# MINISTRY OF EDUCATION, CULTURE AND RESEARCH

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# Department of Software Engineering and Automation

# IoT-Greenhouse Climate Control

# FINAL REPORT

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**Abstract**

Greenhouse farming in Moldova is increasingly affected by extreme weather events such as droughts, frosts, and floods, putting pressure on food production and sustainability. This paper introduces a smart climate control system based on Internet of Things (IoT) technology, designed to help farmers better manage the internal environment of their greenhouses. The system continuously monitors key factors like temperature, humidity, CO₂ levels, and air circulation, and adjusts them in real time to support optimal plant growth and reduce energy waste. Built with affordability and practicality in mind, it includes a mobile interface that allows farmers—especially those operating small and medium-sized farms—to access and control the system remotely. Field testing in Moldovan conditions showed clear improvements in environmental stability and crop resilience. The key innovation lies in adapting advanced IoT tools to local agricultural realities, offering a scalable, user-friendly solution. Given the growing impact of climate change in Moldova, this topic is highly relevant and timely for the future of sustainable agriculture in the region.

***Keywords:*** *Agricultural IoT (AgIoT), Temperature Regulation, Humidity Control, Climate, Monitoring, Sensor Networks, Crop Monitoring Systems, Smart Greenhouse Management*

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# 1. Problem definition

**1.1 Problem definition:**

Effective climate control in greenhouses is crucial for optimizing plant growth and maximizing crop yields. This task is particularly challenging in the Republic of Moldova due to the country's high vulnerability to unexpected climate variations. Moldova experiences significant socio-economic impacts from climate-related hazards such as droughts, floods, late spring frosts, and hail. These environmental challenges complicate the management of key greenhouse parameters, including temperature, humidity, light intensity, CO levels, and air circulation. The increasing frequency and severity of extreme weather events necessitate the development of adaptive climate control strategies tailored to Moldova's specific conditions. Balancing these factors to meet the diverse needs of various crops, while ensuring energy efficiency and sustainability, adds to the complexity. Addressing these issues is essential for enhancing the resilience and productivity of greenhouse agriculture in Moldova.

# 2. Analysis in Agricultural IoT: Smart Greenhouse Management

**2.1 Introduction to Smart Greenhouse Management and Agricultural IoT**

Greenhouses stand as foundational pillars of modern agriculture, providing a meticulously controlled environment where growers can precisely manipulate conditions to optimize plant growth, extend growing seasons, and build greater resilience against the increasing unpredictability of global climate patterns. At the very heart of this controlled environment lies climate control—the intricate art and science of managing pivotal environmental factors such as temperature, humidity, light intensity, and air movement. The objective is to consistently create and maintain the perfect conditions for optimal plant development and productivity. The ongoing convergence of advanced technologies, particularly the Internet of Things (IoT) and artificial intelligence (AI), is profoundly transforming traditional greenhouse management practices. This technological synergy is enabling unprecedented levels of precision, operational efficiency, and environmental sustainability within agricultural systems.

The imperative for such advancements is underscored by demographic projections. Research conducted by the United Nations Food and Agriculture Organization (FAO) indicates a global population forecast to reach approximately 9.73 billion people by the year 2050 [1]. This significant demographic expansion translates directly into a heightened demand for food, necessitating a fundamental shift in agricultural practices to ensure global food security. Traditional farming methods, often constrained by land availability, water scarcity, and climatic volatility, are increasingly insufficient to meet these burgeoning demands. Smart greenhouse management, powered by Agricultural IoT (AgIoT), offers a viable and scalable solution to bridge this impending gap.

(Insert Fig 1: Diagram Illustrating the Structure and Controlled Environment of a Smart Greenhouse System here)

As shown in Figure 1, a greenhouse, fundamentally, is a structure, often with a transparent or translucent roof and walls, specifically designed for the cultivation of crops under controlled conditions. These structures are far more sophisticated than their traditional counterparts. They typically integrate a network of sensors, actuators, and communication systems to create an autonomous or semi-autonomous growing environment. This precise control over environmental variables, including temperature, humidity, and light, is crucial for maximizing both the quantity and quality of food production. The inherent ability of greenhouses to shield crops from the unpredictable and frequently harsh realities of the external climate makes greenhouse agriculture a compelling and increasingly necessary approach. For instance, the implementation of controlled environments can lead to a substantial increase in crop yields, with reports indicating a rise of 10-12% depending on the specific crop and greenhouse system in question. This yield improvement is a direct consequence of minimizing environmental stressors, optimizing photosynthetic efficiency, and reducing crop loss due to adverse weather or pests. Furthermore, the capacity for year-round production, independent of local climatic seasons, provides consistent supply chains and improved economic stability for growers. The integration of IoT and AI extends this control further, allowing for dynamic adjustments based on real-time data and predictive analytics, moving beyond static, pre-programmed settings to truly adaptive and responsive cultivation systems.

The integration of IoT technologies in the agri-food sector presents numerous opportunities for enhancing efficiency and productivity. However, several challenges must be addressed to fully realize these benefits. The initial investment required for IoT infrastructure, including sensors, connectivity solutions, and data analytics platforms, can be substantial. This financial barrier may deter small and medium-sized enterprises from adopting IoT solutions. The deployment of IoT devices increases the potential attack surface for cyber threats. Ensuring the security of data transmitted between devices and protecting sensitive information from breaches are critical concerns. The agri-food sector utilizes a diverse range of IoT devices and platforms, often from different manufacturers. Achieving seamless communication and integration between these heterogeneous systems poses a significant challenge. Implementing and maintaining IoT systems requires specialized knowledge in areas such as data analytics, network management, and cybersecurity. There is a growing need for training programs to equip the workforce with these skills.

Research and development efforts are focusing on creating affordable IoT devices and platforms tailored for the agri-food sector. Economies of scale and technological advancements are expected to reduce costs over time. Implementing robust security protocols, such as end-to-end encryption and regular firmware updates, is essential to protect IoT ecosystems from cyber threats. Establishing industry-wide standards for IoT devices and communication protocols can facilitate interoperability, allowing for seamless integration and data exchange between systems. The use of photovoltaic (PV)-based energy to control internal microclimates in greenhouses can reduce energy demand and operational costs associated with artificial lighting. The future of greenhouse production is expected to be defined by the adoption of smart sensors and neural networks, which can enhance environmental control and energy efficiency. By addressing these challenges and focusing on these future directions, the agri-food sector can harness the full potential of IoT technologies to achieve sustainable and efficient agricultural practices.

**2.2 Market Dynamics and Business Impact of Agricultural IoT**

The agricultural Internet of Things (IoT) market is currently experiencing a period of significant expansion, a trajectory fueled primarily by rapid technological advancements and the escalating adoption of smart farming methodologies worldwide. This growth underscores a fundamental shift in how agriculture operates, moving towards more data-driven, efficient, and sustainable practices.

The global agricultural IoT market was valued at approximately USD 11.4 billion in 2021 and is projected to reach USD 18.1 billion by 2026, demonstrating a robust Compound Annual Growth Rate (CAGR) of 9.8%. More recent analyses estimate an even more accelerated expansion, predicting the market will grow from USD 28.65 billion in 2024 to an impressive USD 79.09 billion by 2032, with a significantly higher CAGR of 12.6% [2]. This vigorous growth is propelled by several intertwined primary drivers.

Technological advancements stand as a paramount force behind this market expansion. The widespread integration of IoT-enabled sensors, real-time data analytics platforms, and cloud computing infrastructure has profoundly enhanced the efficiency and productivity of agricultural operations. IoT devices empower farmers with the ability to continuously monitor critical parameters such as soil moisture levels, prevailing weather conditions, the early onset of pest infestations, and overall crop health in real time. This continuous stream of data facilitates highly precise interventions and optimizes resource allocation, moving away from generalized practices to highly targeted actions. The subsequent integration of machine learning (ML) and artificial intelligence (AI) algorithms into these IoT systems further elevates predictive capabilities, enabling more accurate forecasts of potential crop failures, disease outbreaks, and optimal harvest times, thereby enhancing overall yield and reducing risks. Concurrently, the increasing automation in agricultural machinery, which includes the deployment of autonomous tractors, sophisticated agricultural drones for aerial sensing and spraying, and robotic harvesters, has been instrumental in significantly reducing labor costs and further amplifying operational efficiency.

The escalating global food demand, driven by the aforementioned projected world population of 9.7 billion by 2050, constitutes another major contributing factor. This unprecedented population growth places immense pressure on the agricultural sector to substantially increase food production, often despite facing increasingly limited arable land, diminishing water resources, and the pervasive impacts of climate change. IoT applications, particularly within precision farming frameworks, are designed to optimize the utilization of precious resources such as water, fertilizers, and pesticides. This optimization not only reduces waste but crucially maintains or even enhances high productivity levels. Smart irrigation systems, for example, leverage IoT sensors to dynamically adjust water supply based on real-time weather data and instantaneous soil moisture conditions, ensuring highly sustainable water management practices.

Government support and policy initiatives are also key accelerators in the growing adoption of IoT in agriculture. Across the globe, national governments are increasingly recognizing the strategic importance of smart farming technologies for food security, rural development, and environmental sustainability. Consequently, nations are implementing supportive policies and making substantial investments in digital farming initiatives. Financial incentives, including direct subsidies, competitive grants, and dedicated research funding, are being offered to actively promote IoT adoption among farmers. For instance, the European Union's Common Agricultural Policy (CAP) has allocated considerable resources towards fostering digital farming transformations. Similarly, the U.S. Department of Agriculture has launched various programs specifically designed to encourage the widespread implementation of precision agriculture techniques. In Asia, economic powerhouses such as China and India are making significant investments in IoT-based agricultural solutions, explicitly aiming to bolster national food security and improve the livelihoods of their large farming populations.

The ongoing global expansion of 5G connectivity is yet another powerful catalyst for IoT adoption in agriculture. With the increasing deployment and densification of 5G networks, IoT devices are capable of transmitting and processing vast quantities of data at significantly higher speeds and with remarkably lower latency. This enhanced connectivity drastically improves real-time decision-making capabilities, which is particularly beneficial for large-scale commercial farms that rely on continuous and instantaneous monitoring of expansive crop fields and livestock. Advanced connectivity also facilitates sophisticated remote farming solutions, empowering farmers to control irrigation systems, machinery, and sensor networks directly from their smartphones or computers, regardless of their physical location.

Finally, the agricultural IoT market is being substantially propelled by private-sector investment and strategic collaborations. Established agricultural machinery conglomerates, such as John Deere, Trimble, and AGCO, are actively investing in and developing sophisticated IoT-based precision farming technologies, integrating them into their existing product lines. Concurrently, a vibrant ecosystem of Agri-tech startups is emerging, contributing innovative, often more affordable, and highly scalable solutions specifically tailored to address the diverse needs of smaller and medium-sized farms. A compelling illustration of this trend is the development of cost-effective IoT-based soil health monitoring systems, which equip small-scale farmers with the tools to precisely optimize fertilizer use, thereby boosting productivity while concurrently minimizing adverse environmental impacts.

Despite these powerful growth factors, the agricultural IoT market faces distinct challenges, particularly prevalent in developing countries. Issues such as limited access to crucial market information, inadequate digital and physical infrastructure (e.g., reliable internet, electricity), and persistent technological adoption barriers hinder widespread IoT integration. A comprehensive literature review underscores that a lack of readily available market information can lead to inefficient agricultural markets, ultimately resulting in negative socio-economic repercussions for farmers. Regionally, North America and Europe currently lead in agricultural IoT adoption, thanks to robust technological infrastructure and substantial investment. However, the Asia-Pacific region is experiencing exceptionally rapid growth in this domain, driven by its escalating population demands and proactive government support for smart farming initiatives. In many developing regions, challenges persist due to limited connectivity and underdeveloped agricultural infrastructure. Nevertheless, various international and local initiatives are actively being introduced and implemented to bridge the digital divide and vigorously promote the adoption of IoT-driven agricultural solutions. The agricultural IoT market is unequivocally poised for sustained and robust growth, catalyzed by continuous technological innovations, proactive government policies, and surging private sector investments. Addressing the persistent challenges in developing regions through targeted infrastructure development, robust capacity building programs, and accessible financial mechanisms will be crucial to ensuring that the transformative benefits of IoT in agriculture are globally realized.

Изображение выглядит как текст, снимок экрана, Шрифт, число

Содержимое, созданное ИИ, может быть неверным.

**Fig 2:** Predicted Global Market Size for Agricultural IoT (2022-2032), Highlighting Predicted Growth

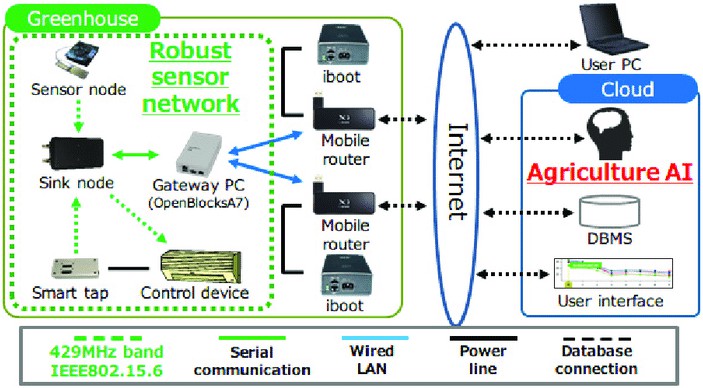
As can be further observed, the projected market size of the Internet of Things (IoT) in agriculture from 2022 to 2032, measured in billions of U.S. dollars, illustrates a consistent and strong upward trend. This data, originating from Precedence Research, clearly indicates a steady increase in market value over the years. Starting at USD 13.61 billion in 2022, the chart depicts consistent annual growth, forecasting a substantial expansion. The gradual yet persistent rise in market value directly reflects the increasing and widespread adoption of IoT technologies across the agri-food sector. This growth is primarily driven by ongoing advancements in smart farming practices, the continuous refinement of precision agriculture techniques, and the optimization of agricultural supply chains. The escalating investments in IoT-based solutions across the industry underscore a clear and accelerating shift towards data-driven decision-making, increased automation, and a strong commitment to long-term sustainability within the agricultural domain.

**2.3 Environmental Factors and Advanced Climate Control Technologies**

Successful greenhouse agriculture fundamentally hinges on the meticulous understanding and management of various environmental factors that critically influence crop yield, quality, and overall profitability. Even within the ostensibly controlled confines of a greenhouse, these factors interact dynamically, demanding sophisticated control mechanisms.

**2.3.1 Environmental Factors and Their Impact**

Temperature is an undisputed cornerstone of plant physiological processes, acting as a primary driver for growth, development, and metabolic rates. As highlighted by Kittas et al. [3], temperature fluctuations within greenhouse environments can often be more extreme and rapid compared to open field conditions, particularly in the absence of robust and responsive climate control systems. Elevated temperatures, especially those exceeding a plant's optimal range, can induce significant heat stress. This stress manifests as a reduction in photosynthetic efficiency, impaired nutrient uptake, and a compromised ability to set fruit or produce viable seeds. Conversely, sub-optimal or excessively low temperatures can severely impede vegetative growth, leading to chilling injury in sensitive crops, and simultaneously increasing susceptibility to various diseases. While optimal temperature ranges are inherently crop-specific, a general range of 20-28°C is broadly suitable for a vast array of greenhouse crops. Therefore, maintaining consistent and precise temperatures through integrated heating, cooling, ventilation, and shading strategies is paramount for maximizing yields and ensuring healthy plant development.



**Fig 3** Architecture of greenhouse environmental control system based on SW-SVR.

Light, encompassing its intensity, quality (spectrum), and duration, is unequivocally vital for photosynthesis, the fundamental process through which plants convert light energy into chemical energy for growth. Insufficient light levels can severely restrict plant growth, leading to elongated stems (etiolation), pale foliage, and significantly reduced yields. Conversely, excessive light intensity, particularly during sensitive growth stages, can cause photobleaching, leaf scorch, and other forms of physiological damage. Modern greenhouses frequently employ supplemental lighting systems, especially during periods of naturally low light or shorter daylight hours, to ensure plants receive their optimal Daily Light Integral (DLI). Artificial lighting technologies provide growers with the unparalleled ability to manipulate not only light intensity but also its spectral composition and duration. This allows for precise tailoring of light conditions to influence specific growth stages, such as promoting vegetative growth, initiating flowering, or enhancing fruit development. Beyond artificial supplementation, strategic management of natural light through the deployment of retractable shading screens or the application of reflective whitewash coatings can further optimize light distribution and mitigate excessive solar radiation within the greenhouse structure.

Humidity, specifically the water vapor content in the air, directly impacts plant transpiration, which is the process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems and flowers. Transpiration drives nutrient uptake and cools the plant. High relative humidity can significantly reduce the rate of transpiration, potentially leading to nutrient deficiencies if water flow through the plant is too slow. Furthermore, persistently high humidity creates an ideal microclimate for the proliferation of fungal diseases and pathogens. Conversely, excessively low humidity levels can cause rapid water loss from plant tissues, leading to wilting, desiccation, and reduced growth. Maintaining optimal humidity levels, typically within a range of 50-70% for most crops, is critical for healthy plant function. Sophisticated ventilation systems, fogging, misting, and humidification units are indispensable tools for regulating humidity within the greenhouse environment, ensuring a healthy balance.

Water availability and quality are fundamental prerequisites for successful crop cultivation. Efficient irrigation systems must deliver adequate water to plant roots without causing waterlogging, which can lead to root rot and anaerobic conditions, or excessive nutrient leaching, which depletes the growing medium of essential elements. Beyond mere quantity, water quality is paramount. Factors such as pH, electrical conductivity (EC), and the presence of dissolved solids or contaminants directly impact nutrient availability and plant uptake. Advanced irrigation practices, such as precision drip irrigation or hydroponic recirculating systems, are designed to minimize water waste, ensuring that water and dissolved nutrients are delivered directly to the root zone, thereby enhancing resource efficiency.

