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Designing an Environmental Sensor-Based Automated Greenhouse Roof System

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Abstract

This community engagement study developed an environmental sensor-based automated greenhouse roof system for a community-based agricultural tourism site in Mojokerto Regency, East Java, Indonesia. An applied engineering design method combined with a participatory design approach was used through five stages: existing-condition assessment, partner requirement analysis, conceptual design, detailed mechanical and control-system design, and design validation. The resulting system integrates environmental sensing, control, and mechanical actuation subsystems. Temperature and rainfall were selected as the principal environmental inputs, while a controller determines three operational responses: opening, closing, or maintaining the roof position. Mechanical movement is generated by a linear actuator connected to the roof panel through a linkage and pivot mechanism. The design emphasizes operational simplicity, mechanical safety, maintainability, accessibility of components, and suitability for educational demonstration. Stakeholder involvement ensured that technical specifications reflected actual operational needs and the greenhouse's dual productive-educational function. The validated design provides a technical basis for subsequent fabrication, installation, calibration, and field-performance testing. The study indicates that context-appropriate greenhouse automation can support both protected cultivation and technology-based learning in community agricultural tourism while avoiding unnecessary technical complexity.

Keywords: *Automated greenhouse, Environmental sensing, Agricultural tourism, Linear actuator, Participatory design.*

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INTRODUCTION

The development of greenhouse technology has become increasingly important in supporting controlled agricultural production under fluctuating environmental conditions. Modern greenhouse systems integrate sensing, automation, environmental monitoring, and intelligent control to improve the management of temperature, humidity, ventilation, and other microclimatic variables that influence plant growth (Shamshiri et al., 2018; Badji et al., 2022). Recent advances in the Internet of Things (IoT), multisensor systems, and data-driven control have further strengthened the capacity of greenhouses to continuously identify environmental changes and respond through automated mechanisms (Bicamumakuba et al., 2025; Hernandez-Morales et al., 2023). These technological developments demonstrate that greenhouse automation has evolved from conventional environmental protection toward integrated systems capable of supporting more efficient, adaptive, and sustainable agricultural management.

Environmental sensing constitutes a fundamental component of greenhouse automation because reliable control decisions depend on accurate information regarding prevailing microclimatic conditions. Sensor-based systems enable continuous measurement of important parameters and provide the data required by controllers to determine appropriate operational responses (Bhujel et al., 2020; Rezvani et al., 2020). IoT-based monitoring has additionally facilitated real-time communication among sensors, controllers, and greenhouse equipment, thereby increasing the responsiveness of protected cultivation systems to dynamic environmental conditions (Sagheer et al., 2020; Soheli et al., 2022). Nevertheless, the effectiveness of environmental monitoring ultimately depends on the ability of the system to convert sensor information into physical actions that can directly modify greenhouse conditions.

Ventilation represents one of the principal mechanisms through which greenhouse temperature and humidity can be regulated, particularly when environmental conditions change rapidly. Automated roof or vent operation can reduce dependence on continuous manual intervention and enable ventilation responses to be initiated according to predetermined environmental criteria (Guesbaya et al., 2023). Studies on controlled environment agriculture indicate that intelligent control strategies can improve microclimate regulation while also contributing to more efficient energy utilization (Chen et al., 2022; Jamshidi et al., 2024). Consequently, an effective automated greenhouse requires not only accurate sensing and appropriate control logic but also a dependable mechanical mechanism capable of repeatedly executing opening and closing movements.

Despite the rapid advancement of smart-greenhouse research, much of the existing literature emphasizes sensor networks, IoT connectivity, predictive models, data processing, and intelligent control rather than the practical integration of mechanical roof-opening mechanisms. Reviews of greenhouse technologies show that sophisticated monitoring and decision-making systems are increasingly available, yet their practical performance still depends on actuators and physical infrastructure that execute the decisions generated by the control system (Ghiasi et al., 2024; Bicamumakuba et al., 2025). The mechanical subsystem must therefore provide adequate force, suitable movement geometry, structural reliability, operational safety, and durability under repetitive operating conditions. Treating mechanical actuation as an integral part of greenhouse automation is particularly important in applied engineering projects where technical feasibility and maintainability are as significant as computational sophistication.

The suitability of greenhouse automation also depends on the technological and operational context in which the system will be implemented. Highly sophisticated greenhouse systems may deliver advanced environmental management, but excessive technological complexity can create difficulties related to installation, maintenance, component replacement, and user competence, particularly in community-based applications. Low-cost and modular automation platforms have demonstrated that effective environmental monitoring and control can be achieved without relying exclusively on highly complex infrastructure (Soheli et al., 2022). Appropriate system design should therefore balance automation performance with simplicity, accessibility of components, operational reliability, ease of maintenance, and the capacity of local users to understand and operate the technology.

