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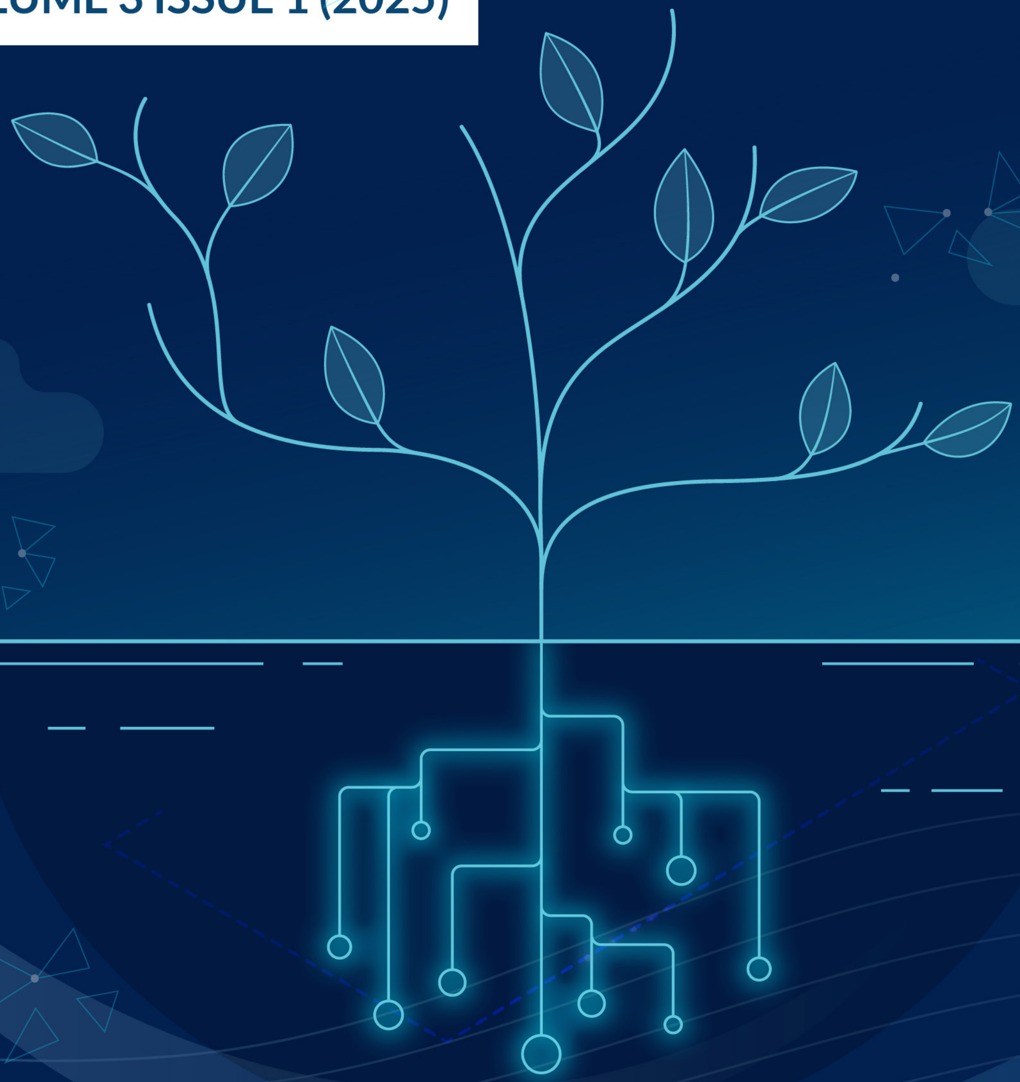

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# Enhancing Protected Agriculture with Smart Technologies: A Review of Innovations for Climate-Resilient Farming

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## ABSTRACT

The enhanced consequences of climate change increase the need for effective sustainability efforts. Protected agriculture, comprising greenhouses, net houses, and vertical farms, provides a good answer as it offers controlled buffers against climatic extremes that threaten crops. The use of smart technologies like IoT monitoring, AI, automation, blockchain and precision farming has advanced the possibilities of these systems. All of these work together to allow monitoring and real-time decision making, optimize resource usage, boost productivity, increase transparency and traceability within the supply chain. Some of the barriers that hinder change are the high costs, lack of technical skills, and limited infrastructure. This paper aims to systematically analyzes recent developments in protected agriculture and autonomous farming systems considering barriers to implementation and explore avenues such as innovative low-cost smart devices, renewable powered systems, and non-adaptive resilient crops integrated with sustainability focused climate policies. By highlighting these innovations, this paper will motivate policymakers, researchers, and practitioners towards devising climate-resilient food systems.