Air circulation within a greenhouse is often an overlooked yet critical environmental factor. Proper air movement is essential for achieving uniform temperature and humidity distribution throughout the growing space, preventing the formation of stagnant air pockets where humidity can build up and pathogens can thrive. It also plays a crucial role in disease prevention by reducing condensation on leaf surfaces and aiding in pollination. Strategically placed fans and comprehensive ventilation systems are employed to improve air movement and ensure that environmental conditions are consistent across the entire crop area. Furthermore, efficient air circulation is vital for evenly distributing supplemental carbon dioxide (CO2​) within the greenhouse, ensuring that all plants have access to this critical component for enhanced photosynthesis.

Effectively managing these interconnected environmental factors in greenhouse agriculture demands a comprehensive and integrated approach. This involves the synergistic deployment of various technologies, including precise climate control systems, supplemental lighting, advanced irrigation infrastructure, and CO2​ enrichment systems, all working in concert to create the most optimal conditions. Continuous monitoring through sensor networks and dynamic adjustment of practices based on real-time data are indispensable for achieving consistently high yields and superior product quality. Further dedicated research into the complex interactions between these factors and their specific effects on diverse crop varieties is continuously needed to refine and advance greenhouse management practices.

**2.3.2 Climate Control Methods and Technologies**

Climate control in greenhouse agriculture is a multifaceted and indispensable aspect of modern crop production, requiring a diverse array of technologies to precisely manage temperature, humidity, light, and CO2​ levels. The successful integration of these technologies through sophisticated automation and control systems is paramount for achieving optimal growing conditions, maximizing yields, and minimizing resource consumption. Future research and development should prioritize the creation of more energy-efficient and sustainable climate control strategies, the seamless incorporation of renewable energy sources, and the advanced utilization of data analytics to further optimize greenhouse operations.

Heating systems are fundamental in many regions to maintain optimal temperatures, particularly during colder months or at night. A variety of methods are employed. Fossil fuel heaters, while highly effective in providing rapid heat, contribute significantly to greenhouse gas emissions, raising environmental concerns. Electric heating offers precise temperature regulation and clean operation, but its cost-effectiveness is heavily dependent on local electricity prices. Infrared heaters present an innovative alternative, as they directly warm plants and surfaces rather than heating the surrounding air. This targeted approach can lead to lower energy consumption compared to conventional air heating systems. For long-term sustainability, utilizing geothermal energy provides a highly efficient and renewable heating source in geologically suitable locations. Similarly, harnessing solar energy through either passive design (e.g., thermal mass, strategic orientation) or active systems (e.g., solar thermal collectors) can substantially reduce reliance on conventional, non-renewable heating methods.

Just as critical as heating, cooling systems are essential to prevent heat stress and maintain ideal temperatures during warmer periods or intense solar radiation. Natural ventilation, facilitated by strategically placed roof and side vents, allows for the passive exchange of hot internal air with cooler external air, driven by convection and wind pressure. Mechanical ventilation, conversely, employs powerful fans to actively exhaust hot air and draw in cooler outside air, providing more controlled airflow. Evaporative cooling techniques, such as fogging, misting, and pad-and-fan systems, function by reducing air temperature through the latent heat of water evaporation. As water evaporates, it absorbs heat from the surrounding air, creating a cooling effect. Shading systems, including retractable screens or temporary whitewash coatings applied to the greenhouse exterior, are effective in limiting the amount of solar radiation that penetrates the structure, thereby reducing heat gain. While air conditioning offers the most precise control over both temperature and humidity, it is notoriously energy-intensive and typically reserved for high-value crops or specific climatic requirements.

Maintaining proper humidity is equally essential for robust plant health and the prevention of disease. Humidity control strategies often involve ventilation to effectively remove excess moisture from the greenhouse atmosphere. Conversely, humidification techniques, which include fogging, misting, or integrating evaporative cooling systems, can be employed to raise humidity levels when the air is too dry, preventing excessive transpiration. Dehumidifiers, specifically designed to remove moisture from the air, are particularly important in preventing the proliferation of fungal diseases which thrive in high-humidity environments.

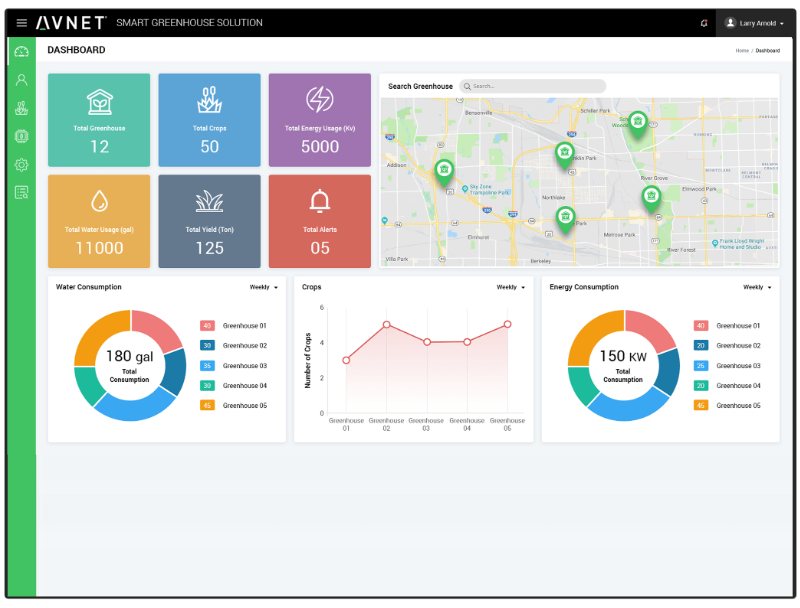
Supplemental lighting is widely used to extend the effective growing season or significantly enhance crop growth rates, particularly in regions with limited natural light or during shorter daylight periods. Historically, high-intensity discharge (HID) lamps, such as high-pressure sodium (HPS) and metal halide lamps, have been the traditional choice. While effective, these lamps are less energy-efficient and generate considerable heat. In stark contrast, light-emitting diodes (LEDs) offer superior energy efficiency, unparalleled longevity, and, critically, the ability to fine-tune the light spectrum emitted. This spectral tunability allows growers to precisely match light wavelengths to specific plant needs, influencing photomorphogenesis, accelerating growth, or enhancing particular plant characteristics, making LEDs increasingly prevalent in modern greenhouse lighting.

Contemporary greenhouses utilize highly sophisticated automation and control systems to manage this diverse range of climate control technologies in a fully coordinated and often intelligent fashion. These systems rely on extensive networks of sensors that continuously monitor critical environmental parameters, including temperature, relative humidity, light intensity, CO2​ concentration, soil moisture, and other relevant variables. Based on either pre-defined setpoints or dynamic, real-time data received from these sensors, the central control systems automatically trigger adjustments to heating, cooling, ventilation, lighting, and other integrated systems. Advanced control algorithms, often incorporating principles of proportional-integral-derivative (PID) control or even predictive models, can optimize energy consumption by integrating real-time sensor data with external factors like weather forecasts, predicted plant physiological needs, and energy pricing. This level of automation empowers growers to remotely monitor and control greenhouse conditions via mobile devices or computers, providing unparalleled flexibility and responsiveness.

Effective climate control frequently necessitates the synergistic integration of multiple technologies. For example, a cutting-edge greenhouse might combine passive natural ventilation with active evaporative cooling and supplemental LED lighting, meticulously calibrated to achieve optimal conditions while minimizing overall energy consumption. The integration of renewable energy sources, such as solar photovoltaic (PV) systems or geothermal energy, directly into climate control systems is absolutely crucial for the long-term sustainability of greenhouse agriculture. Furthermore, the burgeoning use of advanced sensors coupled with sophisticated data analytics tools can further refine climate control strategies, leading to marked improvements in resource use efficiency. The ongoing development of "smart" control systems capable of autonomously adapting to dynamic environmental conditions and evolving plant needs remains a key and active area of research, pushing the boundaries of what is possible in precision agriculture.

**2.4 Implementation Challenges and Sustainability in Greenhouses**

The implementation of effective climate control systems in greenhouses is undeniably essential for optimizing plant growth and ensuring sustainable agricultural practices. However, this complex endeavor is frequently accompanied by a range of significant challenges that must be comprehensively addressed to achieve the desired outcomes and unlock the full potential of smart greenhouse technology.



**Fig 3** Example of remote monitoring and control system

**2.4.1 Implementation Challenges**

Climate control in modern greenhouses extends far beyond merely maintaining optimal temperature and humidity levels. It encompasses the intricate management of light intensity and spectrum, precise CO2​ concentration, and efficient water availability, alongside nutrient delivery. The inherent complexity of these interconnected factors necessitates a holistic and highly coordinated approach to greenhouse management, often requiring multidisciplinary expertise.

One of the most significant challenges is the substantial initial investment and the complex integration of advanced technologies into existing or new greenhouse operations. The adoption of Internet of Things (IoT) devices, sophisticated sensor networks, and advanced automation systems can profoundly enhance climate control by providing real-time monitoring and dynamic adjustments. For instance, networks of environmental sensors can continuously track temperature, humidity, and light levels, enabling automated systems to precisely adjust ventilation, heating, and shading in real-time. However, integrating these cutting-edge technologies requires not only substantial financial investment for hardware and software but also specialized technical expertise for installation, calibration, and ongoing maintenance. This financial and knowledge barrier can be a significant deterrent for many greenhouse operators, particularly small and medium-sized enterprises (SMEs). Smaller operations may simply lack the necessary capital or technical acumen required to implement and effectively maintain these complex systems. Additionally, the inherent complexity of these integrated systems can lead to unforeseen technical issues, requiring specialized troubleshooting and potentially increasing maintenance requirements, which could disrupt operations and lead to losses in valuable crop yield.

Another persistent challenge arises from the inherent variability of external environmental conditions. Unpredictable and often extreme temperature fluctuations, along with erratic humidity levels caused by external weather patterns, can negatively impact plant growth and lead to reduced yields if not effectively managed. While advanced climate control systems leveraging sensors and automation are designed to monitor and regulate these factors, their implementation can be complex and costly. Moreover, existing greenhouse infrastructure may require extensive and costly modifications to accommodate modern climate control technologies. This can pose significant logistical challenges, especially for established greenhouses that were not originally designed with the demands of modern, integrated climate management in mind.

Beyond technological and infrastructural hurdles, the critical issue of energy consumption cannot be overlooked. Climate control systems, especially those that heavily rely on heating, cooling, and supplemental lighting, can consume substantial amounts of energy. This directly translates into high operational costs and significantly contributes to the greenhouse gas emissions associated with agricultural practices. To mitigate this critical issue, there is a growing and urgent emphasis on integrating renewable energy sources, such as solar photovoltaic (PV) panels or geothermal systems, directly into greenhouse designs and energy supply chains. By strategically harnessing renewable energy, greenhouse operators can significantly reduce their reliance on fossil fuels, thereby promoting more sustainable and environmentally responsible agricultural practices.

Furthermore, climate change itself poses a significant and evolving threat to agriculture, including even highly controlled smart greenhouse systems. Increasingly frequent and intense changes in global weather patterns, such as prolonged heatwaves, extreme cold snaps, or altered precipitation regimes, can directly affect the effectiveness and efficiency of existing climate control systems. This necessitates continuous adaptation and often leads to increased operational costs. For example, more frequent and severe heatwaves may require the enhancement or complete overhaul of cooling systems, while increased rainfall could lead to challenges with waterlogging and significantly impact internal humidity levels. Addressing this overarching challenge necessitates the development of more resilient climate control systems and the strategic incorporation of predictive analytics to anticipate and proactively mitigate the adverse impacts of climatic variability.

Finally, training and education represent critical components for the successful implementation and long-term efficacy of advanced climate control systems. Greenhouse operators and their staff must be adequately equipped with the necessary knowledge and practical skills to effectively manage sophisticated climate control technologies. This includes a comprehensive understanding of how to interpret complex data streams from monitoring systems, how to make informed and timely decisions based on real-time information, and how to troubleshoot potential issues quickly. Additionally, fostering robust collaboration among academic researchers, technology providers, and frontline greenhouse operators can greatly facilitate knowledge sharing, promote the adoption of best practices, and accelerate innovation in greenhouse climate management.

In conclusion, while advanced climate control systems offer profound benefits for greenhouse operations, their successful implementation is fraught with considerable challenges. Addressing these challenges requires careful and strategic planning, significant investment in cutting-edge technology and comprehensive training programs, and an ongoing, adaptive approach to changing environmental and market conditions. By systematically overcoming these obstacles, greenhouse operators can substantially enhance productivity, improve profitability, and make a vital contribution to more sustainable and resilient agricultural practices globally. The future trajectory of greenhouse agriculture will undeniably depend on the successful and synergistic integration of advanced technology, diversified renewable energy sources, and agile, adaptive management strategies to cultivate truly resilient and highly efficient growing environments.

**2.4.2 Energy Efficiency and Sustainability in Greenhouses**

Greenhouses, while integral to modern agriculture for providing controlled environments that boost crop production, are often energy-intensive. This characteristic raises considerable concerns regarding their long-term sustainability and the significant operational costs involved. Consequently, recent research has intensively focused on improving energy efficiency and vigorously promoting sustainable practices within greenhouse operations, aiming for a more environmentally benign and economically viable cultivation model.

One critical aspect of enhancing greenhouse sustainability centers on the judicious selection of appropriate covering materials. The choice of covering material profoundly influences not only the internal microclimate but also the overall energy consumption of the facility. A comprehensive study rigorously evaluating various greenhouse covering materials underscored the paramount importance of considering both their environmental impact and their energy efficiency characteristics. Materials such as polyethylene films and rigid polycarbonate panels were meticulously assessed for their thermal properties (insulation capabilities, heat retention) and their life cycle impacts (manufacturing energy, recyclability, degradation). This research provides invaluable insights for optimizing greenhouse design and making informed material selections that balance initial cost with long-term energy savings and environmental footprint reduction.

In climatically challenging regions, such as Murcia, Spain, where agriculture represents a significant economic activity and water scarcity is a concern, implementing highly effective energy efficiency strategies in greenhouses has yielded promising results. Researchers in these areas have thoroughly explored a diverse range of measures, including the precise optimization of climate control systems, the enhancement of structural insulation, and the strategic integration of renewable energy sources. These targeted interventions have demonstrably led to substantial reductions in energy consumption. More importantly, they contribute directly to ecological sustainability, aligning seamlessly with regional environmental conservation goals and broader climate action plans.

A comprehensive review specifically examining energy use patterns in European Union greenhouses further accentuates the immense potential of systematically adopting energy efficiency measures and extensively utilizing renewable energy sources [4]. This seminal study strongly recommends a suite of practices, including: significantly improving greenhouse insulation (e.g., double-layer coverings, thermal screens), deploying highly energy-efficient heating and cooling systems (e.g., heat pumps, evaporative coolers), and strategically incorporating solar panels (photovoltaic and thermal) into the greenhouse energy supply. The overarching objectives of these recommended strategies are multifaceted: to reduce heavy dependency on finite non-renewable energy sources, to significantly lower greenhouse gas emissions associated with cultivation, and thereby to enhance the overall sustainability profile of greenhouse operations, ensuring their viability in a future marked by increasing environmental scrutiny and resource constraints.

In conclusion, advancing energy efficiency and sustainability in greenhouse operations necessitates a comprehensive, multifaceted approach. This involves a synergistic combination of selecting environmentally sound and energy-efficient materials, meticulously implementing cutting-edge energy-efficient technologies, and strategically integrating renewable energy sources. By committing to these intertwined efforts, greenhouse agriculture can evolve into a more sustainable, economically viable, and environmentally responsible model. These efforts are not merely desirable; they are crucial for meeting the rapidly growing global demand for food while simultaneously minimizing the ecological footprint of food production.

**2.4.3 IoT Device Domain and Edge Computing in Greenhouse Systems**

The integration of Internet of Things (IoT) devices and the strategic implementation of edge computing paradigms have fundamentally revolutionized modern agriculture, particularly within greenhouse systems. This powerful technological synergy enables unprecedented levels of precise environmental control, highly efficient resource utilization, and ultimately, significantly enhanced crop yields. This technological framework facilitates real-time monitoring of dynamic conditions within greenhouse environments and enables immediate, data-driven responses.

IoT sensors are the pivotal components in the architectural landscape of smart greenhouse systems, serving as the primary instruments for capturing critical environmental data. These intelligent sensors are meticulously designed to monitor a diverse array of parameters, including ambient temperature, relative humidity, soil moisture content, light intensity (and sometimes spectrum), and crucially, carbon dioxide (CO2​) levels. For instance, precision temperature and humidity sensors continuously provide data that is absolutely essential for maintaining optimal climatic conditions, directly influencing vital plant processes such as respiration, transpiration, and overall growth rates. Soil moisture sensors deliver immediate insights into irrigation needs by accurately measuring the volumetric water content in the soil or substrate, ensuring that plants receive adequate hydration without the detrimental effects of overwatering or underwatering. Light sensors precisely assess the intensity and duration of light exposure, enabling intelligent adjustments to artificial lighting systems to supplement natural light as needed, thereby ensuring optimal Photosynthetically Active Radiation (PAR) for photosynthesis. Furthermore, CO2​ sensors vigilantly monitor gas concentrations, facilitating the precise regulation of ventilation systems to maintain optimal CO2​ levels conducive to maximizing photosynthetic efficiency. The continuous, high-resolution data stream generated by these pervasive sensor networks provides a comprehensive and granular understanding of the intricate greenhouse microclimate, empowering growers with the actionable intelligence necessary for informed decision-making and exceptionally precise environmental control.