Community participation is equally important when engineering technology is introduced within a locally managed agricultural facility. Participatory design enables stakeholders to communicate operational needs, identify practical constraints, evaluate proposed solutions, and contribute to design decisions before a system is fabricated and implemented (Wacnik et al., 2024). Such involvement can improve the contextual suitability of technical specifications because engineering requirements are derived from actual conditions rather than solely from theoretical assumptions. For an automated greenhouse roof, this approach is particularly relevant because roof movement, environmental inputs, maintenance requirements, component accessibility, and operational procedures must correspond to the capabilities and expectations of the community partner.

The application of greenhouse automation within an agricultural tourism destination creates an additional opportunity because the technology can simultaneously perform productive and educational functions. Agritourism experiences are increasingly associated not only with agricultural products but also with learning, uniqueness, interaction, and direct exposure to agricultural practices, all of which can influence visitor engagement and loyalty (Suhartanto et al., 2020). An automated greenhouse can therefore function as a cultivation facility while providing visitors with an observable demonstration of the relationship between environmental sensing, automated decision-making, and mechanical actuation. This dual role strengthens the relevance of designing a technological system whose operation is sufficiently visible, understandable, and technically appropriate for a community-based agricultural tourism environment.

Based on these considerations, a practical research gap remains in developing an environmentally responsive greenhouse roof system that integrates sensing, control, and mechanical actuation while remaining feasible for community-level implementation. The proposed community engagement program addresses this gap through the design of an automated greenhouse roof in which temperature and rainfall information serve as principal environmental inputs for determining roof-opening, roof-closing, or position-holding responses. The novelty of the program lies not in introducing greenhouse automation as an entirely new technology, but in integrating an appropriate, maintainable, mechanically functional, and demonstrative automation system specifically for an agricultural tourism setting. Accordingly, this study aims to develop and validate the technical design of an environmental sensor-based automated greenhouse roof system as the engineering foundation for subsequent fabrication, installation, calibration, and field-performance evaluation.

METHODS

This community engagement program employed an applied engineering design method combined with a participatory design approach to develop an automated greenhouse roof system that corresponded to the operational needs of the partner. The target of the activity was a community-based agricultural tourism destination in Mojokerto Regency, East Java, Indonesia, with the site manager or operational representative involved as the principal stakeholder during the design process. The activity was implemented through five main stages: assessment of existing conditions, identification and analysis of partner requirements, conceptual system design, detailed mechanical and control-system design, and design validation. Data were collected through direct site observation and semi-structured discussions with the partner to obtain information regarding greenhouse location, intended functions, environmental exposure, operating conditions, maintenance considerations, and the expected educational role of the greenhouse. Stakeholder participation was maintained throughout the design process to ensure that the resulting technical specifications reflected actual field requirements and practical implementation conditions (Wacnik et al., 2024).

The collected qualitative information was analyzed descriptively to formulate technical design criteria covering roof movement, environmental parameters, actuator requirements, mechanical safety, component availability, ease of operation, and maintainability. The engineering design process integrated three principal subsystems, namely environmental sensing, control, and mechanical actuation, with temperature and rainfall serving as the main environmental inputs for determining roof-opening and roof-closing responses. Technical parameters such as estimated roof load, actuator force or torque, linkage configuration, movement requirements, and component specifications were evaluated using basic mechanical engineering calculations and predetermined design criteria, while the control architecture followed established greenhouse automation principles that separate sensing, decision-making, and actuation functions (Tzounis et al., 2017; Ouammi et al., 2020; Soheli et al., 2022). The proposed design was subsequently validated through a review with the partner by comparing its functionality, maintainability, site compatibility, operational simplicity, and educational value against the previously identified requirements. The final output of this stage was a validated technical design comprising the roof-opening mechanism, sensor configuration, actuator selection, control-system architecture, component specifications, and preliminary bill of materials, while fabrication, installation, calibration, and field-performance testing were reserved for the subsequent implementation phase.

RESULTS AND DISCUSSION

Existing Conditions, Partner Requirements, and Technical Design Criteria

The initial assessment showed that the proposed greenhouse was situated within a developing agricultural tourism environment in Mojokerto Regency, East Java, where agricultural production and visitor education were expected to operate simultaneously. This dual function distinguishes the facility from a conventional production-oriented greenhouse because the technological infrastructure must support cultivation while remaining understandable and observable to visitors. Such a configuration is consistent with the broader development of greenhouse systems as controlled cultivation environments whose structural and technological components must be adapted to specific operational objectives (Badji et al., 2022). The assessment therefore established that the automated roof system should not be treated merely as a mechanical improvement, but as an integrated component of the agricultural tourism facility.

Field observations indicated that the proposed cultivation area remained exposed to dynamic outdoor environmental conditions, particularly rainfall, solar exposure, and fluctuations in air temperature. Variations in these environmental parameters are important because greenhouse microclimates are strongly influenced by external climatic conditions and the effectiveness of ventilation and environmental control strategies (Bhujel et al., 2020; Rezvani et al., 2020). Continuous environmental monitoring is therefore required to provide information that can support timely adjustments to the protected cultivation environment. The observed site conditions consequently provided the technical justification for integrating environmental sensors with an automated roof-opening mechanism.

