provides flexible decision-making.	Needs optimisation of fuzzy rules.
Hemal *et al.* (2025)	Machine Learning/ANN Control	Supports prediction and optimisation.	Requires quality data and high computing power.
Ficili *et al.* (2025)	AI Predictive Control	Enhances prediction and resource efficiency.	Increases system complexity.
Fernández Mareco and Pinto-Roa (2025)	Hybrid Intelligent Control	Improves adaptability and robustness.	Higher cost and complexity.
Cevallos *et al.* (2022)	Hybrid Control Strategy	Enhances environmental regulation.	Requires advanced integration.

Author(s)/Year	Control Strategy	Advantages	Limitations
Villagran *et al.* (2025)	Hybrid Intelligent Control	Supports autonomous operation.	Needs advanced infrastructure.

5.3 Cloud, Edge and Intelligent Computing

The increasing volume, diversity, and complexity of greenhouse sensor data have encouraged a shift from purely centralised cloud-based processing towards distributed cloud–edge computing architectures. Cloud computing provides extensive storage capacity, powerful computational resources, historical data management, and advanced analytical capabilities, making it suitable for large-scale greenhouse monitoring and data-driven decision support (Dritsas and Trigka, 2025). Shaheen (2024) highlighted the importance of cloud platforms in improving data management and remote supervision, while Ficili *et al.* (2025) demonstrated their value for predictive analytics and integrated greenhouse management. Cloud-based systems support a wide range of applications, including crop monitoring, irrigation scheduling, disease prediction, and resource optimisation (Mohammed *et al.*, 2026), while web and mobile interfaces provide users with remote access to environmental information and control functions (Brăileanu, 2025). However, dependence on remote servers introduces challenges related to communication latency, bandwidth requirements, data transmission costs, and Internet reliability. These limitations make exclusive reliance on cloud processing less suitable for greenhouse applications requiring rapid response and real-time control.

Edge computing addresses these limitations by transferring part of the data-processing workload closer to sensors, gateways, and actuators. Instead of transmitting all collected information to distant cloud servers, edge-enabled systems can analyse data locally and execute immediate control decisions within the greenhouse environment, thereby reducing communication overhead and response delay (Ren *et al.*, 2019). Bicamumakuba *et al.* (2025) demonstrated that local processing improves responsiveness in greenhouse monitoring and control, while Batista and Dos Santos (2024) emphasised its ability to maintain reliable operation when continuous cloud connectivity is unavailable. These characteristics are particularly valuable for applications such as irrigation, ventilation, heating, and cooling, where delayed decisions may affect crop conditions. Nevertheless, edge devices generally have more limited processing capability, storage capacity, and energy availability compared with cloud infrastructures. The evidence therefore suggests that cloud and edge computing serve complementary functions rather than competing alternatives: cloud platforms support computationally intensive analysis, long-term storage, and global optimisation, whereas edge systems provide rapid local processing and immediate control responses.

The integration of cloud and edge computing has consequently led to distributed intelligent architectures in which computational tasks are allocated according to their latency, data-volume, and processing requirements. Yu *et al.* (2025) described cloud–edge frameworks where edge resources support real-time monitoring and control, while cloud platforms provide large-scale analytics, machine learning, and historical data processing. Similarly, Kalyani *et al.* (2023) and Dafhalla *et al.* (2025) showed that collaborative cloud–edge architectures can improve workload distribution and support more responsive automation. As summarised in Table 5, such frameworks provide a more balanced approach than relying exclusively on either cloud or edge computing. However, their implementation introduces additional challenges related to workload allocation, data synchronisation, cybersecurity, interoperability, and architectural complexity. Cloud–edge computing is therefore better understood as a distributed intelligence framework in which processing resources are strategically positioned according to operational needs, enabling fast local responses while retaining the scalability and analytical capabilities required for advanced greenhouse management.