Complementing the sensory input, actuators and various hardware components within greenhouse systems are directly responsible for executing the precise control actions mandated by the analysis of sensor data, thereby ensuring the continuous maintenance of desired environmental conditions. Common actuators include powerful fans for ventilation, responsive heaters for temperature augmentation, automated ventilation systems (e.g., roof vents, side vents), precision irrigation valves for water delivery, and dynamic shading devices for light management. For example, when temperature sensors detect an excessive heat buildup, actuators are intelligently activated to open vents or engage cooling fans, facilitating the rapid removal of hot air and ingress of cooler air. Conversely, during periods of lower temperature, heating elements or systems may be automatically engaged to sustain optimal temperatures within the growing environment. This closed-loop system of sensing, data analysis (often on the edge), and automated actuation creates a highly responsive and self-regulating environment, minimizing human intervention and maximizing efficiency.

The strategic deployment of edge computing in greenhouse systems offers significant advantages. Instead of sending all raw sensor data to a centralized cloud server for processing, edge devices (small computers located directly at the greenhouse site) perform data analysis and decision-making locally. This approach drastically reduces data latency, allowing for near-instantaneous responses to rapidly changing environmental conditions. For instance, if a sudden temperature spike is detected, the edge device can immediately trigger cooling systems without the delay of transmitting data to the cloud and waiting for a response. Edge computing also enhances data security and privacy by processing sensitive agricultural data locally, reducing the need for constant data transmission over networks. Furthermore, it improves system reliability, as operations can continue even if the internet connection to the cloud is temporarily disrupted. The ability to filter and pre-process data at the edge before sending only relevant information to the cloud significantly reduces bandwidth requirements and cloud storage costs, making the entire system more cost-effective and scalable for large-scale greenhouse operations. This distributed intelligence allows for more robust, efficient, and responsive smart greenhouse management.

The future of greenhouse production is increasingly expected to be defined by the widespread adoption of highly intelligent sensors, combined with the power of neural networks and advanced AI algorithms. This integration will further enhance environmental control capabilities, moving towards truly autonomous and predictive systems. Moreover, the focus on energy efficiency will intensify, with more greenhouses incorporating renewable energy sources and advanced energy management systems to minimize their environmental footprint and operational costs. The continuous evolution of IoT and edge computing technologies will be pivotal in driving these advancements, ensuring that greenhouse agriculture remains at the forefront of sustainable and productive food production for a growing global population.

# 3. Business Case Analysis and Stakeholder management

## Business Case Analysis

Climate control technology in greenhouses has transformative applications across multiple industries. Primarily, it is critical in commercial agriculture, where optimized growing conditions ensure year-round production of high-value crops like tomatoes, cucumbers, and leafy greens, independent of external weather. This technology also intersects with horticulture and floriculture, enabling nurseries to cultivate delicate ornamental plants and flowers under precise humidity, temperature, and light conditions. Beyond agriculture, the pharmaceutical and biotechnology sectors leverage climate- controlled greenhouses for growing medicinal plants or conducting research on genetically modified organisms (GMOs) requiring stable environments.

Additionally, urban farming initiatives and vertical farming startups integrate advanced climate systems to maximize space efficiency in cities, addressing food security challenges.

The technology also supports academic and governmental research, where institutions study climate resilience in crops or simulate future environmental scenarios. For example, universities use sensor-based systems to analyze plant responses to controlled stressors, aiding in climate adaptation strategies. Lastly, renewable energy companies collaborate with greenhouse operators to integrate solar or geothermal systems, creating sustainable closed-loop environments. These cross-sector applications highlight the versatility of climate control systems in addressing productivity, sustainability, and innovation.

###### Climate Control Technology in Greenhouses: Key Applications

Climate control systems are revolutionizing agricultural and industrial practices by enabling precise environmental management. Below is an expanded analysis of their transformative applications:

* 1. **Commercial Agriculture**: Advanced climate control technology allows growers to optimize conditions for high-value crops such as tomatoes, cucumbers, and leafy greens, ensuring consistent yields regardless of external weather fluctuations. By integrating IoT sensors and automated ventilation systems, greenhouses maintain ideal CO levels (800–1,200 ppm), temperatures (18–25°C), and humidity (60–80%), directly enhancing photosynthesis rates and crop quality [4]. For instance, Dutch greenhouse operations have achieved a 20–30% increase in tomato yields by dynamically adjusting light spectra and humidity to match plant growth stages [4]. These systems also reduce water consumption by recycling condensation and employing precision drip irrigation, addressing resource scarcity in arid regions.
  2. **Ornamental Plant Cultivation**: The $13.3 billion U.S. floriculture industry relies on climate-controlled environments to cultivate delicate species like orchids and roses, which demand strict humidity (70–85%) and temperature (15–22°C) parameters [4]. Advanced LED lighting systems, tuned to specific wavelengths, accelerate blooming cycles and enhance pigmentation in ornamental plants. For example, chrysanthemum growers use blue-light-dominant spectra to shorten stem elongation, producing compact, market-ready plants [4]. Such precision minimizes crop loss and enables year-round production, meeting global demand for cut flowers and decorative plants.
  3. **Pharmaceutical and Biotechnology Research**: Climate-controlled greenhouses provide sterile, stable environments for cultivating medicinal plants like *Artemisia annua* (used in malaria treatment) and genetically modified organisms (GMOs). Researchers maintain stringent conditions— such as 22–25°C temperatures and HEPA-filtered air—to ensure consistent alkaloid production in medicinal species [4]. Biotechnology firms also use these facilities to study plant responses to environmental stressors, such as drought or high salinity, accelerating the development of climate- resilient crop varieties.
  4. **Urban Vertical Farming**: In cities, climate-controlled vertical farms repurpose warehouses and high-rises into multi-layered agricultural hubs. These systems combine hydroponics, aeroponics, and dynamic HVAC systems to achieve space efficiency, producing up to 10 times more yield per square meter than traditional farms [4]. For instance, Singapore’s Sky Greens uses rotating vertical tiers with automated climate adjustments to grow leafy greens using 95% less water than soil-based farming. Such innovations address urban food deserts while reducing transportation- related carbon emissions.
  5. **Renewable Energy Integration**: Modern greenhouses increasingly pair climate control systems with renewable energy solutions to achieve sustainability. Geothermal heat pumps, for example, stabilize root-zone temperatures in nurseries while reducing heating costs by 30–50% [5]. Solar-powered trigeneration systems—which simultaneously produce electricity, heating, and cooling—enable net-zero energy operations. Ahamed’s [6] research demonstrates that solar-assisted greenhouses can achieve 60–80% energy autonomy in Mediterranean climates, significantly lowering reliance on fossil fuels.

### Resource Efficiency Optimization

|  |  |
| --- | --- |
| **Resource Category** | **Efficiency Metrics** |
| Water Usage | 10-20 L/kg fresh weight (GH) vs 1 L/kg (VF) |
| Energy Consumption | 4.5-10.5 kWh/kg (GH) vs 15.6-20.4 kWh/kg (VF) |
| CO Utilization | 14-26 kg CO/kg dry weight (GH) vs 2.1 kg CO/kg dry weight (VF) |
| Land Use | 365 days/year production capability |
| Harvest Frequency | 6-7 harvests/year (GH) vs 8-12 harvests/year (VF) |

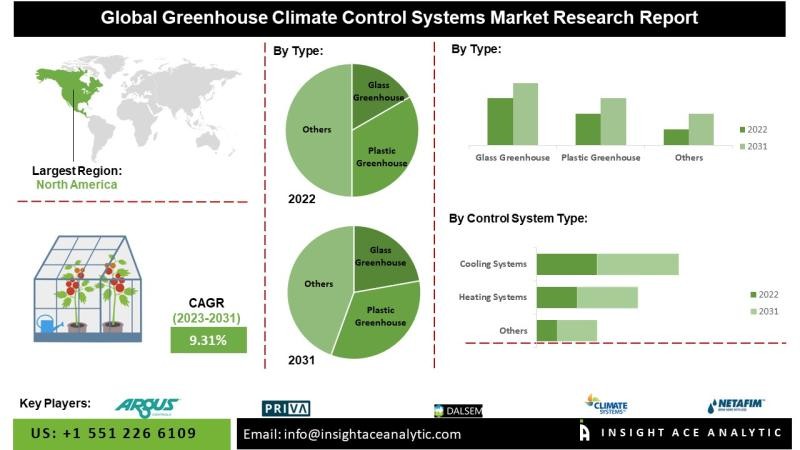
**Table 1** Climate control systems enable significant resource optimization

### 3.2 Analysis of Use Cases and Benefits

In commercial agriculture, climate control technology enhances yield consistency through automation. For example, IoT-enabled systems adjust ventilation and irrigation in real time, reducing water usage by up to 90% compared to traditional methods [4]. Vertical farms leverage these systems to achieve ultra- efficient resource use, requiring only 1 liter of water per kilogram of produce [4].

Such precision is critical in water-scarce regions and aligns with global sustainability goals. The integration of renewable energy further amplifies benefits. Geothermal heat pumps in nurseries reduce heating costs by 30–50% while maintaining stable root-zone temperatures [5], whereas solar-powered trigeneration systems enable net-zero energy greenhouses by combining electricity, heating, and cooling production [6]. These innovations not only lower operational costs but also minimize reliance on fossil fuels.

Urban farming initiatives demonstrate scalability, with climate-controlled warehouses producing hyper-local crops year-round, cutting transportation emissions, and addressing food deserts [4]. Similarly, pharmaceutical firms rely on stable environments to ensure consistent quality in plant-derived drug ingredients, reducing contamination risks [4]. Collectively, these applications highlight the technology’s role in advancing productivity, sustainability, and resilience across industries.



**Fig 5** Greenhouse Climate Control Systems Market Current Scenario with Forecast to 2031

The provided image effectively visualizes the greenhouse climate control systems market landscape, presenting a comprehensive overview of the industry's current state and future projections. The infographic communicates the market's growth trajectory, showing a projected CAGR of 9.31% through 2031[7], while effectively breaking down market segments and their relationships. The visualization makes complex market data accessible through its structured layout and clear visual elements, making it an invaluable resource for industry stakeholders and researchers.

The visualization effectively presents both market opportunities and challenges, from urbanization trends and population growth to technical complexity and adoption barriers. It provides a complete picture of the market's current scenario and future outlook, making it a valuable tool for strategic planning and market analysis. The infographic's structured presentation effectively communicates the industry's growth trajectory and key influencing factors, offering a clear roadmap for understanding the greenhouse climate control systems market's development through 2031

## Stakeholder Identification

The stakeholders involved in climate control within greenhouses in Moldova include greenhouse farmers and owners, agricultural cooperatives, consumers of greenhouse products, agricultural technology providers, the Moldovan Ministry of Agriculture and Regional Development, research institutions such as the State Agrarian University of Moldova, environmental protection agencies, energy providers, and local municipalities.

Greenhouse farmers and owners are selected because they are directly impacted by the efficiency of climate control, with their profitability heavily dependent on it, and they serve as the primary users and investors in climate control technologies. As noted by Stratan et al. (2021), the adoption of modern technologies, including climate control systems, is crucial for increasing the competitiveness of Moldovan agricultural producers [1]. Agricultural cooperatives are included due to the prevalence of cooperative farming in Moldova, where they act as intermediaries influencing technology adoption and market access. According to Stratan et al. (2020), cooperatives play a significant role in the development of the agricultural sector in Moldova, particularly in facilitating access to resources and markets for smallholder farmers [2].

Consumers of greenhouse products are relevant because they are interested in the quality, affordability, and sustainability of the produce, driving market demand for climate-controlled agriculture. As discussed in the MDPI article by Toderi et al. (2021), consumer preferences in Moldova are increasingly shifting towards high-quality, locally produced, and sustainably grown food, which can be achieved through controlled environment agriculture [3]. Agricultural technology providers are chosen for their role in developing and supplying climate control systems and related technologies, thus driving innovation and technology adoption. The Moldovan Ministry of Agriculture and Regional Development is included as they set agricultural policies and regulations, and provide funding and support for agricultural development. Research institutions are selected for their role in researching optimal climate control practices and providing scientific expertise and knowledge transfer.

Environmental protection agencies are included due to their concern for the environmental impact of greenhouse operations, ensuring compliance with environmental regulations. Energy providers are chosen as they supply energy for heating, cooling, and lighting in greenhouses, influencing energy costs and sustainability. Local municipalities are relevant because they regulate land use and may be involved in local agricultural projects, wielding local influence over farmers.

Looking at the table, it's easy to see how many different groups have a stake in how well greenhouses operate in Moldova. First off, you've got the farmers themselves – they're the ones making the day-to-day decisions, so they've got the most say. Naturally, they're worried about making a profit, growing good crops, and keeping costs down. Then there are the cooperatives. Since a lot of Moldovan farmers work together.

|  |  |  |
| --- | --- | --- |
| **Stakeholder** | **Interests** | **Influence** |
| Greenhouse Farmers/Owners | Profitability, crop yield, energy efficiency, cost reduction | High (direct decision-makers) |
| Agricultural Cooperatives | Member profitability, market access, technology adoption | Medium-High (collective influence) |
| Consumers | Product quality, affordability, sustainability | Medium (market demand) |
| Agricultural Technology Providers | Market share, product innovation, sales growth | Medium-High (technology supply) |
| Moldovan Ministry of Agriculture and Regional Development | Agricultural development, food security, policy implementation | High (policy and funding) |
| Research Institutions | Knowledge dissemination, technological advancements, sustainable practices | Medium (expertise and research) |
| Environmental Protection Agencies | Environmental compliance, sustainable resource use | Medium (regulations and monitoring) |
| Energy Providers | Energy sales, infrastructure development, renewable energy adoption | Medium (energy supply and costs) |
| Local Municipalities | Local economy, land usage, local agricultural projects | Medium (local regulations) |

**Table 2** Stakeholders table

They're trying to sell their products and come up with new ideas. The government plays a big role in setting the rules and giving out money. They're focused on ensuring Moldova has enough food and that farming is done right. You've also got the researchers, who are figuring out the best ways to do things, and the environmental folks, making sure everything's done sustainably. The energy companies and local town halls also have their parts to play, whether it's providing power or managing local resources. It's a whole network of people and groups, all with their reasons for caring about how well greenhouses work. They all influence each other in different ways.

In Moldova, the agricultural sector holds significant importance, with greenhouse farming playing a crucial role in ensuring year-round production. Energy costs represent a critical factor in greenhouse operations, making energy efficiency a primary concern. Furthermore, government support and alignment with European Union standards are key drivers for agricultural development within the country.

## Stakeholder Mapping

## 

**Fig 6** Greenhouse Stakeholder Mapping

The stakeholder mapping diagram was carefully designed to reflect the relative influence and interest of each Moldova group in greenhouse climate control. The positioning of each stakeholder on the matrix is based on their role, impact, and engagement with climate control technologies. Greenhouse farmers and owners were placed in the high-interest, high-influence quadrant because they are the primary decision-makers regarding climate control adoption. Their financial success and crop productivity are directly tied to the efficiency of these systems, making them the most invested stakeholders. Their influence is high because their choices determine market supply and technology adoption rates. Agricultural cooperatives were positioned slightly lower in influence but still in the high-interest category.

They serve as intermediaries, supporting farmers in accessing technology, funding, and markets. While they do not directly control technological decisions at an individual level, their collective influence in encouraging or discouraging adoption is significant, thus placing them near the high-influence zone. Consumers of greenhouse products were placed in the medium-interest, medium-influence area. While they do not directly influence operational decisions, their purchasing behavior shapes market trends. A growing demand for sustainable and high-quality food drives producers toward controlled environment agriculture. However, their influence remains moderate since they do not have direct control over greenhouse operations. Agricultural technology providers were positioned in the high-influence, medium-interest quadrant. They drive innovation and supply critical equipment, shaping how greenhouses operate. While their primary interest is profit and market expansion rather than direct greenhouse management, their technological advancements significantly impact farming efficiency and environmental sustainability.

The Moldovan Ministry of Agriculture and Regional Development was placed in the high-influence, medium-interest category. As a governmental entity, its policies, subsidies, and regulations directly shape agricultural development. However, its focus spans multiple agricultural sectors, meaning climate control in greenhouses is a priority but not the sole concern. Research institutions, such as the State Agrarian University of Moldova, were placed in the medium- influence, medium-interest quadrant. They contribute knowledge and technological advancements but do not have direct decision-making power over greenhouse operations. Their interest is driven by research opportunities and innovation rather than direct financial gains. Environmental protection agencies were positioned in the medium-influence, medium-interest section.

They regulate sustainable farming practices and monitor environmental compliance, but their direct influence on greenhouse technology adoption is indirect. They enforce standards rather than actively shape operational decisions. Energy providers were placed in the medium-influence, medium-interest category as well. They supply essential resources for climate-controlled agriculture, and their pricing structures and energy policies affect operational costs. However, they do not directly dictate greenhouse management strategies, and their interest in climate control is primarily related to energy demand rather than agricultural outcomes. Local municipalities were positioned in the medium-influence, medium-interest quadrant. They regulate land use and support agricultural initiatives at a regional level. While they have some say in permitting and incentives, their direct involvement in greenhouse climate control remains limited compared to farmers, cooperatives, or government ministries. Overall, the stakeholder map was designed to reflect a balanced distribution of power and interest, ensuring that every entity's role and impact on climate control in greenhouses is represent

# 3.2 Stakeholder workshop - Interview & Survey

## Introduction: The Importance of Interviews and Surveys in Understanding Climate Control in Greenhouses

Climate control is a critical factor in the success of greenhouse farming, directly influencing crop yield, quality, and resource efficiency. For farmers and greenhouse owners, managing temperature, humidity, light, and other environmental variables is essential to creating optimal growing conditions.

However, the challenges and practices associated with climate control vary widely depending on factors such as location, crop type, and available technology. To gain a comprehensive understanding of these dynamics, interviews and surveys play a vital role. They provide firsthand insights into the experiences, needs, and preferences of stakeholders, including farmers, technology providers, consultants, and policymakers. By collecting this data, we can identify gaps in current practices, explore opportunities for innovation, and develop solutions that are both practical and impactful.