Reliance on manual roof operation was identified as a practical limitation within the intended operating context. Manual operation requires an operator to observe changing environmental conditions and physically adjust the roof whenever ventilation or protection from rainfall is required, thereby increasing dependence on continuous human attention. Comparable challenges have been reported in conventional greenhouse systems, where ventilation openings may still be adjusted manually despite the increasing availability of sensor-based monitoring technologies (Guesbaya et al., 2023). Automation is therefore relevant not simply as a technological enhancement, but as an operational strategy for reducing repetitive manual intervention while improving the responsiveness of the greenhouse to environmental variation.

The need for environmental responsiveness is also closely related to the broader evolution of smart greenhouse management. Modern systems increasingly employ interconnected sensors, controllers, and actuators to provide continuous information about microclimatic conditions and translate those measurements into specific operational actions (Hernandez-Morales et al., 2023; Bicamumakuba et al., 2025). This approach allows environmental control to shift from periodic human observation toward data-supported decision making. In the proposed system, temperature and rainfall were consequently identified as the principal environmental variables for determining whether the roof should open, close, or maintain its existing position.

Discussions with the partner further demonstrated that technological sophistication alone was not considered sufficient for the proposed greenhouse. The system was expected to employ a mechanical configuration that remained relatively simple, used components that could reasonably be accessed for maintenance or replacement, and provided dependable operation under repeated roof movement. This requirement corresponds with the practical orientation of low-cost greenhouse automation, where functional control can be achieved through modular sensing and control architectures without unnecessary technological complexity (Soheli et al., 2022). Maintainability therefore became an essential design consideration alongside automation performance, particularly because the system was intended for a community-based operational environment.

Table 1. Translation of Existing Conditions and Partner Requirements into Technical Design Criteria

Existing condition/identified need	Partner requirement	Technical design implication
Cultivation area is exposed to changing temperature and weather conditions	Environmental conditions should be monitored automatically	Integration of temperature and rainfall sensors
Roof operation would otherwise depend on manual intervention	Roof should open and close automatically	Integration of controller and mechanical actuator
Greenhouse will support crop cultivation	Roof movement must contribute to environmental management	Defined opening, closing, and holding responses
System will be managed in a community-based setting	Components should be accessible for operation and maintenance	Preference for relatively simple and maintainable components
Roof will operate repeatedly	Mechanical system should provide sufficient movement capacity	Actuator, linkage, pivot, and movement limitations must be considered
Greenhouse is part of an agricultural tourism facility	Technology should also be observable and educational	Mechanical movement and system response should be visible to visitors
Uncontrolled mechanical travel may affect safety and durability	Roof movement should remain within defined	Closed and open positions and movement restrictions must be

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	limits	incorporated
Present activity is limited to the design stage	System must be technically prepared for later implementation	Production of validated design, technical specifications, and preliminary component requirements

The translation presented in Table 1 demonstrates that the proposed automation architecture was derived from identified operational problems rather than selected solely on the basis of technological availability. Participatory design literature emphasizes that stakeholder involvement is particularly valuable when user requirements must be converted into engineering specifications that correspond to the actual context of application (Wacnik et al., 2024). In this project, partner discussions helped define requirements concerning automatic operation, maintenance, accessibility of components, safety, and educational value. The resulting criteria consequently provided a structured connection between field conditions and subsequent engineering decisions.

The automatic opening and closing requirement represents the central functional criterion derived from this assessment. Greenhouse ventilation plays an important role in modifying internal environmental conditions, and automated operation can provide more consistent responses than systems that depend exclusively on manual intervention (Shamshiri et al., 2018; Ghiasi et al., 2024). Automated control is particularly relevant when sensor information must be converted into physical changes within the cultivation environment. The proposed roof mechanism therefore requires an actuator capable of executing commands generated by the control subsystem while maintaining mechanically stable movement between predetermined positions.

Operational efficiency also influenced the design requirements because greenhouse environmental management must be achieved without introducing excessive resource consumption or unnecessary operational complexity. Research on controlled-environment agriculture has increasingly emphasized the importance of balancing environmental regulation with efficient use of energy and supporting infrastructure (Chen et al., 2022; Jamshidi et al., 2024). Although the present stage did not measure energy consumption or compare alternative operating strategies experimentally, these considerations reinforce the value of designing a system based on responsive roof ventilation rather than continuous dependence on more energy-intensive mechanical climate-control equipment. The design stage therefore prioritizes a mechanically executable natural-ventilation response whose actual field performance can subsequently be evaluated during implementation.