## INTRODUCTION

The socioeconomic effects of climate change, such as the increase in average global temperatures, inconsistent rainfall, and the rise in frequency of natural disasters, have contributed to the destabilization of agricultural systems around the world. Agriculture is a critical component of a region's food security and people's livelihood. It is also a double-edged sword, it sustains life while at the same time contributes to climate change with a significant portion of greenhouse gas emissions (Kabato *et al.*, 2025; Mešić *et al.*, 2024). The projections point out that areas in the tropics and subtropics, which already have low agricultural productivity, will face further reductions, which will severely impact the food supply. This highlights the need for the development of environmentally friendly, adaptable, and sustainable agriculture solutions.

Net houses, vertical farming, and green houses are example of protected agriculture which has align itself as an anchor for climate strategies. These environments control external conditions. Thus, ensuring consistent production even during volatile weather periods (Hoque *et al.*, 2025). Protected agriculture optimizes microclimate formation with the aim of achieving better chemical dependence reduction, water-use efficiency, increased crop yield and growing seasons, improving crop resilience (Ayilara *et al*, 2025). Their ability to protect crops from the growing pest and disease pressure resulting from climate change helps highlight the importance of such systems (Rani *et al*, 2025). In addition, resource scarce regions are able to farm due to increased efficiency with limited land through innovations in hydroponics and aeroponics systems within protected agriculture (Bhattacharya & Bansal, 2025).

Smart farming technologies integrated with the Internet of Things (IoT) have significantly enhanced the adaptability of protected agriculture to climate-related stressors. IoT-based systems enable real-time environmental monitoring, tracking soil moisture, temperature, and humidity, which facilitates automated decision-making for irrigation, ventilation, and nutrient delivery (Gowda *et al.*, 2021). This enhances both crop productivity and climate resilience. Artificial Intelligence (AI) algorithms further contribute by analyzing sensor data to predict plant diseases and pest outbreaks, allowing timely and preventive interventions (Kamilaris & Prenafeta-Boldú, 2018). Robotics and drones are increasingly deployed to automate labor-intensive tasks such as seeding, spraying, and harvesting, improving operational efficiency and reducing dependency on manual labor (Tsouros *et al.*, 2019). Additionally, blockchain technology is being explored to ensure traceability and transparency in agri-food supply chains, strengthening data integrity and trust among stakeholders (Casino *et al.*, 2019).

These technological advancements do not solely provide operational improvements, but rather optimize the agriculture sector productivity, which is vital for building resiliency to climate change. Precision agriculture technologies contribute to minimizing input wastes and environmentally harmful emissions, such as the greenhouse gases produced from over-fertilization and inefficient irrigation systems (Gryshova *et al.*, 2024). Additionally, the use of solar panels to power automated greenhouses showcases the incorporation of renewables which bolsters agricultural development that is low in carbon emissions (Mešić *et al.*, 2024). The combination of smart technologies and protected agriculture is critical in addressing the disparity between the need for more food and the impact of climate change.

This review reports an attempt to outline and analyze



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the most recent developments in smart technologies for protected agriculture with an emphasis on fostering climate change resilience. It is designed to follow stepwise the development of new approaches, assess existing technological solutions, and analyze the inadequacies that impede effective utilization. This work identifies gaps in research and calls for policy actions necessary to shift towards sustainable, technology-based agriculture (Prajapati & Pandya, 2025; Rao & Ranganath, 2025). This paper aims to offer evidence from interdisciplinary studies and practice to help policymakers, scholars, and practitioners devise strategies for building agricultural systems with controlled adaptability for increasingly uncertain climate conditions.

## LITERATURE REVIEW

### Current Smart Technologies in Protected Agriculture

### IoT Systems and Environmental Sensors

The use of IoT systems and environmental sensors underscores the importance of real-time monitoring for the automation of various processes in protected agriculture. These systems are vital in controlling the basic parameters of humidity, soil moisture, temperature and light intensity, providing dynamic changes which are important to the health and productivity of plants (Shukla *et al*., 2025). Through the utilization of wireless sensor networks, farmers are provided with real-time information regarding the microclimatic processes occurring in the greenhouses, protecting the crops from remaining within suboptimal growth conditions even when external factors change (Ojha *et al*., 2015).