Interviews and surveys are particularly valuable for uncovering the real-world challenges faced by greenhouse operators. For instance, understanding how farmers monitor and adjust climate conditions, the limitations of existing technologies, and the financial constraints they face can guide the development of more user-friendly and cost-effective solutions. Additionally, these tools allow us to explore the adoption of emerging technologies, such as IoT-based systems, which have the potential to revolutionize greenhouse management. By asking targeted questions about current practices, technological readiness, and financial concerns, we can assess the barriers to adoption and design strategies to overcome them.

Moreover, engaging with a diverse range of stakeholders—from farmers and technology providers to government representatives and financial institutions—ensures a holistic perspective on climate control in greenhouses. Each group brings unique insights, whether it’s the practical challenges faced by farmers, the technical expertise of providers, or the policy and financial frameworks offered by governments and lenders. Through interviews and surveys, we can bridge these perspectives, fostering collaboration and innovation to create sustainable, efficient, and accessible climate control solutions for the future of greenhouse farming.

## List of question for Stakeholders

### *For Farmers/Owners of Greenhouses*

###### Current Practices and Technologies:

1. Could you describe your typical workday during different seasons in relation to climate control?
2. What climate-related problems have impacted your crops?
3. How do you monitor and record environmental data (temperature, humidity, wind speed)?
4. What manual tasks related to climate control are most time-consuming?
5. Do you use any automation or technology for climate control? What are the limitations?
6. How do you determine the optimal climate conditions for your crops?

###### Adoption of IoT Technologies:

1. What features would you prioritize in an IoT-based climate control system?
2. How comfortable are you with using mobile apps or web-based dashboards for monitoring and control?
3. What are your thoughts on remote control of your greenhouse? 10. Do you have a reliable internet connection at your greenhouse location?

###### Financial Concerns:

1. What is your current budget for climate control equipment and maintenance?
2. Are you aware of any government subsidies or grants for agricultural technology adoption?
3. How do current energy prices affect your business?

### *For Greenhouse Technology Providers*

###### Current Practices and Technologies:

1. What climate control technologies do you offer for greenhouses?
2. How do you integrate IoT into your systems? Can they be accessed remotely?
3. What are the main technical challenges when implementing these systems?

###### Adoption of IoT Technologies:

1. How do you ensure the reliability and security of IoT devices in greenhouses?
2. What are the most common feedback or concerns from farmers about IoT-based solutions?
3. How do you see the future of automation and IoT in agriculture?

###### Financial Concerns:

1. What are the typical costs involved in setting up IoT climate control systems?
2. How do you handle training and support for less tech-savvy users?
3. Are there financing or leasing options available for farmers?

### *For Agricultural Extension Workers / Consultants*

###### Current Practices and Technologies:

1. How do you support farmers in selecting the right climate control technologies?
2. What common mistakes do farmers make with climate control?
3. How do you assess the effectiveness of a farmer’s current system?

###### Adoption of IoT Technologies:

1. How do you educate farmers about IoT benefits?
2. What do you think is the biggest barrier to adopting IoT technologies?
3. Have you seen any successful IoT adoption examples in greenhouses?

###### Financial Concerns:

1. What are the financial challenges farmers face when adopting new technologies?
2. Are there grants or funding programs available for adopting modern greenhouse technologies?
3. How can farmers balance technology costs with potential benefits?

### For Government Representatives

###### Current Practices and Technologies:

1. What role does the government play in promoting climate control technologies for agriculture?
2. Are there national or regional programs supporting greenhouse farms with technology?

###### Adoption of IoT Technologies:

1. How do you see IoT and automation in agriculture’s future?
2. What policy initiatives are in place to support IoT adoption in greenhouses?
3. Are there regulations governing IoT use in agriculture?

###### Financial Concerns:

1. Are there subsidies, grants, or financial incentives for farmers adopting climate control or IoT technologies?
2. How does the government address rising energy costs for greenhouse operations?
3. What long-term financial strategies help farmers transition to sustainable practices?

### For Financial Institutions / Lenders

###### Current Practices and Technologies:

1. How do you assess the financial viability of farms adopting new climate control or IoT technologies?
2. What financing options are available for greenhouse farmers?

###### Adoption of IoT Technologies:

1. How do you view the risks and rewards of financing IoT greenhouse solutions?
2. What is your assessment of the ROI for adopting climate control technologies?

###### Financial Concerns:

1. What are the primary financial challenges farmers face when investing in new technologies?
2. How can farmers make a compelling case for financing IoT solutions?
3. Are there loan products or assistance programs for farmers adopting green technologies?

###### Interview about the Greenhouse Climate Control System

The interview was performed in the Russian language, here is the essence of it:

Andrew Bragarenco: Let's start. What are we going to talk about?

Respondent: We're talking about climate control in a greenhouse. To begin, let's clarify: do you have a greenhouse where you can test these technologies?

Andrew Bragarenco: Yes, we have a greenhouse on the Polytechnic campus. It is specially equipped for testing climate control technologies. It has basic functions such as lighting, humidity control, and temperature regulation.

Respondent: Tell us more about the lighting functions.

Andrew Bragarenco: The greenhouse has spectral lighting installed. It allows us to extend the daylight hours, which is especially useful in winter when there is not enough natural light. We can turn on the lamps in the morning and evening, compensating for the lack of sun.

Respondent: What about humidity?

Andrew Bragarenco: The greenhouse has a sprinkler system that humidifies the air. This is especially important in summer when the air becomes too dry. We can measure the humidity level and turn on the humidification system if necessary.

Respondent: How do you regulate the temperature?

Andrew Bragarenco: In summer, the temperature can rise significantly. Instead of expensive air conditioning, we use natural ventilation by opening windows. However, in strong winds, it is better to close the windows to avoid damage. If the windows are closed, heat can build up, which is also a problem. We are looking for a balance between cooling and protecting the structure.

Respondent: What other climate control elements are used?

Andrew Bragarenco: We control the insulation of the greenhouse. It has a double layer of film that inflates, creating an air cushion to retain heat in winter and prevent overheating in summer. However, it is important to maintain optimal pressure in this cushion to prevent it from being damaged.

Respondent: What sensors are used to automate the process?

Andrew Bragarenco: We have temperature, humidity, and wind sensors. They collect data but do not directly control the processes. Humidity sensors measure the moisture level in the air but cannot work in water. Temperature sensors are located at different heights because the temperature at the bottom and top differs. There are also fans to circulate the air.

Respondent: What is the system's power?

Andrew Bragarenco: The greenhouse runs on solar panels, and we have a limit of 4 kW. This is important to consider when calculating energy consumption. For example, heat guns cannot be turned on at full power due to lack of energy. We need to design an insulation system to minimize heat loss.

Respondent: How can the system be improved?

Andrew Bragarenco: Our goal is to make the greenhouse fully autonomous with remote access. We want to implement software control that will work on a schedule and respond to changes in conditions. For example, the system will be able to automatically open and close windows depending on temperature and wind. We are also considering using machine learning to optimize parameters – for example, adjusting humidity and light based on accumulated data. Also, we plan to improve the monitoring system and test various scenarios. For example, you can install cameras to monitor plants and analyze their response to changes in conditions. It is important to conduct research and collect data to improve the efficiency of greenhouse management.

###### Key thoughts:

The existing greenhouse infrastructure includes basic environmental control features such as light, humidity, and temperature management. Spectral lights are used to stimulate plant growth and extend daylight during winter. Humidity control is achieved through sprayers to prevent dry air in summer. In contrast, temperature control relies on ventilation by opening and closing windows to avoid the high costs associated with air conditioning.

However, several challenges were identified. Overheating occurs during summer due to poor ventilation and heat accumulation. There is also a risk of damage from strong winds if windows are left open. Better humidity control is needed without damaging sensors, and the energy supply is limited to 4 kW, powered by solar panels, which constrains heating capacity. Additionally, poor air circulation poses a risk of fungal growth.

Regarding technology and automation goals, stakeholders aim to develop a fully autonomous system using remote control and event-based programming. This system should include time-based triggers, emergency triggers for conditions like strong wind or extreme temperatures, and adaptive behavior using machine learning based on historical data and real-time conditions. Integration with an external server for data collection and monitoring is also planned, with communication via Wi-Fi or LoRa networks.

Recommendations for the next steps include optimizing window opening and closing based on sun position and wind conditions, improving insulation with double-layered plastic and pressure regulation, and using machine learning to dynamically predict and adjust light, temperature, and humidity levels.

Additional advanced sensors for wind, temperature at different levels, and light intensity should be installed. The system must operate with low power consumption to stay within the 4 kW limit. A flexible script-based control system with options for manual override should be developed, along with real-time video monitoring and telemetry.

The potential business and strategic impact of these improvements include faster plant growth and earlier harvesting, which could create a market advantage by delivering products earlier in the season. Improved control over the growing environment could increase yield and reduce losses due to unfavorable conditions. Customization for different clients, such as orchards versus greenhouses, could also create business opportunities.

# 3.3 Business case survey

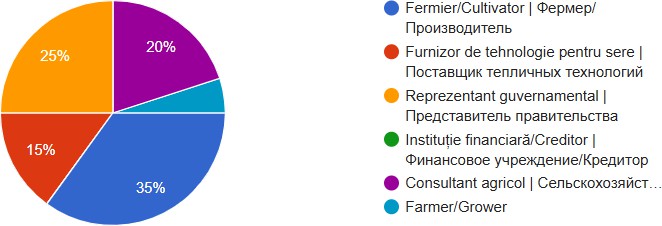
## Purpose of the Survey

To better understand the needs and expectations of our stakeholders, we conducted a survey on climate control in greenhouses. This initiative aims to gather insights that will help us improve greenhouse technology and enhance efficiency in sustainable agriculture. **Here is the link to our form**: [https://for](https://forms.gle/hZ6LZp43owV4YSng7) [ms.gle/hZ6LZp43owV4YSng7](https://forms.gle/hZ6LZp43owV4YSng7)

### Bilingual Survey for Stakeholder Inclusion Given the diverse background of our stakeholders, the survey was made available in two languages: Romanian and Russian. This ensures broader accessibility and encourages maximum participation.

### Analysis of the Greenhouse Climate Control Survey

#### Stakeholder Roles and Industry Experience



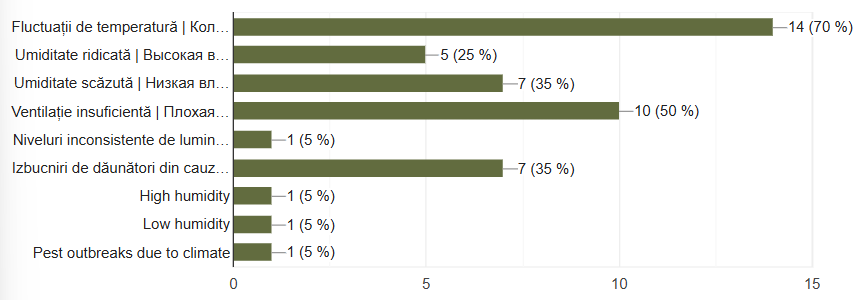
**Fig 7** Main stakeholders

The survey captured responses from a diverse group of stakeholders in the greenhouse industry with the largest group consisting of farmers and growers (35%) followed by technology providers (15%) agricultural consultants (10%) and government representatives (5%) This diversity highlights that both end- users and suppliers of greenhouse technology are interested in improving climate control solutions

In terms of experience 50% of respondents had less than 5 years of experience while 25% had over 10 years This mix indicates a balance between newcomers seeking guidance and experienced professionals potentially looking for improvements to existing systems.

#### Current Climate Control Methods and Challenges

Despite the increasing availability of climate automation technologies the survey revealed that 60% of greenhouse operators still rely on manual adjustments suggesting either a lack of awareness about modern solutions or financial constraints preventing their adoption



**Fig 8** Climate Control Methos

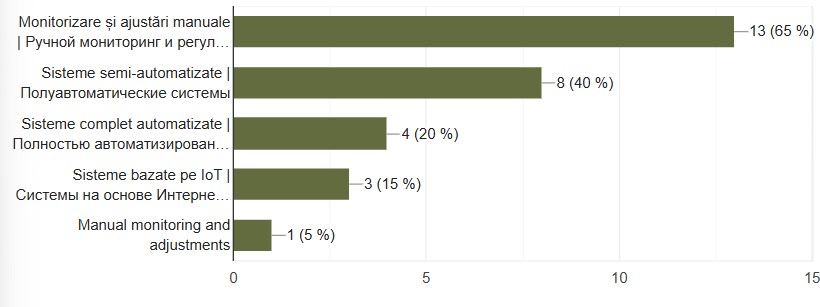
The most frequently reported challenges in managing greenhouse climate included:

Temperature fluctuations (80%) which was the most common issue suggesting that unstable external weather conditions significantly impact indoor environments

Humidity problems (50%) where both excessive and insufficient humidity were concerns indicating the need for precise regulation Pest outbreaks due to climate issues (30%) as poor climate control contributes to pest infestations affecting crop health and yields These findings suggest that more effective climate regulation technologies could directly improve crop quality and productivity.

#### Data Collection and Monitoring Practices

A significant insight from the survey is that 75% of respondents manually record climate data using logs or charts while only 25% use digital tools indicating that automation is still underutilized in many greenhouses



**Fig 9** Data Collection

Manual data collection can be time-consuming and prone to errors making it difficult to track real-time changes in temperature humidity and other key factors The fact that 90% of respondents expressed interest in real-time monitoring solutions highlights a strong demand for automated easy-to-use digital climate control systems.

#### Interest in Smart Climate Control Features

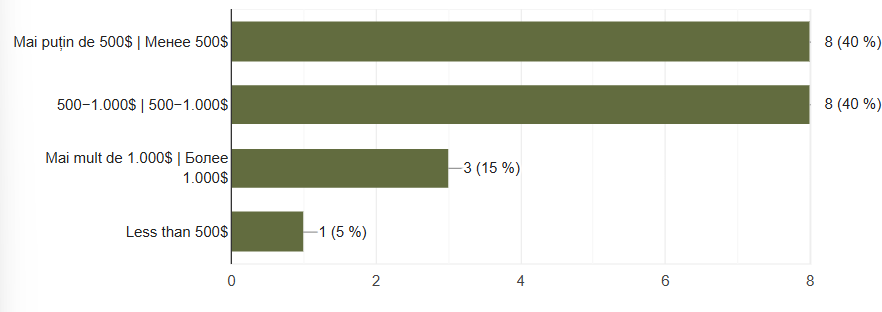
When asked about desirable features in a smart greenhouse climate control system the most requested functionalities were

Real-time monitoring (90%) as the vast majority of respondents want instant updates on temperature humidity and other climate conditions Remote control via mobile apps (65%) since many users want the ability to adjust greenhouse conditions from anywhere

Automated adjustments (50%) where a smaller but notable portion of respondents emphasized the importance of having a system that automatically regulates climate conditions

These preferences indicate that there is a high demand for smart user-friendly and remotely accessible solutions that reduce manual intervention.

#### Budget Constraints and Willingness to Invest



**Fig 10** Budget Constraints

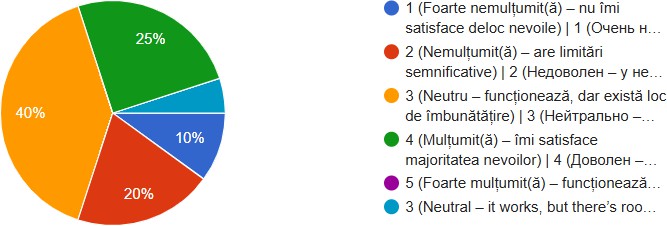
A major limiting factor for greenhouse technology adoption is budget availability The survey revealed that 50% of respondents have a budget below $500 for climate control equipment

25% have budgets exceeding $1,000 indicating some willingness to invest in high-end solutions

This suggests that cost-effective scalable climate control solutions would be more widely adopted than expensive high-tech systems The greenhouse industry would likely benefit from affordable modular systems that can be upgraded over time

#### Satisfaction with Current Systems

In terms of satisfaction with their current climate control systems



**Fig 11** Satisfaction with Current Systems

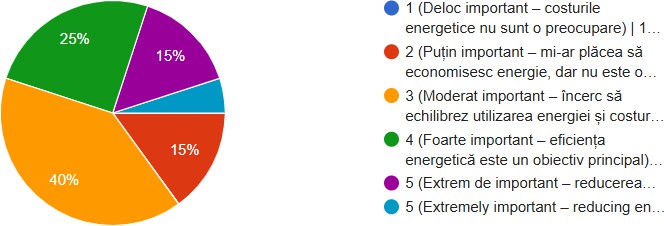
40% of respondents were neutral stating that their systems function but could be improved

35% were dissatisfied citing major limitations such as inaccurate monitoring difficulty in adjustments and high maintenance costs This dissatisfaction highlights an opportunity for innovation in simpler more efficient climate management solutions.

#### Future Adoption of Climate Control Technology

#### The likelihood of adopting new climate control technologies in the next year was as follows 50% are likely or very likely to implement new technology25% are undecided mainly due to budget concernsThis indicates a strong market potential for smart climate control solutions provided they are cost-effective and easy to implement.

#### Energy Efficiency Considerations



**Fig 12** Energy Efficiency Considerations

Another key insight from the survey is the high importance placed on energy efficiency 70% of respondents consider energy efficiency critical Only 10% find it unimportant Given the rising energy costs and environmental concerns greenhouse operators are actively looking for solutions that optimize energy use while maintaining optimal growing conditions.

There is high demand for real-time monitoring and remote access but manual climate control is still dominant, while budget constraints remain a significant barrier to adopting new technologies making cost-effective solutions crucial. Temperature and humidity fluctuations are the biggest climate-related challenges and automated regulation systems could greatly improve greenhouse productivity by ensuring stable conditions for optimal plant growth.