The agricultural tourism context introduced an additional requirement that extends beyond conventional greenhouse climate management. Visitor experience in agritourism is influenced by learning opportunities, uniqueness, and meaningful interaction with agricultural activities, suggesting that technology can contribute to both operational and educational dimensions of the destination (Suhartanto et al., 2020). An observable automated roof provides a direct illustration of how environmental information can trigger mechanical responses, thereby transforming an otherwise functional greenhouse component into an educational demonstration. The system is therefore designed not only to operate automatically but also to make the relationship among sensing, control, and mechanical movement perceptible within the visitor environment.

The assessment further indicated that mechanical reliability and safety should be incorporated from the design stage rather than addressed only after fabrication. The actuator must provide sufficient capacity to move the roof, while the linkage, mounting arrangement, pivot, and predetermined movement limits must collectively prevent unnecessary mechanical loading during repeated operation. This emphasis reflects the broader argument that greenhouse automation depends not only on sensors and intelligent controllers but also on reliable physical infrastructure capable of executing environmental-control commands (Shamshiri et al., 2018; Ghiasi et al., 2024). Accordingly, actuator capacity, roof movement, mechanical support, maintainability, and movement restriction became interconnected technical criteria for the proposed design.

The first-stage assessment produced a clearly defined set of partner requirements that could be translated into measurable and technically actionable design criteria. The principal requirements comprised automatic roof movement, environmental sensing, adequate mechanical capacity, defined movement limitations, operational safety, ease of maintenance, accessible components, and compatibility with the greenhouse's educational function. These findings establish the conceptual foundation for developing the sensing, control, and actuation architecture discussed in the subsequent section, while avoiding premature claims regarding system performance because fabrication and field testing have not yet been conducted. The present findings therefore represent a validated design basis rather than evidence of operational effectiveness, with implementation, calibration, and performance evaluation reserved for the next stage of the program.

Integrated System Architecture and Automated Greenhouse Roof Mechanism Design

The second stage of the design process focused on translating the previously identified partner requirements into an integrated automated greenhouse roof architecture. The proposed system was structured around three principal functional stages, namely input, process, and output, so that environmental information could be transformed systematically into mechanical roof movement. The input stage represents environmental parameters detected by sensors, the process stage represents evaluation by the control unit, and the output stage represents actuator-driven movement of the roof. This structure is consistent with greenhouse automation frameworks in which environmental sensing, computational decision making, and physical actuation are interconnected as distinct but mutually dependent subsystems (Bhujel et al., 2020; Tzounis et al., 2017). The functional relationship among these three stages and their connection to the mechanical roof actuator is illustrated in Figure 1.

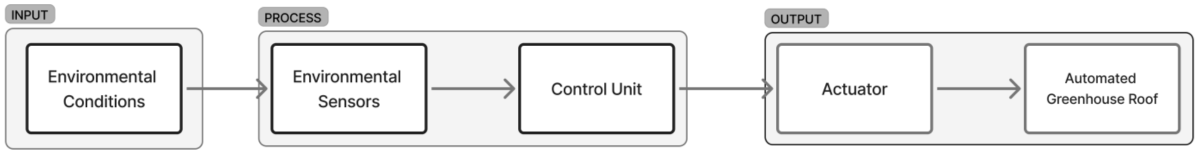

Figure 1. Architecture of the Automated Greenhouse Roof System

As illustrated in Figure 1, the proposed architecture establishes a sequential flow in which environmental conditions are first detected by the sensing subsystem, subsequently evaluated by the control unit, and finally translated into mechanical action through the actuator**.** The separation of sensing, processing, and actuation functions provides an important advantage for system development because each subsystem can be designed, maintained, and modified independently. Sensor devices can be selected according to the environmental parameters of interest, while the control unit can be programmed without requiring fundamental modification of the mechanical roof structure. IoT-based greenhouse research similarly demonstrates that modular architectures facilitate data acquisition, environmental monitoring, and actuator management while allowing system components to be developed according to their individual functional requirements (Sagheer et al., 2020; Hernandez-Morales et al., 2023). Such modularity is particularly relevant for community-oriented systems because component replacement and future technical modification can be undertaken without reconstructing the entire automation platform.

The proposed architecture also reflects the increasing integration of multisensor technologies within smart greenhouse systems. Contemporary greenhouse management increasingly employs multiple environmental sensors to generate continuous information that can support control decisions and improve system responsiveness (Bicamumakuba et al., 2025). More advanced systems may incorporate data fusion, predictive analysis, and intelligent control to determine optimal environmental responses under changing conditions (Rezvani et al., 2020; Ouammi et al., 2020). The present design intentionally adopts a more practical architecture in which the benefits of environmental sensing are retained while unnecessary computational complexity is minimized for community-level implementation.