Table 5: Comparative analysis of computing frameworks in smart greenhouse systems

Author(s)/Year	Computing Approach	Advantages	Limitations
Dritsas and Trigka (2025)	Cloud-Edge Computing	Improves data processing and decision support.	Requires reliable communication networks.
Shaheen (2024)	Cloud Computing	Enables remote monitoring and data management.	Suffers from latency and bandwidth issues.
Ficili *et al.* (2025)	Cloud-Based AI Analytics	Supports data storage and predictive analysis.	Depends on internet connectivity.
Mohammed *et al.* (2026)	Cloud Platform	Supports crop monitoring and analytics.	Increases network demand.
Brăileanu (2025)	Cloud Monitoring	Provides remote access and control.	Not ideal for real-time control.

Author(s)/Year	Computing Approach	Advantages	Limitations
Ren *et al.* (2019)	Edge Computing	Reduces latency and communication load.	Limited processing capacity.
Bicamumakuba *et al.* (2025)	Edge Computing	Enables fast local processing and control.	Requires additional hardware.
Batista and Dos Santos (2024)	Edge Architecture	Improves real-time response.	Limited large-scale analytics.
Yu *et al.* (2025)	Cloud-Edge Integration	Combines scalability and rapid response.	Higher system complexity.
Kalyani *et al.* (2023)	Hybrid Cloud-Edge	Balances workload and automation.	Requires effective integration.
Dafhalla *et al.* (2025)	Cloud-Edge Framework	Enhances intelligent greenhouse operation.	Integration challenges.

5.4 Energy Management and Sustainable Operation

Energy management in smart greenhouses involves addressing two interconnected demands: the substantial energy required for climate regulation and the continuous power required by sensing, communication, computing, and automation infrastructure. Greenhouse design, climatic conditions, and environmental-control requirements strongly influence overall energy consumption (Nawalany *et al.*, 2024), while the increasing adoption of IoT-based monitoring and control introduces additional electrical demands associated with sensors, communication networks, gateways, and computing devices (Nagarsheth *et al.*, 2025). Liu *et al.* (2020) identified sensing, communication, and control operations as important contributors to agricultural system energy consumption, with communication becoming particularly significant in distributed WSN deployments (Liu *et al.*, 2022). Energy-efficient communication protocols, low-power sensing technologies, and adaptive operating modes can reduce this demand and extend system lifetime (Engmann *et al.*, 2018), while energy-aware routing approaches further minimise unnecessary communication expenditure (Iyaomolere *et al.*, 2026). However, aggressive energy reduction strategies, such as reducing sampling frequency or communication activity, may affect data availability and control responsiveness. Effective energy optimisation must therefore balance power conservation with the monitoring and control performance required for reliable greenhouse operation.

At the facility level, sustainable energy management increasingly combines energy-demand reduction, renewable generation, and intelligent optimisation strategies. Automated control can reduce unnecessary operation of heating, cooling, ventilation, lighting, and irrigation systems by adjusting energy use according to actual environmental conditions and crop requirements (Daraz *et al.*, 2025). Real-time monitoring further enables adaptive scheduling of energy-consuming devices and supports more efficient resource utilisation (Batista and Dos Santos, 2024). Renewable energy technologies provide an additional pathway for reducing dependence on conventional energy sources, with photovoltaic systems being particularly relevant for powering greenhouse monitoring and control infrastructure (Acosta-Silva *et al.*, 2019; Maraveas and Bartzanas, 2021). Kamyab *et al.* (2024) associated renewable integration with reduced operating costs and lower carbon emissions; however, challenges related to energy intermittency, storage requirements, installation cost, and maintenance remain significant barriers. Intelligent energy-management systems address some of these limitations by coordinating energy generation, storage, and consumption through IoT and computational approaches (Lee *et al.*, 2024), while machine-learning techniques can support demand forecasting, equipment scheduling, and predictive energy optimisation (Rane *et al.*, 2024). Shaheen (2024) similarly highlighted the potential of adaptive and predictive strategies for improving resource utilisation. These developments represent a shift from isolated energy-saving practices towards integrated management of energy supply, demand, and operational efficiency.