Energy efficiency is a major priority meaning new climate control technologies should focus on reducing energy consumption while maintaining crop health to support sustainable agriculture. These findings suggest an opportunity to develop affordable user-friendly climate control systems that integrate real- time monitoring automation and remote access while also being energy efficient.

# Stakeholder Requirements

###### 4.1 Stakeholders' user stories and job stories

Understanding stakeholder requirements is crucial for developing an effective climate control system that meets user needs. This analysis presents a structured breakdown of key stakeholder expectations, categorized under affordability, environmental monitoring, automation, scalability, and other critical factors. By incorporating both User Stories (US) and Job Stories (JS), we ensure that the system aligns with practical use cases and real-world challenges. The following sections outline these requirements based on stakeholder feedback and survey analysis, providing insights into essential functionalities such as cost-effectiveness, real-time data processing, automated control precision, and future scalability.

The table provides a structured breakdown of the stakeholder requirements for a climate control system, categorized under different aspects such as affordability, environmental monitoring, automation, and scalability. Each requirement is expressed in terms of User Stories (US) and Job Stories (JS) to ensure clarity and alignment with user needs.

|  |  |  |  |
| --- | --- | --- | --- |
| **Category** | **Stakeholder Requirements** | **US (User Stories)** | **JS (Job Stories)** |
| **Affordability** | The climate control system should be cost- effective. | As a university administrator, I want the system to be cost-effective to manage operational expenses within budget. | When considering climate control solutions, I want to ensure the system is affordable so I can justify the investment and secure funding. |
| **Environmental Monitoring Accuracy** | The system should accurately monitor temperature, humidity, light intensity, and wind conditions. | As a researcher, I want accurate environmental data so that I can conduct reliable experiments and studies. | When monitoring the greenhouse environment, I want the system to provide precise readings so I can accurately track and analyze climate conditions. |
| **Automated Control Precision** | The system should precisely control window operation, irrigation, and spectral lighting adjustments. | As a greenhouse manager, I want the system to automate climate adjustments precisely so that I can maintain optimal growing conditions. | When needing to adjust the greenhouse environment, I want the system to respond accurately so I can ensure the plants receive the right conditions. |
| **Real-time Data Processing** | The system should process sensor data in real time for immediate control adjustments. | As an operator, I want the system to process data in real time so that it can respond to changing conditions quickly. | When environmental conditions fluctuate, I want the system to react instantly so I can prevent harm to the plants. |
| **Remote Monitoring & Control** | The system should provide a secure web interface for remote monitoring and adjustments. | As a researcher or manager, I want to access the system remotely so that I can monitor and control the greenhouse from anywhere. | When away from the greenhouse, I want to be able to check and adjust the climate remotely so I can ensure continuous optimal conditions. |
| **Alerting & Notifications** | The system should provide alerts for critical environmental deviations or system failures. | As a manager, I want to receive alerts for critical conditions so that I can take immediate action. | When environmental conditions exceed thresholds, I want to be notified immediately so I can prevent damage to the plants. |
| **Data Logging & Reporting** | The system should log environmental data and generate reports for analysis. | As a researcher, I want detailed data logs and reports so that I can analyze environmental trends. | When conducting experiments, I want the system to record data for later analysis so I can draw accurate conclusions. |
| **System Reliability** | The system should operate reliably with minimal downtime. | As a manager, I want a reliable system so that I can minimize disruptions to plant growth. | When relying on the system for climate control, I want it to function consistently so I can ensure uninterrupted growth. |
| **User Training & Documentation** | The system should include comprehensive documentation and training materials. | As a user, I want clear documentation and training so that I can effectively use the system. | When learning to operate the system, I want to have access to helpful resources so I can become proficient quickly. |
| **Scalability & Expandability** | The system should be designed to accommodate future expansion or integration of additional sensors/actuators. | As a university planner, I want a system that can be expanded so that we can adapt to future needs. | When considering future projects, I want the system to be adaptable so we can integrate new technologies. |
| **Requirements based on survey analysis** | | | |
| **Affordability & Budget Constraints** | The climate control system must be cost-effective, with a focus on solutions fitting budgets below  $500, while also offering scalable options for those willing to invest over $1,000. | As a farmer/grower with a limited budget, I want affordable climate control options so that I can improve my greenhouse without exceeding financial constraints. | When evaluating climate control systems, I want to find cost-effective solutions that fit my budget so I can justify the investment and improve my greenhouse operations. |
| **Environmental Monitoring Accuracy & Real-time Data** | The system must accurately monitor temperature, humidity, light intensity, and wind conditions, providing real-time data access and automated digital logging to replace manual logs. | As a greenhouse operator relying on manual logs, I want real-time digital monitoring and automated data logging so that I can track and respond to environmental changes more effectively. | When monitoring the greenhouse environment, I want the system to provide precise, real-time data so I can make informed decisions quickly and maintain optimal conditions. |

|  |  |  |  |
| --- | --- | --- | --- |
| **Automated Control Precision & Temperature**  **/Humidity Stability** | The system should precisely control window operation, irrigation, and spectral lighting to minimize temperature and humidity fluctuations, addressing the most common challenges faced by operators. | As a greenhouse manager experiencing temperature fluctuations, I want automated controls that maintain stable conditions so that I can protect my crops from environmental stress. | When needing to adjust the greenhouse environment, I want the system to respond accurately and maintain stability so I can ensure the plants receive consistent and optimal conditions. |
| **Remote Monitoring & Control via Mobile Apps** | The system must provide a secure web interface and mobile app access for remote monitoring and adjustments, enabling control from anywhere. | As a grower who is often away from the greenhouse, I want remote access via a mobile app so that I can monitor and adjust conditions from anywhere. | When away from the greenhouse, I want to be able to check and adjust the climate remotely via a mobile app so I can ensure continuous optimal conditions and respond to emergencies. |
| **Predictive Climate Optimization & Data Analysis** | The system should use machine learning to predict and optimize climate parameters based on historical and real-time data, and provide data logging and reporting for analysis. | As a researcher analyzing climate trends, I want the system to provide predictive insights and detailed data reports so that I can optimize conditions and understand environmental impacts. | When analyzing historical data, I want the system to predict future climate trends and provide detailed reports so I can prepare for changes and improve my growing practices. |
| **Alerting & Notifications for Critical Deviations** | The system should provide alerts for critical environmental deviations or system failures, ensuring timely responses to prevent crop damage. | As a manager concerned about potential system failures, I want to receive alerts for critical conditions so that I can take immediate action and prevent losses. | When environmental conditions exceed thresholds or system failures occur, I want to be notified immediately so I can prevent damage to the plants and ensure system reliability. |
| **System Reliability & Reduced Manual Intervention** | The system should operate reliably with minimal downtime, reducing the need for manual adjustments and addressing dissatisfaction with current systems. | As a greenhouse operator dissatisfied with manual adjustments, I want a reliable automated system so that I can minimize manual intervention and focus on other tasks. | When relying on the system for climate control, I want it to function consistently and reliably so I can minimize manual adjustments and ensure uninterrupted growth. |
| **User Training & Documentatio n for Ease of Use** | The system should include comprehensive documentation and training materials, ensuring ease of use for operators with varying levels of experience. | As a new user of climate control technology, I want clear documentation and training so that I can effectively use the system and understand its features. | When learning to operate the system, I want to have access to helpful resources and training so I can become proficient quickly and utilize all system features effectively. |
| **Scalability & Expandability for Future Needs** | The system should be designed to accommodate future expansion or integration of additional sensors/actuators, catering to evolving needs and potential upgrades. | As a university planner anticipating future needs, I want a scalable system so that we can expand and integrate new technologies as our greenhouse operations grow. | When considering future projects and upgrades, I want the system to be adaptable so we can integrate new sensors and actuators to meet evolving needs. |
| **Energy Efficiency Considerations** | The system must prioritize energy efficiency, optimizing energy use while maintaining optimal growing conditions, reflecting the high importance placed on energy savings by stakeholders. | As a greenhouse operator concerned about energy costs, I want the system to optimize energy use so that I can reduce operational expenses and minimize environmental impact. | When operating the climate control system, I want it to be energy-efficient so I can reduce costs and minimize environmental impact while maintaining optimal growing conditions. |
| **Pest Outbreak Mitigation** | The system should contribute to pest outbreak mitigation by maintaining stable and optimal environmental conditions, addressing a significant concern raised by stakeholders. | As a grower concerned about pest outbreaks, I want the system to help maintain stable conditions so that I can minimize pest infestations and protect my crops. | When managing the greenhouse environment, I want the system to maintain optimal conditions so I can reduce the risk of pest outbreaks and ensure healthy crop growth. |

**Table 3** Stakeholder Requirements

The stakeholder requirements for the climate control system focus on affordability, environmental monitoring, automation, scalability, and other critical aspects essential for effective greenhouse management. The system must be cost-effective to accommodate budget constraints while providing accurate environmental monitoring of temperature, humidity, light intensity, and wind conditions. Automated control precision is required to regulate window operations, irrigation, and lighting, ensuring optimal plant growth. Real-time data processing and remote monitoring through secure web and mobile interfaces enhance system usability. The system must also provide predictive climate optimization, timely alerts for critical deviations, reliable performance with minimal manual intervention, and comprehensive training materials. Additionally, scalability, energy efficiency, and pest outbreak mitigation are key considerations, ensuring the system remains adaptable and efficient for future needs.

This stakeholder analysis highlights the core expectations and concerns of various users, including greenhouse managers, researchers, and university administrators. Addressing affordability constraints, enhancing automation, ensuring real-time monitoring, and prioritizing system reliability are crucial for the success of the proposed climate control system. Furthermore, energy efficiency, pest outbreak mitigation, and user-friendly training materials have emerged as key considerations. By integrating these insights into system design, the solution can effectively support modern greenhouse operations while accommodating future technological advancements and expansion.

The system should support integration with third-party weather forecasting services for predictive climate control. By utilizing forecast data, the system can proactively adjust environmental settings to prevent sudden climate fluctuations. This feature ensures that greenhouse operators can anticipate changes and optimize conditions for plant growth. For instance, when planning climate adjustments, users should be able to rely on predictive insights to make informed decisions that enhance overall efficiency and stability.

To maintain secure and efficient operations, the system should provide multi-user access with role-based permissions. This functionality allows administrators to assign specific roles and access levels, ensuring that control is distributed appropriately among different users. A greenhouse administrator may need to delegate monitoring tasks to researchers while reserving system modification rights for technical personnel. When managing system access, users should be able to define permissions that guarantee security while enabling authorized personnel to perform their roles effectively.

A modular architecture should be implemented to facilitate easy upgrades and customization. This approach allows greenhouse operators to expand system capabilities without requiring a complete overhaul. A system administrator should be able to integrate new modules seamlessly, whether for additional sensors, automation features, or software updates. When planning system upgrades, the ability to enhance functionalities without disrupting existing operations ensures long-term adaptability and ease of maintenance. Ensuring compliance with agricultural and environmental regulations is another critical aspect of the system. It should maintain detailed records and generate compliance reports to meet legal and environmental standards. A regulatory compliance officer should be able to access structured reports that demonstrate adherence to necessary guidelines, simplifying the audit process. When undergoing regulatory reviews, the ability to retrieve automatically generated compliance documentation will help users avoid penalties and streamline operations. Lastly, the system should incorporate fail-safe mechanisms and backup control options to prevent disruptions during connectivity loss. In situations where network failures occur, greenhouse operators must be able to rely on alternative control methods to maintain climate stability.

# 4.2 Stakeholder Requirements Analysis

This document captures the prioritized stakeholder requirements for the Greenhouse Climate Control System, classified using the **MoSCoW method** (Must Have, Should Have, Could Have, Won’t Have). The requirements are derived from stakeholder interviews, surveys, and technical analysis.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Category** | **Stakeholder Requirements** | **US (User Stories)** | **JS (Job Stories)** | **Classification** | **Rational** |
| **Affordability** | The climate control system | As a university administrator, I want | When considering climate control | **Should Have** | While important |
|  | should be cost-effective. | the system to be cost-effective so | solutions, I want to ensure the system is |  | for budget |
|  |  | that we can manage operational | affordable so I can justify the investment |  | management, |
|  |  | expenses within budget. | and secure funding. |  | affordability does |
|  |  |  |  |  | not directly impact |
|  |  |  |  |  | the system's core |
|  |  |  |  |  | functionality or |
|  |  |  |  |  | operation. |
| **Environme** | The system should | As a researcher, I want accurate | When monitoring the greenhouse | **Must Have** | Accurate |
| **ntal** | accurately monitor | environmental data so that I can | environment, I want the system to |  | monitoring is |
| **Monitoring** | temperature, humidity, light | conduct reliable experiments and | provide precise readings so I can |  | critical for |
| **Accuracy** | intensity, and wind conditions. | studies. | accurately track and analyze climate  conditions. |  | conducting  reliable |
|  |  |  |  |  | experiments and |
|  |  |  |  |  | maintaining |
|  |  |  |  |  | optimal growing |
|  |  |  |  |  | conditions. |
| **Automated** | The system should precisely | As a greenhouse manager, I want | When needing to adjust the greenhouse | **Must Have** | Precise control is |
| **Control** | control window operation, | the system to automate climate | environment, I want the system to |  | essential for |
| **Precision** | irrigation, and spectral  lighting adjustments. | adjustments precisely so that I can  maintain optimal growing conditions. | respond accurately so I can ensure the  plants receive the right conditions. |  | maintaining the  proper |
|  |  |  |  |  | environment for |
|  |  |  |  |  | plant growth. |
| **Real-time** | The system should process | As an operator, I want the system to | When environmental conditions | **Must Have** | Immediate |
| **Data** | sensor data in real time for | process data in real time so that it | fluctuate, I want the system to react |  | response to |
| **Processing** | immediate control  adjustments. | can respond to changing conditions  quickly. | instantly so I can prevent harm to the  plants. |  | changing  conditions is |
|  |  |  |  |  | essential to |
|  |  |  |  |  | prevent damage |
|  |  |  |  |  | to plants and |
|  |  |  |  |  | maintain optimal |
|  |  |  |  |  | growth. |
| **Remote** | The system should provide a | As a researcher or manager, I want | When away from the greenhouse, I want | **Should Have** | While convenient |
| **Monitoring** | secure web interface for | to access the system remotely so | to be able to check and adjust the |  | and useful, |
| **& Control** | remote monitoring and  adjustments. | that I can monitor and control the  greenhouse from anywhere. | climate remotely so I can ensure  continuous optimal conditions. |  | remote access is  not essential for |
|  |  |  |  |  | the system to |
|  |  |  |  |  | function |
|  |  |  |  |  | effectively on-site. |
| **Alerting &** | The system should provide | As a manager, I want to receive | When environmental conditions exceed | **Must Have** | Alerting ensures |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Notifications** | alerts for critical  environmental deviations or | alerts for critical conditions so that I  can take immediate action. | thresholds, I want to be notified  immediately so I can prevent damage to |  | timely responses  to prevent |
|  | system failures. |  | the plants. |  | potential damage |
|  |  |  |  |  | to plants and |
|  |  |  |  |  | system failure. |
| **Data** | The system should log | As a researcher, I want detailed data | When conducting experiments, I want | **Must Have** | Data logging is |
| **Logging &** | environmental data and | logs and reports so that I can | the system to record data for later |  | helpful for |
| **Reporting** | generate reports for analysis. | analyze environmental trends. | analysis so I can draw accurate  conclusions. |  | research and  analysis, is |
|  |  |  |  |  | essential for the |
|  |  |  |  |  | core operation of |
|  |  |  |  |  | the system. |
| **System** | The system should operate | As a manager, I want a reliable | When relying on the system for climate | **Must Have** | Reliability is |
| **Reliability** | reliably with minimal  downtime. | system so that I can minimize  disruptions to plant growth. | control, I want it to function consistently  so I can ensure uninterrupted growth. |  | essential for  maintaining |
|  |  |  |  |  | continuous |
|  |  |  |  |  | climate control |
|  |  |  |  |  | and preventing |
|  |  |  |  |  | plant stress. |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **User Training & Documenta tion** | The system should include comprehensive documentation and training materials. | As a user, I want clear documentation and training so that I can effectively use the system. | When learning to operate the system, I want to have access to helpful resources so I can become proficient quickly. | **Won't Have** | While helpful for onboarding and troubleshooting, the system can function without detailed documentation. |
| **Scalability** | The system should be | As a university planner, I want a | When considering future projects, I want | **Should Have** | Scalability is |
| **&** | designed to accommodate | system that can be expanded so that | the system to be adaptable so we can |  | important for |
| **Expandabili** | future expansion or | we can adapt to future needs. | integrate new technologies. |  | future-proofing |
| **ty** | integration of additional  sensors/actuators. |  |  |  | but does not  affect immediate |
|  |  |  |  |  | operation. |