The mechanical subsystem constitutes the final stage through which the control architecture produces a physical response. In the proposed configuration, a linear actuator is mechanically connected to the roof panel through a linkage and mounting arrangement, allowing linear displacement to be converted into rotational movement around a pivot or hinge. This configuration provides a clear relationship between control-system commands and the physical opening or closing of the greenhouse roof. The design therefore addresses an important practical dimension of greenhouse automation identified in previous research, namely that sensing and control systems ultimately require reliable mechanical equipment capable of executing environmental-control decisions (Shamshiri et al., 2018; Ghiasi et al., 2024). The mechanical relationship among the actuator, connecting linkage, pivot, and movable roof panel is schematically presented in Figure 2.

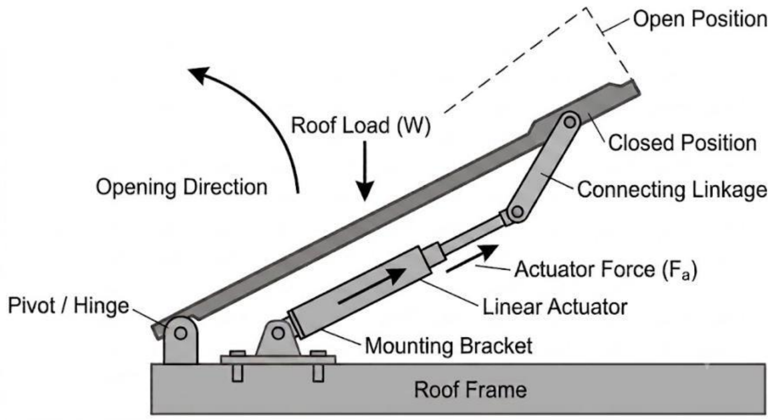

Figure 2. Schematic of the Proposed Automated Greenhouse Roof Opening Mechanism

As shown in Figure 2, linear displacement generated by the actuator is transmitted through the connecting linkage and converted into rotational movement of the roof panel around the pivot point. Two principal roof positions were defined within the design: a closed position and an open position. In the closed condition, the roof panel covers the greenhouse, whereas actuator extension or retraction generates linkage movement that rotates the panel toward or away from the open position. Defining these positions establishes a predetermined mechanical travel range and reduces the need for continuous manual adjustment by the operator. The resulting configuration is compatible with the broader development of automated greenhouse systems in which mechanical ventilation components are operated according to environmental and control-system requirements rather than direct human intervention (Guesbaya et al., 2023; Chantadze, 2026).

Table 2. Functional Integration of the Automated Greenhouse Roof System

System component	Primary function	Design consideration	Expected technical output
Environmental sensors	Detect relevant environmental conditions	Measurement reliability and suitability for greenhouse conditions	Environmental input data
Control unit	Evaluate sensor inputs and generate commands	Simple logic, compatibility, and ease of modification	Open, close, or hold command
Linear actuator	Produce linear mechanical force	Required force, travel distance, operating frequency, and durability	Controlled linear displacement
Connecting linkage	Transfer actuator motion to roof panel	Geometry, force transmission, and structural integrity	Conversion of linear to rotational movement
Pivot/hinge	Provide rotational axis for roof panel	Load capacity and mechanical stability	Controlled roof rotation
Mounting bracket	Secure actuator to fixed structure	Structural support and accessibility	Stable actuator installation
Roof panel	Provide movable enclosure element	Mass, dimensions, movement range, and environmental exposure	Defined open and closed positions
Movement limitation	Prevent excessive travel	Operational safety and protection of mechanical components	Restricted mechanical operating range

Table 2 demonstrates that system performance depends on the coordinated operation of several components rather than on the actuator alone. The sensor and control subsystems determine when movement is required, while the actuator, linkage, pivot, and mounting components determine whether that movement can be performed mechanically. Such integration reflects the principle of smart greenhouse design in which environmental monitoring and control infrastructure must operate as a unified system rather than as independent technological elements (Ghiasi et al., 2023; Soheli et al., 2022). The table also indicates that each component introduces specific engineering requirements that must be considered before fabrication and field implementation.

Actuator selection represents one of the most critical mechanical decisions because the component must generate sufficient force to overcome the moment produced by the roof load and other mechanical resistances. The source design identifies roof mass, actuator position, linkage geometry, required opening angle, and movement limitations as principal parameters for determining actuator capacity. In mechanical terms, the interaction between roof load and actuator force can be evaluated through moment equilibrium around the roof pivot, providing a basis for determining whether the selected actuator can safely produce the required movement. The current study does not report a finalized numerical actuator capacity because actual dimensions and roof mass are intended to be confirmed during implementation, thereby avoiding unsupported performance claims at the design stage.

Energy and operational efficiency further support the use of a mechanically actuated roof as part of the proposed greenhouse design. Contemporary research demonstrates that greenhouse energy management increasingly requires coordination between environmental control objectives and the energy demands generated by heating, cooling, ventilation, and other supporting systems (Chen et al., 2022; Jamshidi et al., 2024). Intelligent environmental regulation can reduce unnecessary operation when control actions are activated only under predefined conditions rather than continuously. The proposed roof mechanism provides a structural basis for such responsive operation, although quantitative energy savings remain outside the scope of the present design-stage activity and require subsequent field evaluation.