The broader sustainability of smart greenhouses cannot, however, be evaluated solely by reductions in electricity consumption. Sustainable operation requires a balance among productivity, resource efficiency, economic feasibility, and environmental impact. Ghiasi *et al.* (2023) emphasised that greenhouse sustainability depends on the interaction between technological innovation, resource conservation, and productive performance, while Ficili *et al.* (2025) highlighted the importance of integrating digital technologies with broader resource-management strategies. Consequently, precision irrigation, efficient climate regulation, renewable energy integration, low-power communication, and intelligent optimisation should be considered as interconnected components of a sustainable greenhouse framework rather than isolated interventions. As summarised in Table 6, individual energy-management strategies provide specific advantages but also introduce trade-offs related to cost, complexity, reliability, infrastructure requirements, and environmental performance. Sustainable smart-greenhouse development therefore requires a comprehensive evaluation of energy demand, renewable supply, digital infrastructure, resource efficiency, life-cycle impacts, and crop productivity when assessing the overall value of technological solutions.

Table 6. Comparative Analysis of Energy Management Strategies in Smart Greenhouse Systems

Author(s)/Year	Strategy	Advantages	Limitations
Nagarsheth *et al.* (2025)	IoT-Based Energy Monitoring	Enables real-time energy monitoring and optimisation.	Requires continuous power for devices.
Nawalany *et al.* (2024)	Energy-Efficient Greenhouse Design	Reduces energy demand through optimised structures.	Depends on climatic and design conditions.
Liu *et al.* (2020)	Energy-Efficient Communication	Reduces power consumption in sensor networks.	Limited by network constraints.
Iyaomolere *et al.* (2026)	Energy-Aware Routing Protocol	Improves network lifetime and reduces communication energy usage.	May increase routing complexity.
Maraveas *et al.* (2023)	Renewable Energy Integration	Reduces emissions and dependence on conventional energy.	High initial installation cost.
Kamyab *et al.* (2024)	Renewable Energy Systems	Lowers operating cost and carbon footprint.	Requires energy storage solutions.
Lee *et al.* (2024)	Intelligent Energy Management	Supports predictive control and energy optimisation.	Requires advanced computation and data.
Ficili *et al.* (2025)	Digital Sustainable Management	Enhances resource efficiency and sustainable operation.	Depends on advanced digital infrastructure.

5.5 Performance Evaluation and Comparative Evidence

Performance evaluation provides the basis for determining whether smart greenhouse technologies translate technological capability into reliable environmental regulation, efficient resource utilisation, and improved production outcomes. Andronie *et al.* (2021) emphasised that integrated IoT, WSN, computing, and automation systems should be assessed across multiple performance dimensions, while Batista and Dos Santos (2024) highlighted the importance of evaluation frameworks for comparing technologies, identifying limitations, and guiding system improvement. At the sensing and communication levels, important indicators include measurement accuracy, precision, response time, data availability, sensor drift, spatial representativeness, and calibration stability, since unreliable measurements can affect subsequent monitoring and control decisions (Gurban and Andreescu, 2018). Similarly, communication performance is commonly evaluated using parameters such as packet delivery ratio, latency, throughput, coverage, signal strength, packet loss, energy consumption per transmission, and network lifetime (Mowla *et al.*, 2023). These indicators demonstrate that sensing and communication performance should be considered together because accurate measurements have limited operational value if information cannot be transmitted reliably and within the time required for effective control.