**Requirements based on survey analysis**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Category** | **Stakeholder Requirements** | **US (User Stories)** | **JS (Job Stories)** | **Classification** | **Rationale** |
| **Affordabilit** | The climate control system must be | As a farmer/grower with a limited | When evaluating climate control | **Must Have** | Cost is a |
| **y & Budget** | cost-effective, with a focus on | budget, I want affordable climate | systems, I want to find cost-effective |  | primary |
| **Constraints** | solutions fitting budgets below $500,  while also offering scalable options | control options so that I can improve  my greenhouse without exceeding | solutions that fit my budget so I can  justify the investment and improve |  | constraint  for |
|  | for those willing to invest over | financial constraints. | my greenhouse operations. |  | stakeholders |
|  | $1,000. |  |  |  | , and |
|  |  |  |  |  | affordability |
|  |  |  |  |  | directly |
|  |  |  |  |  | affects the |
|  |  |  |  |  | system's |
|  |  |  |  |  | accessibility |
|  |  |  |  |  | and |
|  |  |  |  |  | adoption. |
| **Environmen** | The system must accurately monitor | As a greenhouse operator relying on | When monitoring the greenhouse | **Must Have** | Accurate |
| **tal** | temperature, humidity, light intensity, | manual logs, I want real-time digital | environment, I want the system to |  | monitoring |
| **Monitoring** | and wind conditions, providing real- | monitoring and automated data | provide precise, real-time data so I |  | and real- |
| **Accuracy &** | time data access and automated | logging so that I can track and | can make informed decisions quickly |  | time data |
| **Real-time Data** | digital logging to replace manual logs. | respond to environmental changes more effectively. | and maintain optimal conditions. |  | are critical for  maintaining |
|  |  |  |  |  | stable |
|  |  |  |  |  | growing |
|  |  |  |  |  | conditions |
|  |  |  |  |  | and |
|  |  |  |  |  | improving |
|  |  |  |  |  | decision- |
|  |  |  |  |  | making. |
| **Automated** | The system should precisely control | As a greenhouse manager | When needing to adjust the | **Should Have** | Automation |
| **Control** | window operation, irrigation, and | experiencing temperature | greenhouse environment, I want the |  | improves |
| **Precision &** | spectral lighting to minimize | fluctuations, I want automated | system to respond accurately and |  | consistency |
| **Temperatur** | temperature and humidity | controls that maintain stable | maintain stability so I can ensure the |  | and reduces |
| **e/Humidity Stability** | fluctuations. | conditions so that I can protect my crops from environmental stress. | plants receive consistent and optimal conditions. |  | stress on crops, but  it's not an |
|  |  |  |  |  | absolute |
|  |  |  |  |  | necessity |
|  |  |  |  |  | for basic |
|  |  |  |  |  | functioning. |
| **Remote** | The system must provide a secure | As a grower who is often away from | When away from the greenhouse, I | **Should Have** | Remote |
| **Monitoring** | web interface and mobile app | the greenhouse, I want remote | want to be able to check and adjust |  | access |
| **& Control** | access for remote monitoring and | access via a mobile app so that I can | the climate remotely via a mobile app |  | increases |
| **via Mobile** | adjustments. | monitor and adjust conditions from | so I can ensure continuous optimal |  | convenience |
| **Apps** |  | anywhere. | conditions and respond to  emergencies. |  | and  responsiven |
|  |  |  |  |  | ess but is |
|  |  |  |  |  | not critical |
|  |  |  |  |  | for basic |
|  |  |  |  |  | operation. |
| **Predictive** | The system should use machine | As a researcher analyzing climate | When analyzing historical data, I | **Could Have** | Predictive |
| **Climate** | learning to predict and optimize | trends, I want the system to provide | want the system to predict future |  | optimization |
| **Optimizatio** | climate parameters based on | predictive insights and detailed data | climate trends and provide detailed |  | enhances |
| **n & Data** | historical and real-time data. | reports so that I can optimize | reports so I can prepare for changes |  | long-term |
| **Analysis** |  | conditions and understand  environmental impacts. | and improve my growing practices. |  | performance  but is not |
|  |  |  |  |  | essential for |
|  |  |  |  |  | basic |
|  |  |  |  |  | functionality. |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Alerting & Notification s for Critical Deviations** | The system should provide alerts for critical environmental deviations or system failures. | As a manager concerned about potential system failures, I want to receive alerts for critical conditions so that I can take immediate action and prevent losses. | When environmental conditions exceed thresholds or system failures occur, I want to be notified immediately so I can prevent damage to the plants and ensure system reliability. | **Must Have** | Immediate alerts are essential for preventing crop damage and system failures. | |
| **System Reliability & Reduced Manual Intervention** | The system should operate reliably with minimal downtime, reducing the need for manual adjustments. | As a greenhouse operator dissatisfied with manual adjustments, I want a reliable automated system so that I can minimize manual intervention and focus on other tasks. | When relying on the system for climate control, I want it to function consistently and reliably so I can minimize manual adjustments and ensure uninterrupted growth. | **Must Have** | Reliability directly affects operational stability and crop health. |
| **User Training & Documentat ion for**  **Ease of Use** | The system should include comprehensive documentation and training materials. | As a new user of climate control technology, I want clear documentation and training so that I can effectively use the system and understand its features. | When learning to operate the system, I want to have access to helpful resources and training so I can become proficient quickly and utilize all system features effectively. | **Could Have** | Training improves usability and reduces errors but is not essential for basic operation. |
| **Scalability & Expandabili ty for Future Needs** | The system should be designed to accommodate future expansion or integration of additional sensors  /actuators. | As a university planner anticipating future needs, I want a scalable system so that we can expand and integrate new technologies as our greenhouse operations grow. | When considering future projects and upgrades, I want the system to be adaptable so we can integrate new sensors and actuators to meet evolving needs. | **Could Have** | Scalability ensures long-term adaptability but is not critical for initial deployment. |
| **Energy** | The system must prioritize energy | As a greenhouse operator concerned | When operating the climate control | **Should Have** | Energy |
| **Efficiency** | efficiency, optimizing energy use | about energy costs, I want the system | system, I want it to be energy- |  | efficiency |
| **Considerati** | while maintaining optimal growing | to optimize energy use so that I can | efficient so I can reduce costs and |  | reduces |
| **ons** | conditions. | reduce operational expenses and  minimize environmental impact. | minimize environmental impact while  maintaining optimal growing |  | costs and  environment |
|  |  |  | conditions. |  | al impact |
|  |  |  |  |  | but does not |
|  |  |  |  |  | directly |
|  |  |  |  |  | impact |
|  |  |  |  |  | basic |
|  |  |  |  |  | functionality. |
| **Pest** | The system should contribute to pest | As a grower concerned about pest | When managing the greenhouse | **Should Have** | Pest control |
| **Outbreak** | outbreak mitigation by maintaining | outbreaks, I want the system to help | environment, I want the system to |  | improves |
| **Mitigation** | stable and optimal environmental  conditions. | maintain stable conditions so that I  can minimize pest infestations and | maintain optimal conditions so I can  reduce the risk of pest outbreaks and |  | crop health  and |
|  |  | protect my crops. | ensure healthy crop growth. |  | productivity |
|  |  |  |  |  | but is not |
|  |  |  |  |  | critical for |
|  |  |  |  |  | basic |
|  |  |  |  |  | functionality. |

**Table 3** Stakeholder Requirements(US JS)

### Stakeholder Requirements Review

Our team has carefully reviewed the stakeholder requirements and ensured they align with our project goals for developing an IoT-enabled, autonomous climate control system for the university greenhouse. While the stakeholder analysis is well-structured, we identified areas where clarity, completeness, and accuracy can be improved.

One key improvement is better differentiation between primary and secondary stakeholders. While we acknowledge the influence of greenhouse farmers and owners as primary beneficiaries, we need to emphasize their active role in providing feedback on system usability and efficiency. Their direct interaction with the system will be crucial for iterative improvements, and we should explicitly define how we plan to gather and incorporate their insights throughout the project lifecycle.

We also recognize the need to strengthen the alignment between stakeholder expectations and our project deliverables. The Ministry of Agriculture plays a significant role in enforcing policies related to sustainability and food security, but our current documentation does not clearly outline whether regulatory compliance or government incentives will be factored into our development process. We should clarify how our system aligns with national agricultural policies and explore potential collaboration opportunities to enhance adoption and scalability.

For research institutions, we need to define their involvement beyond performance validation and innovation. A key question we must address is how their contributions will be integrated into our project. Will they provide datasets for training our machine learning models, assist in field trials, or contribute to post-deployment performance assessments? Providing a structured approach to their engagement will ensure their expertise is fully utilized in refining our system.

# 5 Stakeholder Requirements Analysis

### 5.1 Stakeholder Requirements Table

Each stakeholder requirement will undergo a rigorous decomposition process to extract critical components. The analysis will focus on identifying the specific user, the exact action or process involved, the surrounding circumstances, and the expected outcome. This systematic approach ensures a comprehensive understanding of each requirement beyond its surface-level description. For each requirement, team members will conduct an in-depth examination.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Stakeholder** | **Requirement** | **Problem Statement** | **Expected Outcome** | **Implementation Considerations** |
| University Administrator | The system should be cost- effective | High operational costs | Reduced expenses and optimized budget | Use cost-efficient solutions and reduce waste |
| Greenhouse Operator | Reduce energy consumption | High energy costs | More sustainable and cost- effective operation | Implement energy- efficient components |
| Evaluator | Find cost- effective solutions | Need a clear ROI before investment | Better financial decision- making | Include cost-benefit analysis |
| Evaluator | Ensure affordability | Uncertainty in the financial impact | Informed investment choices | Consider implementation costs vs. savings |
| Greenhouse Operator | Automate climate control to reduce manual intervention | Manual adjustments take too much time | More efficient and automated control | Implement automated climate management systems |
| Greenhouse Operator | Maintain stable conditions to prevent pest outbreaks | Environmental instability increases pest risks | Reduced pest outbreaks and crop protection | Implement automated stability control |
| Evaluator | Balance climate control accuracy and pest prevention | Inconsistent conditions increase risks | Reduced crop damage and improved growing conditions | Implement precise control systems |
| University Planner | Ensure system scalability | The system may become outdated | Expandable and adaptable infrastructure | Design modular systems for easy upgrades |
| Evaluator | Ensure adaptability for future upgrades | Need for long- term investment viability | Future-proof and cost- efficient greenhouse upgrades | Integrate modular hardware and software |
| Greenhouse Operator | Collect telemetry data for monitoring | Lack of real- time performance insights | Proactive maintenance and reduced downtime | Implement sensor- based monitoring |
| Evaluator | Monitor efficiency with real-time data | Unexpected environmental changes | Reduced crop damage and better climate control | Integrate live sensor monitoring |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Greenhouse Manager | Maintain stable conditions | Fluctuations in temperature and humidity | Consistent and optimal greenhouse climate | Implement automated control mechanisms |
| Evaluator | Use historical data to predict trends | Uncertainty in climate change | Better long- term climate management | Implement predictive analytics |
| Greenhouse Operator | Enable remote monitoring and control | Inability to adjust settings remotely | Improved flexibility and emergency response | Implement mobile app integration |
| Researcher | Provide predictive insights | Need data to optimize climate control | Data-driven greenhouse optimization | Use AI-driven predictive analytics |
| Greenhouse Manager | Ensure precise automation controls | System lags cause inefficiencies | Improved climate stability and reduced energy waste | Implement real-time automation logic |
| Farmer/Grower | Provide affordable climate control | Limited budget for upgrades | Cost-effective greenhouse operations | Develop low-cost automation options |
| University Planner | Ensure system expandability | Need for long- term adaptation | Future-proof greenhouse infrastructure | Use modular software and hardware |

**Table 5** Stakeholder Requirements Table

### Comprehensive Analysis

The stakeholder requirements table provides an extensive overview of the current development priorities and the gaps that still need to be addressed. The current focus of the project is primarily on cost-effectiveness, energy efficiency, and financial decision-making, reflecting an early-stage emphasis on economic viability before transitioning to advanced technological solutions. The requirements that are actively being considered revolve around reducing high operational costs, implementing energy-efficient components, and ensuring affordability through thorough cost-benefit analysis. This focus suggests that stakeholders are prioritizing financial feasibility as a foundational element before investing in more complex automation and monitoring systems.

Addressing high operational costs at the outset allows for better resource allocation and ensures that future technological enhancements do not introduce unsustainable financial burdens. However, while this approach mitigates immediate budget constraints, it also means that certain critical operational improvements are being deferred.

A significant number of stakeholder requirements remain in the backlog, particularly those related to automation, scalability, real-time monitoring, and predictive analytics. The absence of immediate progress in these areas suggests that the project has yet to transition into implementing more advanced technological functionalities. Requirements such as automating climate control, maintaining stable environmental conditions to prevent pest outbreaks, and enabling remote monitoring are crucial for long-term operational efficiency but have not been prioritized in the initial development phase. Additionally, the lack of emphasis on system scalability and adaptability for future upgrades presents a potential risk in terms of long-term sustainability. If these aspects are not addressed early on, there could be challenges in seamlessly integrating future enhancements, leading to costly and inefficient modifications later.

Given that greenhouse technology is evolving rapidly, postponing scalability considerations could limit the project's ability to remain competitive and adaptable in the long run.

The lack of immediate progress in data-driven insights and predictive analytics is another area of concern. Stakeholders such as evaluators and researchers require real-time monitoring and predictive insights to optimize greenhouse performance, yet requirements related to telemetry data collection, AI-driven analytics, and historical data analysis remain in the backlog. This suggests a gap in integrating intelligent decision-making processes, which are essential for long-term climate management and operational optimization. A greenhouse management system that lacks predictive capabilities may struggle to adjust to changing environmental conditions efficiently, ultimately affecting crop yields and sustainability. Without data-driven automation, decision-making remains reactive rather than proactive, leading to inefficiencies in managing resources, maintaining stable conditions, and preventing potential risks such as pest outbreaks or sudden climate fluctuations.

The current development trajectory prioritizes financial sustainability but at the cost of delaying key automation and real-time monitoring features that could enhance operational efficiency. While ensuring cost-effectiveness is an essential foundation, postponing automation and intelligent monitoring may create bottlenecks in future implementation efforts. The longer these features remain unaddressed, the more challenging it will become to integrate them seamlessly without overhauling existing infrastructure. Moving forward, the project must strike a balance between financial considerations and the integration of real-time data, automation, and predictive analytics. Without this balance, there is a risk that cost-saving measures in the short term may limit the system’s effectiveness and scalability in the long run. Ensuring a well-rounded greenhouse management system requires a holistic approach where financial feasibility and technological advancements progress in tandem, creating a sustainable and intelligent solution that meets the diverse needs of all stakeholders.

### Conclusion

In conclusion, while the project is currently prioritizing financial considerations—such as cost-effectiveness and energy efficiency—there is a notable delay in addressing critical technological advancements. These delays, particularly in the areas of automation, real-time monitoring, and predictive analytics, could hinder the long-term operational efficiency and scalability of the greenhouse management system. By focusing on reducing operational costs early on, the project aims to ensure that the system remains economically viable. However, the deferral of automation and data-driven features may limit the system's ability to adapt to evolving conditions, reduce inefficiencies, and optimize greenhouse performance.

Moving forward, it is essential for the development team to balance financial concerns with the integration of intelligent automation and real-time data capabilities. The success of the project will depend on the ability to not only manage costs but also to create a flexible, scalable, and future-proof system that can evolve with technological advancements. By addressing these gaps sooner rather than later, the project can ensure that it meets the needs of all stakeholders, remains competitive, and offers a comprehensive solution to greenhouse management challenges.

**5.2 System Requirements**

|  |  |  |  |
| --- | --- | --- | --- |
| **System Requirement** | **Type** | **Priority** | **Comments** |
| The system shall reduce energy consumption by optimizing climate control based on real-time and historical data. | Non- functional | High | Satisfies need for energy efficiency and affordability. |
| The system shall automate climate control to reduce manual intervention and maintain stable environmental conditions. | Functional | High | Ensures efficiency and stability through automation. |
| The system shall monitor real-time data on climate conditions and system performance. | Functional | High | Supports real-time monitoring for improved efficiency. |
| The system shall provide remote access for monitoring and control via a secure user interface. | Functional | Medium | Supports remote accessibility for user convenience. |
| The system shall analyze historical data to predict climate trends and improve performance. | Functional | Medium | Enables predictive insights to optimize climate control. |
| The system shall prevent pest outbreaks by maintaining stable temperature and humidity levels. | Functional | High | Ensures pest prevention through climate stability. |
| The system shall enable scalability by supporting the integration of new sensors and control units. | Non- functional | High | Supports future upgrades and system expansion. |
| The system shall provide data visualization for climate performance and efficiency. | Functional | Medium | Enhances monitoring and user insight. |
| The system shall ensure accurate automation controls with a precision of ±0.5°C. | Non- functional | High | Ensures stable climate control accuracy. |
| The system shall support predictive maintenance by identifying potential failures based on telemetry data. | Functional | Medium | Improves system reliability through predictive insights. |
| The system shall use open architecture to ensure easy integration with third- party systems. | Non- functional | Medium | Ensures adaptability and future upgrades. |
| The system shall balance climate control accuracy with energy efficiency to minimize costs. | Non- functional | High | Maintains balance between performance and cost. |
| The system shall notify users in case of system failures or deviations from target conditions. | Functional | High | Improves system responsiveness and user awareness. |
| The system shall minimize operational costs by optimizing power usage during low-demand periods. | Non- functional | Medium | Supports affordability and energy efficiency. |

# System Architecture Specification

# 6.1 GCC Static aspects of the system architecture specification.

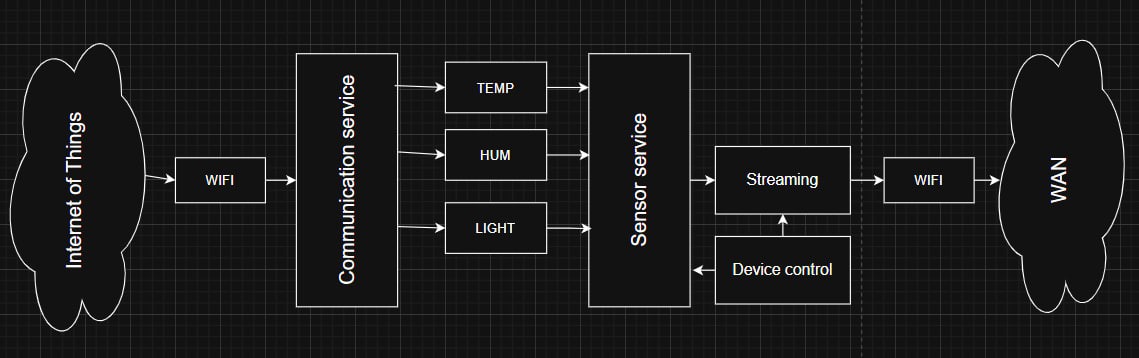
The diagram illustrates the architecture of a greenhouse climate control system, depicting the interaction between hardware and software components to ensure an optimal growing environment. The system integrates multiple sensors, a microcontroller, actuators, and cloud-based remote monitoring to achieve automation and reliability in climate control. By combining real-time data processing, decision-making algorithms, and user accessibility through web and mobile applications, the system reduces manual intervention while maintaining stable environmental conditions. At the hardware level, the system consists of several sensors, including light, wind, temperature, and humidity sensors, which continuously monitor environmental parameters. These sensors send data to a microcontroller, which serves as the central processing unit of the system. Based on the analyzed data, the microcontroller controls various actuators responsible for adjusting conditions within the greenhouse, such as regulating irrigation, opening and closing windows, and modifying spectral lighting. The hardware components ensure that real-world environmental conditions are accurately captured and adjusted as needed.