Mechanical simplicity was also treated as an important criterion because the system is intended for operation within a community-based agricultural tourism environment. A highly sophisticated actuator configuration could increase technical capability but simultaneously create challenges in maintenance, component replacement, and local troubleshooting. Low-cost greenhouse automation studies demonstrate that effective control systems can be developed using relatively accessible hardware when system architecture is appropriately matched to user requirements (Soheli et al., 2022). The proposed linear-actuator and linkage configuration therefore prioritizes understandable mechanical operation and accessible maintenance while retaining the capability for automatic movement.

The architecture also provides a foundation for future expansion because sensing and control functions can be modified without fundamentally changing the basic mechanical principle. Advanced greenhouse systems increasingly incorporate predictive control, multisensor data processing, and intelligent environmental management, indicating that automation platforms may evolve progressively as operational needs and technical capacity increase (Bicamumakuba et al., 2025; Shojaei-Nia et al., 2026). A modular mechanical system can therefore support future enhancement of the control layer while preserving the principal actuator-linkage-pivot arrangement. This characteristic is important for community technology adoption because it allows technological development to occur incrementally rather than requiring complete system replacement.

The integrated architecture establishes a direct engineering pathway from environmental detection to physical roof movement. The system combines sensors, a control unit, a linear actuator, linkage, pivot, mounting structure, and defined movement limitations to create an automated mechanism that is technically understandable and suitable for subsequent implementation. This configuration responds to the broader transition toward automated controlled-environment agriculture while maintaining the practical considerations of simplicity, maintainability, mechanical safety, and contextual appropriateness emphasized throughout the design process (Shamshiri et al., 2018; Badji et al., 2022; Ghiasi et al., 2024). The resulting mechanical and system architecture consequently provides the structural foundation for the environmental sensing and control logic discussed in the next subsection.

Environmental Sensing, Control Logic, and Implementation Readiness

The environmental sensing subsystem was designed as the primary information source for automated roof operation because the mechanical mechanism requires reliable environmental inputs before any movement command can be generated. Temperature and rainfall were selected as the principal variables because they represent conditions that directly influence the need for greenhouse ventilation and protection from external weather. Temperature provides information concerning the thermal condition within the greenhouse, whereas rainfall indicates an external environmental event that may require the roof to return to its closed position. This configuration is consistent with sensor-based greenhouse management, in which continuous environmental measurements provide the basis for automated control decisions (Bhujel et al., 2020; Rezvani et al., 2020).

The selection of temperature as a principal control variable reflects its importance in maintaining an appropriate greenhouse microclimate. Excessive thermal accumulation can negatively affect plant growth and may require increased ventilation to facilitate heat exchange between the internal and external environments. Contemporary smart-greenhouse systems increasingly employ continuous temperature monitoring as part of integrated environmental management architectures that combine sensing, communication, and automated responses (Hernandez-Morales et al., 2023; Bicamumakuba et al., 2025). The proposed system therefore positions temperature sensing as a functional input for determining whether roof ventilation should be activated under predefined operating conditions.

Rainfall sensing performs a complementary function because roof opening must also consider the possibility of direct precipitation entering the greenhouse. A system that responds exclusively to temperature could create operational risks if ventilation remains active during rainfall, particularly when crop protection and internal environmental stability are required. Multisensor greenhouse technologies address similar problems by combining several environmental variables rather than relying on a single parameter for control decisions (Bicamumakuba et al., 2025; Ghiasi et al., 2024). The integration of temperature and rainfall information consequently provides a more context-sensitive basis for determining roof position than a single-variable control approach.

The proposed control architecture separates environmental detection from decision making and physical actuation. Sensor readings are first transmitted to the control unit, where predefined logical conditions determine whether the system should generate an opening, closing, or holding command. Similar layered architectures are widely employed in IoT-supported agricultural systems because they distinguish data acquisition from computational processing and actuator control (Tzounis et al., 2017; Sagheer et al., 2020). This separation also improves the practical flexibility of the proposed design because sensing parameters or control rules can later be modified without requiring major changes to the mechanical roof mechanism.

The control process begins with continuous environmental monitoring after system activation. Sensor inputs are repeatedly evaluated against predetermined operating criteria before a mechanical response is authorized, thereby preventing the actuator from operating independently of the control system. Decision-support approaches for smart greenhouses similarly emphasize continuous observation and systematic evaluation of microclimatic variables before environmental-control equipment is activated (Ouammi et al., 2020). The proposed control sequence therefore establishes a direct but controlled relationship between environmental measurements and mechanical roof responses. The complete sequence of environmental sensing, condition evaluation, and actuator response is illustrated through the conceptual control logic presented in Figure 3.