Beyond data acquisition and transmission, performance evaluation must establish whether reliable information leads to effective environmental regulation and improved resource utilisation. Control performance can be assessed through parameters such as regulation accuracy, steady-state error, overshoot, settling time, disturbance rejection capability, actuator activity, and the ability to maintain environmental variables within desired operating ranges. Shamshiri *et al.* (2018a) associated successful greenhouse automation with the ability to respond effectively to environmental disturbances and changing crop requirements, indicating that control performance should ultimately be interpreted alongside crop outcomes and resource consumption. Energy performance represents another important consideration because technological improvements that increase computational or communication requirements may offset operational savings. Haseeb *et al.* (2020) identified energy efficiency as a key criterion for IoT- and WSN-based agricultural systems, suggesting that energy consumption should be interpreted relative to factors such as greenhouse area, production duration, crop yield, and climatic conditions. Similarly, Ficili *et al.* (2025) identified productivity and resource-use efficiency as important indicators of intelligent greenhouse performance, requiring assessment of yield, crop quality, water and fertiliser efficiency, and labour reduction rather than technical performance alone.

Comparative assessment should further extend beyond short-term technical demonstrations to include economic feasibility and environmental sustainability. Installation cost, operational expenditure, maintenance requirements, return on investment, payback period, life-cycle cost, equipment replacement, water conservation, renewable-energy contribution, and greenhouse-gas emissions provide important indicators of long-term viability. Shaheen *et al.* (2024) linked sustainability assessment with resource conservation and environmental performance, while Nawalany *et al.* (2024) demonstrated the relationship between greenhouse technologies, resource optimisation, environmental impact, and economic performance. However, meaningful comparison across published studies remains challenging because investigations often differ in greenhouse structure, crop type, climatic conditions, experimental duration, system scale, and reported performance metrics. Future evaluation frameworks should therefore encourage greater consistency in performance reporting, standardised comparison criteria, and crop-specific as well as multi-season validation. Such an evidence-based approach enables smart greenhouse systems to be evaluated not merely by the successful operation of individual technologies, but by their ability to deliver reliable, resource-efficient, economically practical, and sustainable cultivation outcomes.

6. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant advances in IoT, WSNs, cloud–edge computing, and intelligent automation, the transition from experimental smart greenhouse technologies to reliable and large-scale deployment remains incomplete. Shaheen (2024) identified persistent challenges associated with energy efficiency, communication reliability, cybersecurity, and system integration, while Ficili *et al.* (2025) emphasised the continuing need for more intelligent and autonomous agricultural systems. In addition, much of the available evidence is still derived from prototypes, short-term experiments, and controlled environments, creating uncertainty regarding long-term reliability, scalability, economic feasibility, and practical sustainability. Addressing these limitations requires a shift from isolated technological improvements towards integrated, validated, and deployable smart greenhouse systems capable of operating effectively under realistic cultivation conditions.

6.1 Key Research Gaps

Several interconnected technological limitations continue to restrict the scalability and sustained operation of smart greenhouse systems, particularly in relation to energy autonomy, communication resilience, interoperability, and large-scale network deployment. Battery-powered IoT and WSN nodes remain constrained by the continuous energy requirements of sensing, processing, and wireless communication, with communication activities representing a significant proportion of network energy consumption (Liu *et al.*, 2022). Although reducing sampling frequency and transmission rates can extend network lifetime, such approaches may reduce data availability and delay control responses, creating a fundamental balance between energy conservation and real-time environmental management. Communication reliability is also affected by signal attenuation, interference, greenhouse structures, humidity, and increasing sensor-node density. Although redundant communication paths can improve network resilience, they may introduce additional routing complexity and energy demand. Furthermore, heterogeneous devices, proprietary platforms, incompatible communication protocols, and inconsistent data formats continue to limit seamless integration across smart greenhouse architectures (Fischer *et al.*, 2020). These challenges become increasingly significant as systems transition from laboratory prototypes to commercial-scale deployment, highlighting the need for energy-efficient, interoperable, and resilient architectures validated under realistic greenhouse conditions.