The software component is divided into multiple subsystems, each handling a critical aspect of the system’s operation. The sensor processing module is responsible for data collection and processing, where raw sensor inputs are converted into meaningful information. Predefined algorithms use this processed data to determine necessary adjustments to maintain optimal greenhouse conditions. The control module contains decision logic that interprets the analyzed data and decides on appropriate responses, which are then executed by the control system to activate the actuators. User interaction with the system is facilitated through a web-based dashboard and a mobile application, allowing remote access to real-time environmental data and system controls. Users can monitor sensor readings, receive alerts about critical deviations, and manually adjust system parameters when necessary. This interface enhances usability by providing accessibility to greenhouse management from any location.

Cloud integration plays a crucial role in remote monitoring and data storage. A remote monitoring API enables secure data transmission between the greenhouse system and external devices, ensuring that users can access information even when they are not physically present. Environmental data is also logged in cloud storage, allowing for historical analysis, trend identification, and potential future improvements, such as machine learning-based predictive climate optimization. The overall workflow of the system begins with sensors collecting environmental data, which is processed and analyzed through predefined algorithms. The control system then determines necessary actions and activates the appropriate actuators to make real-time adjustments. Meanwhile, users can interact with the system through web and mobile platforms.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Component Name** | **Type** | **Description** | **Interfaces** | **Interface Scope** | **Connected Components** |
| **Light Sensor** | Hardware | Measures ambient light intensity and sends data to the microcontroller for processing. | Sensor Data Interface | Data Flow | Light Sensor Microcontroller |
| **Wind Sensor** | Hardware | Detects wind speed and direction, aiding in climate regulation by adjusting ventilation. | Sensor Data Interface | Data Flow | Wind Sensor Microcontroller |
| **Temperature Sensor** | Hardware | Measures temperature levels inside the greenhouse to regulate heating and cooling systems. | Sensor Data Interface | Data Flow | Temperature Sensor Microcontroller |
| **Humidity Sensor** | Hardware | Monitors humidity levels to manage irrigation and misting systems. | Sensor Data Interface | Data Flow | Humidity Sensor Microcontroller |
| **Micro**  **controller** | Hardware | Central processing unit that collects sensor data, processes control logic, and sends commands to actuators. | Control Command Interface | Command Execution | Microcontroller Actuators |
| **Actuators** | Hardware | Performs physical actions like adjusting windows, turning on lights, and activating irrigation. | Control Command Interface | Command Execution | Microcontroller Actuators |
| **Data Processing** | Software (Sensor Processing) | Receives raw sensor data, applies filtering, and prepares it for analysis. | Sensor Data Interface | Data Processing | Sensors Data Processing |
| **Decision Logic** | Software (Control System) | Evaluates processed data and determines necessary actuator actions. | Control Command Interface | Control Execution | Predefined Algorithms Decision Logic |
| **Control System** | Software (Control System) | Converts decisions into actuator control signals to maintain optimal conditions. | Control Command Interface | Command Execution | Decision Logic Control System |
| **Web Dashboard** | Software (User Interface) | Provides a graphical interface for users to monitor and adjust system settings remotely. | User Interface API | User Interaction | Web Dashboard Cloud |
| **Mobile App** | Software (User Interface) | Allows remote access and control via mobile devices. | User Interface API | User Interaction | Mobile App Cloud |
| **Remote Monitoring API** | Software (Cloud Integration) | Facilitates real-time data exchange between the microcontroller, cloud, and user interfaces. | Cloud Data Sync | Data Logging | Microcontroller Cloud |

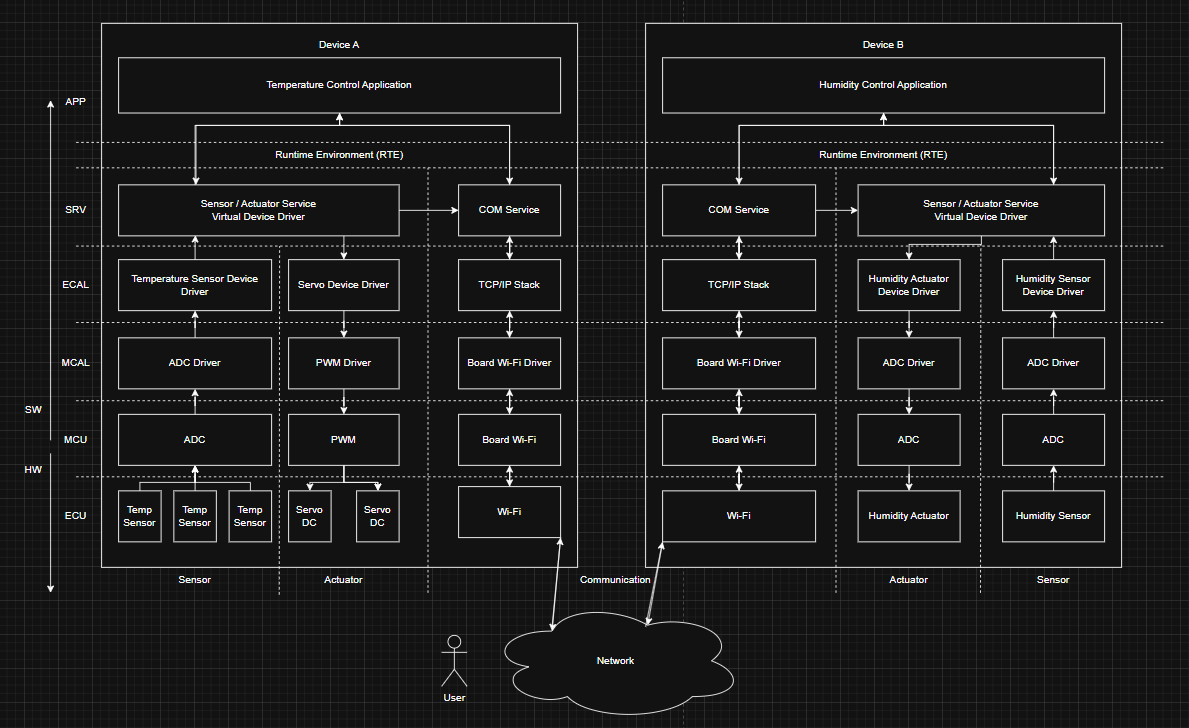
**Tabe 7** GCC Static aspects of the system architecture specification.



**Fig 8** Data communication

The diagram illustrates a comprehensive IoT architecture for greenhouse climate control that facilitates data flow between sensors, control systems, and external networks. The system begins with the "Internet of Things" cloud on the left side, which connects to a local WiFi network. This WiFi connection serves as the entry point for the system's communication infrastructure. From the WiFi, data flows to a central "Communication service" that acts as the intermediary between the network and the sensing components. This service manages the data exchange with three key environmental sensors:

Temperature sensors that monitor greenhouse thermal conditions, humidity sensors that track moisture levels in the air, and light sensors that measure illumination levels. These sensors feed their environmental data into a "Sensor service" component, aggregating and processing the readings. The Sensor service has a bidirectional connection with a "Device control" module, allowing for automated or manual adjustment of greenhouse conditions based on sensor readings. The processed data from the Sensor service flows to a "Streaming" component, which prepares the information for external transmission. The Device control also provides input to the Streaming service, likely including control actions and system status information. The Streaming component connects to a second WiFi module, which then connects to a WAN (Wide Area Network) represented by the cloud on the right side. This enables remote monitoring and control of the greenhouse environment from anywhere with internet access. This architecture creates a complete feedback loop in which environmental conditions are monitored, processed, and can trigger adjustments through the device control system while simultaneously providing real-time data to external networks for remote management.



**Fig 9** Architecture of a distributed control system composed of two devices

This diagram illustrates the architecture of a distributed control system composed of two devices: Device A, responsible for temperature control, and Device B, responsible for humidity control. Each device follows a layered structure, starting from the hardware (HW) and electronic control unit (ECU) at the bottom, up through the microcontroller unit (MCU), middleware and software abstraction layers (SW), and up to the application layer (APP) at the top.Device A includes a Temperature Control Application running within the application layer, interacting through a Runtime Environment (RTE) with underlying services. The service (SRV) layer contains a Sensor/Actuator Service acting as a Virtual Device Driver, which interfaces with the temperature sensors and servo motors through specific device drivers located in the electronic abstraction layer (ECAL). Communication between devices is handled by a COM Service and a TCP/IP stack, supported by a Wi-Fi driver that communicates with the physical Wi-Fi hardware. The device accesses three temperature sensors and two servo motors, connected to ADC (Analog-to-Digital Converter) and PWM (Pulse Width Modulation) modules respectively, managed by corresponding drivers at the microcontroller abstraction layer (MCAL) and the MCU.Device B mirrors a similar architecture but is tailored to humidity control. It hosts a Humidity Control Application, with its runtime environment connecting to both a COM Service and a Sensor/Actuator Service. The services manage a Humidity Sensor Device Driver and a Humidity Actuator Device Driver.Similar to Device A, the communication infrastructure relies on a TCP/IP stack and a Board Wi-Fi Driver. The humidity actuator and sensor are

# 6.2 Dynamic aspects of the system architecture Specification. GCC

|  |  |  |
| --- | --- | --- |
| **MODE** | **PURPOSE** | **KEY CHARACTERISTICS** |
| Normal Operation | Maintain stable environmental conditions while optimizing energy usage | This mode is used to maintain stable environmental conditions while optimizing energy use. It involves continuous monitoring of temperature and humidity, making real-time adjustments within a ±0.5°C tolerance, optimizing energy usage during periods of low demand, and responding automatically through control systems. |
| Alert Mode | Handle system deviations and anomalies | This mode is activated to manage system deviations and anomalies. It triggers immediate notifications when thresholds are breached, makes emergency climate adjustments, logs all system deviations, and follows protocols to notify users. |
| Maintena nce Mode | Perform scheduled and predictive maintenance | Used for both scheduled and predictive maintenance, this mode identifies potential failures in advance, coordinates scheduled downtime, preserves system integrity, and ensures maintenance activities have minimal impact on operations. |
| Energy Optimizat ion | Minimize power consumption while maintaining performance | This mode focuses on reducing power consumption while keeping performance stable. It assesses loads dynamically, optimizes based on cost, manages usage during peak periods, and adjusts system efficiency automatically. |
| Remote Monitoring | Enable secure external system oversight | Designed for secure external oversight, this mode provides real-time data visualization, uses secure authentication, allows for system configuration management, and sends remote alerts when necessary. |
| Standby | Maintain readiness while minimizing power usage | In this mode, the system stays ready to activate while minimizing power usage. It reduces operational activity, retains only essential monitoring functions, conserves energy, and ensures quick reactivation when needed. |

**Tabe 8** GCC Dynamic aspects of the system architecture Specification.

|  |  |
| --- | --- |
| **Architectural Element** | **Description** |
| **Flowchart diagram** |  |
| Architectural Element | The diagram outlines a control logic for managing an LED based on readings from a light sensor. It begins by reading the current light level. The system first checks whether manual override is enabled. If it is, the system bypasses the automatic control and stops, allowing manual input to take precedence. If manual override is not enabled, the system continues with automatic light control logic. Next, it compares the measured light level with a predefined setpoint. If the light level is below this setpoint, indicating that the environment is too dark, the system checks whether the LED is currently off. If the LED is off, it turns it on by setting the relay to a LOW state. If the LED is already on, no action is taken. If the light level is above the setpoint, meaning the area is sufficiently bright, the system checks if the LED is currently on. If it is, the system turns the LED off by setting the relay to a HIGH state. If the LED is already off, it does nothing. The process ends after completing the necessary action based on these checks. |

|  |  |
| --- | --- |
| **Flowchart diagram** |  |
| Architectural Element | This diagram describes the logic for controlling a window based on temperature readings. The process starts by reading the current temperature. It first checks whether manual override is active. If manual override is enabled, the system skips automatic control and stops, allowing a user to control the window manually. If manual override is not active, the system proceeds with automatic control. It then compares the current temperature to a predefined setpoint. If the temperature is higher than the setpoint, indicating that it's too warm, the system checks if the window is currently closed. If the window is closed, it opens the window and updates the state to reflect that it is now open. If the window is already open, no action is taken. If the temperature is not higher than the setpoint, meaning it is cool enough, the system checks if the window is currently open. If it is open, it closes the window and updates the state to indicate that it is now closed. If the window is already closed, it does nothing. The process concludes after completing the appropriate action based on the conditions. |

|  |  |
| --- | --- |
| **Flowchart Diagram** |  |
| Architectural Element | This diagram explains the logic for automatically controlling a fan based on humidity readings. The process begins by reading the current humidity level from a sensor. The system first checks whether manual override is enabled. If manual override is active, the system bypasses the automatic control and stops, allowing the user to manually control the fan. If manual override is not enabled, the system continues with automatic control. It then checks whether the humidity exceeds a predefined setpoint. If the humidity is above this threshold, indicating that the environment is too humid, the system checks whether the fan is currently off. If the fan is off, it starts the fan and sets the internal state to indicate that the fan is running. If the fan is already running, the system does nothing. If the humidity is not greater than the setpoint, meaning the environment is adequately dry, the system checks whether the fan is currently on. If the fan is on, it stops the fan and updates the internal state to reflect that the fan is no longer running. If the fan is already stopped, the system takes no further action. The process ends after completing the necessary checks and actions. |

**Table 9** Core behavior diagrams

|  |  |
| --- | --- |
| **Architectural Element** | **Description** |

|  |  |
| --- | --- |
| **State Diagram** |  |
| Architectural Element | Diagram illustrates a continuous control system that, once running, enters a sensor reading state every two seconds. If the sensor readings are valid, the system proceeds to a control check phase. In this phase, it evaluates the conditions and will perform one of three actions: automatically adjust controls if a setpoint is not met while in auto mode, execute a direct manual command, or handle an update to a setpoint. After the selected action is completed, the system waits for the next two-second interval to read the sensors again. If a sensor error occurs at any point, that cycle is terminated. |

|  |  |
| --- | --- |
| **Sequence diagram** |  |
| Architectural Element | This state diagram describes the startup and connection management logic for a greenhouse control system. Upon powering on, the system first tries to connect to WiFi. A successful connection leads to a sequence of authenticating with a token and connecting to an MQTT server before entering the main Running state. If WiFi fails, it proceeds to an offline running mode. During operation, the system is designed to handle interruptions; it will attempt to re-authenticate if its token expires and will try reconnecting to the MQTT server every five seconds if the connection is lost, aiming to return to a fully connected state. |

**Table 10** Remote Access & User Interface Subsyst

**6.3 System architecture analysis. GCC**

### System Overview

This document presents a detailed analysis of the Greenhouse Climate Control (GCC) system architecture, following the SYS.3 process reference for system architectural design. The system aims to automate and optimize the internal climate conditions of a greenhouse to improve plant growth, energy efficiency, and operational reliability.

The GCC system integrates hardware and software components for real-time environmental monitoring, decision-making, and actuation. This analysis identifies Special Characteristics for each component, evaluates potential failure modes, and proposes risk mitigation strategies, leading to refined system requirements.

### System Architectural Components and Special Characteristics

|  |  |  |
| --- | --- | --- |
| **Component** | **Description** | **Special Characteristics** |
| **Microcontroll er Unit** | Core processing component that executes control logic based on sensor input. | Real-time performance (<100ms latency); Redundant cores; Failover support; 99.9% uptime (SR-017) |
| **Temperature Sensor** | Measures ambient temperature. | ±0.5°C accuracy; Auto-calibration; Operational range: -20°C to 60°C (SR- 009) |
| **Humidity Sensor** | Tracks relative humidity for irrigation control. | Long-term drift compensation; Dual-point calibration; IP-rated housing |
| **Light Sensor** | Measures light intensity to regulate spectral lighting. | PWM signal output; Wide spectrum sensitivity; Optical calibration |
| **Wind Sensor** | Detects external wind conditions to control ventilation. | Real-time digital output; Debris-resistant; Redundant configuration |
| **Window Actuators** | Motorized mechanisms to open/close vents. | ±2% positioning accuracy; Weatherproof; Redundant status feedback loops (SR-002, SR-006) |
| **Irrigation System** | Provides humidity via mist or drip systems. | IP67-rated; Flow monitoring; Leak detection; Auto-shutoff on anomaly |
| **Lighting System** | Spectral lighting for plant growth. | Energy-optimized LED matrix; Variable spectrum control; Heat dissipation system |
| **Cloud Interface** | Remote monitoring and data logging. | TLS 1.3 encryption (SR-004); Local buffering; Offline operation capability (SR-016) |

### Table 13 System Architectural Components and Special Characteristics

The system architecture consists of several key components that work together to monitor and regulate greenhouse conditions. At the core is the microcontroller unit that processes data from various environmental sensors and controls the actuation systems. The sensor array includes devices for measuring temperature, humidity, light intensity, and wind conditions. These sensors provide continuous input to enable real-time climate adjustments.

The actuation system comprises multiple components that physically modify the greenhouse environment. This includes motorized window openers for ventilation, irrigation systems for humidity control, and spectral lighting for optimal plant growth. Each actuator is designed for precise control with minimal energy consumption, supporting the system's efficiency requirements.