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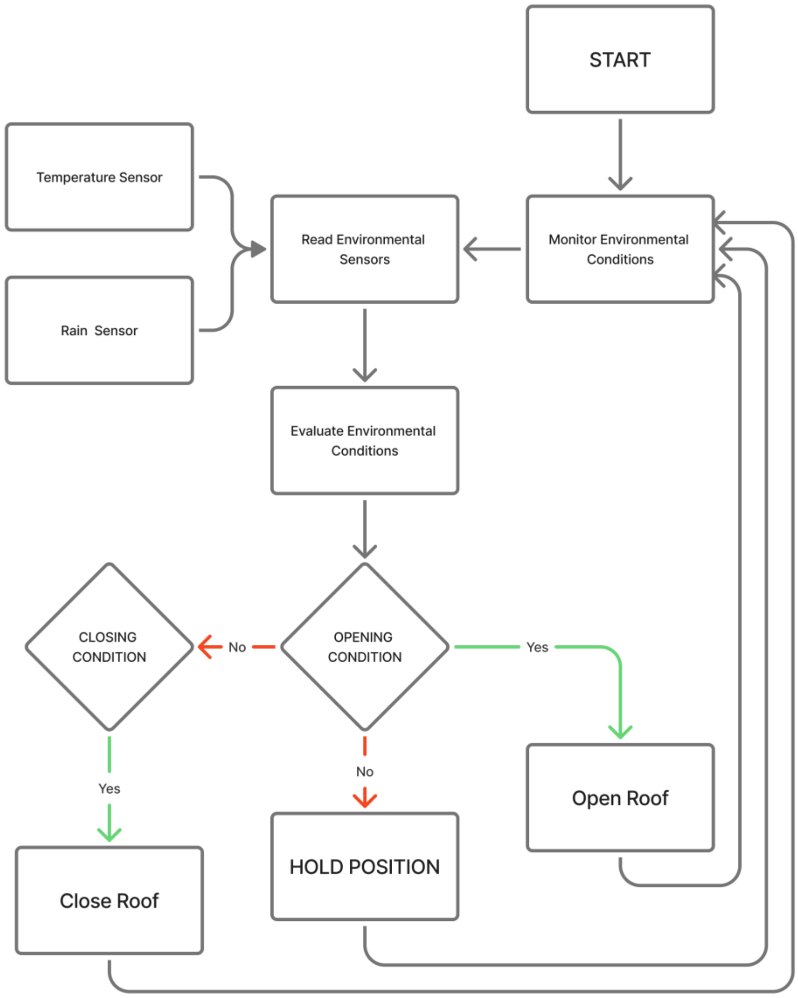

Figure 3. Conceptual Control Logic for Automated Greenhouse Roof Operation

As illustrated in Figure 3, the control process begins with continuous acquisition of temperature and rainfall information, followed by evaluation of predefined operating conditions before an opening, closing, or position-holding command is transmitted to the actuator**.** This sequence ensures that mechanical roof movement is not initiated directly by environmental changes but occurs only after the sensor information has been evaluated by the control unit. The three operational responses consequently establish a simple rule-based mechanism for connecting environmental monitoring with controlled mechanical actuation.

Table 3. Conceptual Environmental Control Logic of the Automated Greenhouse Roof

Environmental/control condition	**Sensor information**	**Control decision**	**Roof response**	**Primary design objective**
Temperature satisfies predefined opening criteria and no closing condition is detected	Temperature sensor indicates opening requirement	Open Roof	Actuator moves roof toward open position	Increase natural ventilation
Rainfall satisfies predefined closing criteria	Rain sensor detects rainfall condition	Close Roof	Actuator moves roof toward closed position	Protect greenhouse interior from precipitation
Environmental conditions satisfy predefined closing	Sensor information indicates closure is	Close Roof	Roof returns toward	Maintain protected

criteria	required		closed position	cultivation condition
Neither opening nor closing criterion is satisfied	Sensor values remain outside trigger conditions	Hold Position	Current roof position is maintained	Avoid unnecessary actuator movement
Environmental condition changes during operation	Updated sensor data are transmitted to controller	Re-evaluate conditions	Command adjusted according to current inputs	Maintain continuous environmental responsiveness
System parameters require modification during calibration	Sensor thresholds or response settings are adjusted	Revised decision rules	Response follows calibrated criteria	Adapt operation to actual field conditions
Mechanical movement reaches predetermined limit	Position/movement condition reaches defined boundary	Stop movement	Roof remains at defined open or closed position	Prevent excessive mechanical travel
System enters subsequent implementation stage	Calibrated sensor and actuator parameters become available	Validate control response	Field-tested roof operation	Evaluate practical system performance

The three-state response of Open Roof, Close Roof, and Hold Position provides a relatively simple control structure suitable for the present design objective. When opening conditions are satisfied, the controller sends a command that activates the actuator and transfers mechanical movement through the linkage to the roof panel, whereas closing conditions cause the reverse response. When neither condition is fulfilled, the current roof position is maintained while environmental monitoring continues, thereby avoiding unnecessary actuator movement and repeated mechanical loading. This logical structure corresponds with greenhouse automation principles in which control actions are triggered selectively according to environmental conditions rather than through continuous mechanical operation (Soheli et al., 2022; Chantadze, 2026).