Beyond communication and infrastructure challenges, important research gaps remain in sensor reliability, cybersecurity, performance benchmarking, economic assessment, and long-term validation. Environmental exposure, contamination, ageing, and calibration drift can progressively affect measurement accuracy (Belgacem and Chihi, 2025), while maintaining long-term data reliability still requires effective calibration procedures and maintenance strategies (Aarif *et al.*, 2025). Although approaches such as sensor fusion, self-calibration, fault detection, and redundancy offer potential solutions, their effectiveness throughout complete cultivation cycles remains insufficiently validated. Increased connectivity also exposes greenhouse systems to cybersecurity risks (Yazdinejad *et al.*, 2021), while the limited computational capability of many IoT devices restricts the implementation of complex security mechanisms (Shaheen, 2024). More broadly, meaningful comparison among existing studies remains difficult because reported results are influenced by differences in crop type, greenhouse structure, climatic conditions, system scale, experimental duration, and evaluation criteria. Future research should therefore prioritise standardised technical and agricultural benchmarks, economic and life-cycle assessments, and long-term crop-specific field validation to determine whether improvements reported in sensing, networking, and automation can be sustained under practical operating conditions.

6.2 Emerging Technologies and Research Priorities

Emerging technologies are increasingly focused on addressing current limitations in prediction capability, computational responsiveness, energy autonomy, and communication reliability within smart greenhouse systems. Artificial intelligence and machine-learning approaches can exploit historical and real-time environmental data to predict greenhouse conditions, crop requirements, and resource demand, thereby supporting adaptive and increasingly autonomous management (Hemal *et al.*, 2025; Abioye *et al.*, 2022; Ficili *et al.*, 2025). However, their practical effectiveness depends on the availability of representative datasets, model generalisation capability, interpretability, and adequate computational resources. Edge intelligence provides a complementary solution by transferring time-sensitive processing closer to sensors and actuators, reducing latency and dependence on continuous cloud connectivity. Integrated cloud–edge architectures can consequently combine rapid local control with the analytical capability of cloud platforms for large-scale data management and advanced modelling (Kalyani *et al.*, 2023; Yu *et al.*, 2025). Similarly, energy-harvesting technologies offer opportunities for improving sensor-node autonomy by utilising locally available renewable energy sources, although variability in energy availability, conversion efficiency, and storage capacity remain important practical limitations (Khernane *et al.*, 2024). Emerging communication technologies such as 5G may support low-latency and high-density agricultural connectivity (Tang *et al.*, 2021), while future 6G systems may provide further improvements in intelligent communication and massive connectivity. Nevertheless, infrastructure availability, deployment cost, rural connectivity limitations, and technological maturity remain barriers to widespread agricultural adoption.

Research is also expanding towards digital twins, lightweight cybersecurity solutions, and more autonomous greenhouse operation. Digital twins integrate real-time sensing with virtual representations of greenhouse and crop processes, enabling prediction of system behaviour and evaluation of management strategies before physical implementation (Shaheen, 2024; Ficili *et al.*, 2025). However, their effectiveness depends on model accuracy, sensor reliability, continuous updating, and validation against real crop responses. As greenhouse systems become increasingly connected and autonomous, lightweight encryption, authentication, intrusion detection, and access-control mechanisms will become essential for protecting resource-constrained IoT infrastructures (Yazdinejad *et al.*, 2021). Blockchain-based approaches may provide additional support for data integrity and traceability in selected applications, although their suitability remains dependent on computational requirements, scalability, interoperability, and implementation complexity (Morchid *et al.*, 2025). Collectively, these developments suggest that future research should focus not simply on increasing technological sophistication, but on demonstrating measurable improvements in autonomy, responsiveness, security, energy efficiency, interoperability, and crop performance through long-term validation under realistic greenhouse conditions.