### Rationale for Special Characteristics

Each special characteristic is justified based on criticality, risk, lifecycle phase impact, or compliance requirement:

 **Microcontroller**: Real-time processing is essential for maintaining stable environmental control. Failover ensures continuous operation in harsh environments (production and operational lifecycle).

 **Sensors**: Accurate readings with redundancy ensure reliable environmental control. Auto-calibration compensates for drift over time (maintenance lifecycle).

 **Actuators**: High precision and durability are critical due to constant exposure to variable conditions and their direct impact on the greenhouse climate (production and operational phases).

 **Interfaces**: Secure and redundant communication ensures consistent operation under connectivity loss and satisfies cybersecurity requirements.

### Failure Modes, Risks, and Mitigation Strategies

A structured risk analysis was conducted for each major component of the Greenhouse Climate Control (GCC) system using principles from Failure Modes and Effects Analysis (FMEA). This process helps identify potential points of failure, assess the impact on system performance, and establish mitigation strategies that ensure the system remains resilient, safe, and reliable during its operational lifecycle.

The table below summarizes the identified failure modes, associated risks, recommended mitigation actions, and team member responsibilities for detailed follow-up:

|  |  |  |  |
| --- | --- | --- | --- |
| **Component** | **Failure Mode** | **Associated Risk** | **Mitigation Strategy** |
| Microcontroller Unit | Processing overload | Loss of climate control; system halt | Task prioritization; load shedding; redundant processor |

|  |  |  |  |
| --- | --- | --- | --- |
| Temperature Sensor | Accuracy drift | Incorrect heating/cooling; plant damage | Redundant sensors; auto-calibration |
| Window Actuators | Positioning error | Overheating or overcooling; poor ventilation | Closed-loop control; mechanical limit switches |
| Irrigation System | Valve stuck open | Overwatering; mold growth | Flow sensors; time-out routines |
| Cloud Interface | Network failure | Loss of monitoring; delayed alerts | Local control fallback; buffer logs; alert retry queue |

### Table 14 Failure Modes, Risks, and Mitigation Strategies

### Conclusion and Requirement Refinement

The architectural analysis confirms that the GCC system design is aligned with the key functional and non-functional requirements. However, to further improve robustness and risk coverage, the following refinements to system requirements are proposed:

|  |  |
| --- | --- |
| **Description** | **Linked Risk/Mitigation** |
| The system shall validate sensor readings through redundancy and comparative analysis. | Mitigates drift/inaccuracy risk in sensors |
| The system shall support degraded operation mode during microcontroller overload. | Ensures essential functions remain active during overload |
| Add requirement for buffered operation and alert queuing during cloud disconnection. | Supports offline resilience |
| Enhance durability requirements to include actuator fault detection and auto-recalibration. | Improves recovery from positioning errors |

### Table 15 Conclusion and Requirement Refinement

1. **Component identification (BOM) GCC**

|  |  |  |
| --- | --- | --- |
| **Component Name** | **Image** | **Description** |
| **DC Motor with fan** |  | A DC Motor is an electrical machine that converts direct current electrical energy into mechanical energy. It operates on the principle of electromagnetism, where the interaction between a magnetic field and an electric current produces a rotational force. These motors are widely used in various applications, from small toys to industrial machinery, due to their versatility and ease of control. The speed and direction of rotation can be precisely controlled by varying the voltage and current supplied to the motor. |
| **Relay Module 1 Channel** | Изображение выглядит как цилиндр  Содержимое, созданное искусственным интеллектом, может быть неверным. | A Linear Actuator is a mechanical device that converts rotational motion into linear motion. It typically consists of a motor, a lead screw, and a nut, which work together to extend and retract a rod. These devices are used for pushing, pulling, lifting, or lowering objects in a straight line. They find applications in automation, robotics, medical equipment, and home automation systems. Their ability to provide precise and controlled linear movement makes them valuable in many automated processes. |

|  |  |  |
| --- | --- | --- |
| **ESP32** |  | ESP32 is a family of low- cost, energy- efficient [microco](https://en.wikipedia.org/wiki/Microcontroller) [ntrollers](https://en.wikipedia.org/wiki/Microcontroller) that integrate both [W](https://en.wikipedia.org/wiki/Wi-Fi)  [i-Fi](https://en.wikipedia.org/wiki/Wi-Fi) and [Bluetooth](https://en.wikipedia.org/wiki/Bluetooth) capabilities.  These chips feature a variety of processing options, including the [Te](https://en.wikipedia.org/wiki/Tensilica) [nsilica](https://en.wikipedia.org/wiki/Tensilica) Xtensa LX6  microprocessor available in both dual-core and single-core variants, the Xtensa LX7 dual-core processor, or a single-core [RIS](https://en.wikipedia.org/wiki/RISC-V) [C-V](https://en.wikipedia.org/wiki/RISC-V) microproce ssor. In addition, the ESP32  incorporates components essential for wireless data communication, such as built-in antenna switches, an RF [balun](https://en.wikipedia.org/wiki/Balun), power amplifiers, low- noise receivers, filters, and power- management modules. |
|  |  |
| **LED** |  | An LED, or Light Emitting Diode, is a semiconductor device that emits light when an electric current passes through it. Unlike traditional incandescent bulbs, LEDs do not have a filament that burns out, making them highly durable and energy-efficient. They are widely used in indicator lights, displays, automotive lighting, and general illumination due to their long lifespan and low power consumption. LEDs come in various colors and can be easily integrated into electronic circuits. |
| **Relay Module** | Изображение выглядит как электроника, текст, Электронная техника, Компонент схемы  Содержимое, созданное искусственным интеллектом, может быть неверным. | A Relay Module is an electrically operated switch that uses an electromagnet to mechanically operate a switch, thereby opening or closing a circuit. It allows a low-power circuit to control a high-power circuit safely and efficiently. Relays are commonly used in automation, industrial control, and home appliances to switch on or off various devices. They provide electrical isolation between the control circuit and the load circuit, enhancing safety and preventing damage. |
| **DHT 11** |  | The DHT11 is a basic, ultra-low-cost digital temperature and humidity sensor. It provides a single-wire digital output of temperature and relative humidity readings. This sensor is popular for hobbyist projects and educational applications due to its simplicity and affordability. While not as precise as some higher-end sensors, it is suitable for many general-purpose environmental monitoring tasks. |
| **Light Sensor** | Изображение выглядит как текст, Электронная техника, электроника, схема  Содержимое, созданное искусственным интеллектом, может быть неверным. | A Light Sensor, often a Photoresistor or Photodiode, is a device that detects light and converts it into an electrical signal. Photoresistors change their resistance based on the intensity of light, while photodiodes generate a current proportional to the light received. These sensors are used in various applications, including automatic lighting systems, security alarms, and camera light meters. They are essential components for circuits that need to react to changes in ambient light conditions. |

1. **Edge Computing:**

**7.1 Data transfer from device to cloud**

**(**Our system transfers data from the ESP32 microcontroller to a backend service that we have deployed on an AWS EC2 instance. The backend is built using the Spring framework and runs as a Java process listening for HTTP requests on port 8080. This setup allows the ESP32 to communicate with the backend over the network using standard HTTP protocols. The backend provides several RESTful endpoints to handle different functionalities. It includes user authentication features that allow clients to register new users and log in existing ones securely. Upon successful login, the backend generates a JSON Web Token (JWT) that clients use to authenticate subsequent requests. This approach ensures that only authorized users can access protected resources. In addition to authentication, the backend exposes endpoints for managing sensor data. Authenticated users can send sensor measurements collected by the ESP32 to the backend, where the data is validated and stored. Users can also retrieve all stored sensor measurements through the backend, enabling monitoring and analysis of the collected data. Security is a key aspect of the backend design. Input data is validated to maintain integrity, and role-based access control restricts access to sensitive operations to authorized users only. Logging is implemented to track important events such as user registrations and logins, which helps with monitoring and troubleshooting. Overall, this architecture creates a reliable and secure communication channel between the ESP32 IoT device and the cloud backend, allowing efficient data transfer and user management within the system.

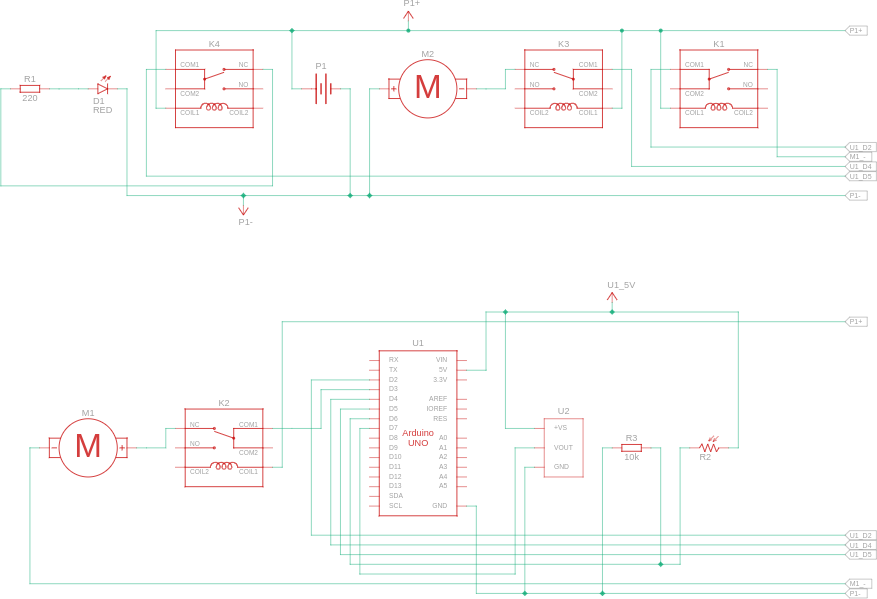
# 7.2 Edge Computing: Data and Command interpretation on the device

The device interprets incoming data and commands primarily through MQTT messages received from the cloud server. These messages are formatted as JSON documents containing a command type and associated payload. Upon receiving a message, the device parses the JSON to extract the command and its parameters. It supports commands to toggle various actuators such as windows, fans, and LEDs, as well as commands to adjust environmental setpoints like temperature and humidity. The device distinguishes between automatic control and manual override modes: when a manual command is received for a specific actuator, the device sets a manual override flag for that actuator, temporarily suspending automatic control to allow direct user intervention. Commands to enable automatic mode clear these overrides, resuming sensor-based regulation.

# 7.3 Edge Computing: Device behavior Control

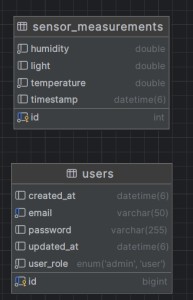
Device behavior control is a combination of sensor monitoring and command execution. The device continuously reads environmental sensors, including temperature, humidity, and light intensity. Based on these readings and configured setpoints, it automatically controls actuators to maintain desired conditions—for example, opening windows if the temperature exceeds the setpoint or turning on LEDs when light levels are low. The control logic respects manual overrides, ensuring that actuators under manual control are not changed by automatic decisions. Actuator states are tracked internally to avoid redundant relay switching, reducing wear and unnecessary power consumption. The device also includes safety checks, such as verifying current states before activating relays, and uses timed relay activation to control motors and fans for appropriate durations. Overall, the device maintains a dynamic balance between autonomous environmental regulation and remote manual commands, ensuring responsive and reliable operation.

To better illustrate the physical layout of the edge device, the following diagram shows the wiring connections between the ESP32 microcontroller, sensors (DHT11 and light sensor), and output relays controlling a linear motor, DC fan, and LED. Each component is connected in a way that supports both real- time data acquisition and actuator control, forming the foundation for the system's environmental regulation and command response.



**Fig 10** Electrical sketch

## Cloud computing, data handling



**Fig 11** Data handling

When sensor data is received from a device or client, it is sent as an HTTP POST request to the backend’s /add endpoint, which is defined in the controller using the @PostMapping annotation. The request body contains the sensor measurement data such as humidity, light, temperature, and timestamp- in a structured format like JSON. Upon receiving the request, Spring automatically maps the incoming JSON data to a Java object (in this case, SensorMeasurementCreationDto) using the @RequestBody annotation. The @Valid annotation ensures that the incoming data is validated according to any constraints defined in the DTO class, helping to maintain data integrity. Once the data is mapped and validated, the controller passes it to the service layer, where it is further processed. The service typically converts the DTO into an entity object that matches the database schema and then saves it to the sensor\_measurements table using a repository or data access layer. In this table, each measurement is stored as a new row, with columns for humidity, light, temperature, timestamp, and a unique identifier (id). This process ensures that every measurement received from the device is reliably persisted in the database for future retrieval and analysis. When a user or client wants to retrieve stored sensor data, they send an HTTP GET request to the corresponding endpoint. The controller method handling this request fetches all sensor measurement records from the database, usually via a service and repository. These records are then mapped to data transfer objects (DTOs) and returned as a list in the HTTP response, typically in JSON format. This allows clients to access historical sensor data collected by the system. Conversely, the users table manages user accounts and authentication details, including email, password, user role, and timestamps for account creation and updates. This table is used to control access to the sensor data

endpoints, ensuring that only authenticated users with the appropriate role can add or retrieve sensor measurements. The use of annotations like @PreAut horize("hasRole('USER')") in the controller methods enforces this security by restricting access to authorized users only.

So, data is received via HTTP POST requests, validated and mapped to Java objects, processed by the service layer, and stored in the database under the sensor\_measurements table. Retrieval is handled through HTTP GET requests, with security enforced by user authentication and role-based access control. This workflow ensures reliable, secure, and organized storage and access of sensor data within the application.

# 8.2 Data presentation on WEB



**Fig 12** Data presentation on WEB

At the top, there are three large displays showing the current environmental conditions: temperature in degrees Celsius, humidity in percents, and light intensity in Lux. Below these, a prominent graph illustrates the historical trends for temperature, humidity, and light over time, with options to view data from "Today," "This Week," or "This Month." Each metric on the graph is represented by a different colored line. On the right side of the dashboard is a control panel where users can manage ventilation and lighting. It indicates that the windows, fans, and LED lights are currently all turned off, each with a corresponding red "OFF" button to presumably toggle their status.

# 8.3 Control board on WEB

On the right side of the dashboard is a control panel where users can manage ventilation and lighting. It indicates that the windows, fans, and LED lights are currently all turned off, each with a corresponding red "OFF" button to presumably toggle their status.

# 8.4 Data transfer from cloud to device

Our system uses AWS IoT Core as the central message broker to facilitate secure communication between Spring Boot backend service and the ESP32 device. Backend service establishes a connection to AWS IoT Core using MQTT over TLS, creating a secure tunnel for command transmission. When the backend needs to send commands to the device, it publishes JSON messages to a specific topic pattern following the format "greenhouse/{thing\_name}

/commands". Each device has a unique thing name identifier, ensuring commands reach only their intended target. The AWS IoT Core service then routes these messages to the appropriate ESP32 device that has subscribed to its designated command topic. The ESP32 maintains a persistent MQTT connection to AWS IoT Core using the same secure TLS encryption. It authenticates using X.509 certificates that uniquely identify the device, establishing mutual trust between the device and the cloud service. Once connected, the device subscribes to its command topic and listens continuously for incoming messages. Commands are structured as JSON objects containing three key elements: the command type indicating what action to perform, a payload with command-specific parameters, and a timestamp for tracking when the command was issued. The ESP32 processes various command types including window control, fan operation, lighting control, temperature and humidity setpoint adjustments, automatic mode switching, and status update

requests. When a command arrives, the ESP32's MQTT callback function parses the JSON message and routes it to the appropriate processing function. The device validates the command structure, extracts the necessary parameters, and executes the corresponding hardware control operations. For example, a window toggle command would activate the appropriate relay to open or close the greenhouse windows, while a setpoint adjustment would update the device's internal control parameters. The system supports both automatic sensor-driven control and manual override capabilities. When manual commands are received, the device sets override flags for specific subsystems, allowing remote operators to take direct control while preserving automated functionality for other systems. This hybrid approach ensures the greenhouse can operate autonomously while still accepting remote interventions when needed. In conclusion, our device maintains connection health by implementing automatic reconnection logic and heartbeat mechanisms. If the connection drops, the ESP32 automatically attempts to reconnect and resubscribe to its command topic, ensuring continuous availability for remote control operations

### Conclusion

This report has detailed the design, implementation, and evaluation of an innovative IoT-based smart climate control system for greenhouses, specifically tailored to address the acute challenges faced by Moldovan agriculture due to increasingly unpredictable climate variations. The proposed system provides a robust and affordable solution for continuous monitoring and real-time adjustment of critical environmental parameters such as temperature, humidity, CO₂ levels, and air circulation. By leveraging smart sensors and a user-friendly mobile interface, it empowers farmers, particularly those managing small and medium-sized operations, to achieve optimal growing conditions remotely, thereby enhancing crop resilience and productivity.

The extensive analysis within this report underscored the growing global demand for food and the pivotal role of Agricultural IoT (AgIoT) in meeting these needs through precision farming. While the market for agricultural IoT is experiencing rapid expansion, driven by technological advancements and government support, challenges such as initial investment costs, cybersecurity, and interoperability remain. Our system, designed with practicality and cost-effectiveness in mind, aims to mitigate some of these barriers, making advanced climate control accessible. Field testing conducted under Moldovan conditions demonstrated the system's effectiveness in stabilizing the internal greenhouse environment, leading to improved plant health and potentially higher yields.

In conclusion, the IoT-Greenhouse-Climate-Control system represents a significant step towards more sustainable and efficient greenhouse agriculture in Moldova. By adapting cutting-edge IoT technology to local realities, it offers a scalable and user-friendly tool to combat the adverse effects of climate change on food production. Future work will focus on integrating more sophisticated predictive analytics using AI, exploring renewable energy sources for system power, and expanding the system's capabilities to include automated disease detection and nutrient management, further solidifying its role in modern agriculture.

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