The simplicity of this control logic is particularly relevant for a community-based agricultural tourism setting because system intelligibility and maintainability are important dimensions of technological appropriateness. Advanced greenhouse environments may employ nonlinear predictive control, artificial intelligence, or highly integrated optimization algorithms to achieve precise environmental regulation (Chen et al., 2022; Shojaei-Nia et al., 2026). Such approaches provide important opportunities for future development, but their computational and maintenance requirements may exceed what is necessary during the initial implementation stage of a community-oriented system. The present design therefore prioritizes an understandable rule-based architecture that can subsequently be expanded if field conditions and partner capabilities justify greater technological sophistication.

The proposed sensing and control configuration may also contribute to more efficient greenhouse operation by activating mechanical responses only when predefined environmental conditions require intervention. Research on smart greenhouse energy management demonstrates that coordinated control strategies can reduce unnecessary operation of environmental-control equipment and improve the balance between crop requirements and energy consumption (Jamshidi et al., 2024). The present study does not quantify energy savings because no fabricated system has yet undergone field testing, and any numerical claim regarding efficiency would therefore be premature. Nevertheless, the use of condition-based actuation establishes an engineering basis for later evaluating whether automated natural ventilation can reduce unnecessary operational effort and energy demand.

Control-system flexibility is another important characteristic because actual operating thresholds cannot be determined conclusively before installation and calibration under field conditions. The specific temperature threshold, rainfall detection criterion, sensor sampling interval, actuator response time, and safety interlocks remain parameters to be established during the subsequent implementation stage. This approach is methodologically consistent with applied greenhouse design, where preliminary system architecture is commonly followed by calibration, performance evaluation, and optimization under actual environmental conditions (Badji et al., 2022; Ghiasi et al., 2023). The present stage therefore defines the functional logic and subsystem relationships without presenting unverified parameter values as completed experimental results.

The educational function of the system further strengthens the relevance of a visible relationship between environmental sensing and roof movement. In an agricultural tourism context, automated mechanical responses can become part of the visitor learning experience because they demonstrate how environmental data are translated into practical engineering actions. Research on agritourism indicates that learning and uniqueness contribute significantly to visitor experience and loyalty, suggesting that observable agricultural technology can provide value beyond its production function (Suhartanto et al., 2020). The proposed greenhouse thus combines environmental management with a demonstrative function in which visitors can understand the interaction among sensing, control logic, and mechanical actuation.

The third design component completes the integration of the environmental, computational, and mechanical layers of the proposed automated greenhouse roof system. The resulting concept establishes temperature and rainfall sensing as environmental inputs, a controller as the decision-making element, and a linear-actuator roof mechanism as the physical output, while retaining flexibility for calibration and future intelligent-control development. The design is consistent with the transition toward sensor-integrated and increasingly intelligent controlled-environment agriculture while preserving the practical requirements of accessibility, maintainability, modularity, and community participation emphasized in the present project (Shamshiri et al., 2018; Wacnik et al., 2024; Bicamumakuba et al., 2025). Consequently, the completed design stage provides a technically grounded basis for subsequent fabrication, installation, sensor calibration, actuator testing, and field-performance evaluation without claiming operational effectiveness before such empirical validation has been conducted.

CONCLUSION

The community engagement program successfully produced a validated technical design for an environmental sensor-based automated greenhouse roof system tailored to the operational requirements of a community-based agricultural tourism site. The proposed design integrates three principal subsystems consisting of environmental sensing, control, and mechanical actuation, with temperature and rainfall serving as the main environmental inputs. A linear actuator, linkage, pivot, and supporting structure were designed to translate control commands into automated roof-opening and roof-closing movements, while the control logic provides three operational responses: open, close, and hold position. The resulting configuration emphasizes mechanical reliability, operational safety, maintainability, component accessibility, and technological simplicity, thereby providing an appropriate engineering solution for community-level implementation.

The integration of automation technology with the educational function of agricultural tourism represents an important contribution of the proposed system because the greenhouse can simultaneously support protected cultivation and demonstrate the relationship between environmental sensing, automated decision making, and mechanical movement. Stakeholder participation throughout the design process also ensured that the technical specifications corresponded to actual operational needs and site conditions. Nevertheless, the present activity was limited to assessment, system development, and design validation; therefore, no claims regarding operational performance, energy efficiency, environmental-control effectiveness, or crop productivity can yet be established. Subsequent implementation should focus on fabrication, installation, sensor and actuator calibration, safety verification, and field-performance testing to determine the technical reliability and practical effectiveness of the proposed system under actual operating conditions.

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