6.3 Next-Generation Smart Greenhouses

The findings of this review suggest that future smart greenhouses should progress beyond the integration of individual technologies towards coordinated, crop-responsive, and adaptive system architectures. Reliable sensing should provide accurate and spatially representative environmental information, while interoperable communication frameworks should support seamless data exchange among diverse devices and platforms. Energy-aware networking and energy-harvesting approaches can improve operational longevity, whereas edge intelligence can process time-critical information close to sensors and actuators, allowing cloud platforms to focus on large-scale analytics, historical data management, and predictive modelling. These capabilities should operate alongside adaptive control strategies and lightweight cybersecurity mechanisms to enhance autonomy without compromising reliability or system security. Importantly, technology selection should be guided by crop requirements, greenhouse scale, climatic conditions, available infrastructure, and economic feasibility rather than by technological complexity alone.

Within this framework, next-generation smart greenhouses should combine sensor reliability, energy awareness, interoperability, edge intelligence, cybersecurity, adaptive control, crop responsiveness, and economic viability into a unified operational model. Their success should therefore be evaluated not only through technical indicators such as sensing accuracy, communication latency, network lifetime, and control response, but also through crop yield and quality, water and energy efficiency, operating costs, and environmental impact. Digital twins and predictive intelligence could further enhance decision-making by allowing alternative management strategies to be assessed before implementation, while cloud–edge architectures can distribute computational tasks according to urgency and complexity. However, the practical value of these integrated systems must ultimately be demonstrated through standardised evaluation frameworks, economic and life-cycle assessments, and long-term multi-season trials under realistic greenhouse conditions. Future smart greenhouse research should therefore move beyond demonstrating individual technological capabilities and focus on establishing how coordinated technological ecosystems can deliver reliable, scalable, resource-efficient, and sustainable crop production.

7. CONCLUSION

This review has synthesised recent developments in IoT- and WSN-enabled greenhouse monitoring and control, highlighting the close relationship among environmental requirements, sensing infrastructure, communication networks, computing architectures, control strategies, and energy management. The reviewed literature demonstrates that no single technological configuration can satisfy all smart greenhouse requirements simultaneously. Instead, system performance depends on balancing competing factors, including communication range, energy consumption, latency, reliability, scalability, computational capability, and implementation cost. Consequently, effective greenhouse automation requires the coordinated selection and integration of sensing, networking, computing, and control technologies according to crop requirements, greenhouse characteristics, climatic conditions, available infrastructure, and operational objectives.

The evolution of smart greenhouse systems reflects a transition from conventional monitoring and reactive control towards integrated, data-driven, and increasingly autonomous management frameworks. However, greater technological complexity does not necessarily translate into improved greenhouse performance unless supported by reliable operation, appropriate deployment strategies, and practical validation. The ultimate value of these systems should therefore be assessed through their ability to improve crop productivity, resource-use efficiency, operational reliability, economic feasibility, and environmental sustainability under realistic cultivation conditions. Future research should focus on developing integrated and adaptive architectures, combining renewable-energy solutions with intelligent energy management, strengthening interoperability and security, and establishing long-term evaluation frameworks that demonstrate how advances in sensing, connectivity, computing, and automation can deliver scalable and sustainable improvements in greenhouse production.

Acknowledgements

The authors wish to acknowledge both the Tertiary Education Trust Fund (TETFund) and Management of Federal University of Technology, Akure (FUTA), for their administrative and institutional support throughout the course of this research.

Author Contributions

BAI: Conceptualisation, methodology, literature search, data curation, formal analysis, and writing; JJP: Supervision, communication technologies, methodology, validation, and critical review; KFA: Control and monitoring systems, validation, and editing; OPA: Agronomic expertise, validation, and editing. All authors read and approved the final manuscript.

Funding: This work was supported by TETFund through the 2025–2026 Institution-Based Research (IBR) Grant awarded to the Federal University of Technology, Akure, Nigeria through the award letter with reference FUTA/CRD/TETF/IBR/26/24 and Grant Number: TETF/DRandD/CE/UNI/AKURE/IBR/2026.

Data Availability: Not applicable.

Declarations

Ethics Approval and Consent to Participate: Not applicable.

Consent for Publication: All authors have read and approved the final version of this manuscript and consent to its publication in this journal.

Competing Interests: The authors declare no competing interests.

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