High-level IoT-enabled environmental monitoring systems consist of a set of sensors that are appropriately distributed over the different zones of a greenhouse. Their main function is to provide data at high densities. Soil moisture sensors notify the system for irrigation scheduling, and temperature and humidity sensors perform the functions of automatic control for ventilation, heating, cooling and conditioning systems associated with the greenhouse. (Bhattacharya & Bansal, 2025). These systems have been acclaimed for their ability to minimize the amount of water consumed by as much as 50%, crucial for regions facing droughts due to climate change. Sensor-based smart irrigation can significantly enhance water use efficiency, as demonstrated in a recent study on cherry tomato greenhouses, where precision irrigation models led to improved yield and water savings (Wang *et al*., 2025).

One of the most remarkable Sundrop Farms in Port Augusta, Australia, is exemplifying interdisciplinary technology integration. Sundrop Farms operates in an IoT-enabled arid land, which, coupled with renewable energy, such as solar energy and desalination, allows for vegetables to be grown all year round (Shukla *et al*., 2025). Crop optimization is achieved through automatic environmental condition control, calibrated by real-time climate data sensors situated within the facility. The increase in technological scaling on Sundrop Farms promotes agricultural development in water-scarce areas, exhibiting innovative sustainability (Shukla *et al*., 2025).

In addition, remote monitoring together with predictive capabilities is made possible through analytics and cloud computing within IoT systems. Farmers' real time access to vital data through mobile gadgets increases efficiency and responsiveness to critical decision-making, courtesy of advanced cloud systems integration (Ojha *et al*., 2015). Maintenance or pest infestation and other stress condition forecasts derived from historical and live data are possible through predictive models, and this fosters proactive risk interventions while maintaining yield and stability (Bhattacharya & Bansal, 2025).

Such developments have highlighted the importance of IoT systems and environmental sensors in enhancing climate resilient farming operations. In addition to improving environmental sustainability and the efficient use of resources, these systems enable farmers to control sophisticated growing systems with accuracy and foresight.

### Artificial Intelligence and Machine Learning

The opportunities presented by Artificial Intelligence (AI) and Machine Learning (ML) technologies are being recognized for their potential contributions in protected agriculture and farming under climatic stress. AI-driven predictive analytics aids in promptly diagnosing and preventing pest and disease epidemics in closed systems like greenhouses. This not only safeguards crop health but also minimizes the need for chemical interventions, thus promoting more sustainable farming practices (Aziz *et al*., 2025; Kariyanna & Sowjanya, 2025).

As an example, remote sensing incorporated with AI algorithms provides alerts to farmers about historical trend-based predictive analytics empowering timely pest-management (Aziz *et al*., 2025). Another area of AI impact is automation related to climate control, which poses a significant opportunity. AI-powered climate-control in greenhouses can optimally manage and adjust environmental parameters like temperature, air humidity, light radiation, etc., in-situ to foster the best growing conditions (Gryshova *et al*., 2024). In addition to yield quality improvement, precision control saves energy by reducing excess supply.

These systems utilize deep learning networks that have been trained on extensive datasets to preemptively forecast weather-related disruptions and modify greenhouse operations accordingly to maintain optimal conditions for growth, which ensures that plants are thriving.

Moreover, interdisciplinary study highlights the effect of combining Artificial Intelligence with IoT networks. This integration magnifies the level of monitoring and control, forming a dynamic responsive ecosystem of agriculture (Ahmad *et al*., 2025). AI not only facilitates environmental surveillance but also actively participates in decision support systems which aid in monitoring data and managing resources efficiently (Botero-Valencia *et al*., 2025).

Further evidence in support of the global transformation of farming into a data-driven activity is that AI technologies are able to integrate a multitude of data sources and analyze them in real time to offer insightful information on pest activity, which enhances crop management significantly (Maryam *et al.*, 2025).

To summarize, the integration of AI and Machine Learning in protected agriculture systems is transforming the world of farming towards climate resilient agriculture systems. Enhancing predictive models and automating controls of the environmental systems not only augments productivity but also ensures sustainability in the face of uncertainties brought about by climate changes.

**Automation & Robotics**

The use of automation and robotics in protected agriculture has led to the development of systems for climate-resilient farming. Above all else, the importance of Automated irrigation systems is unquestionable. They provide specific consider of water delivery to crops by economically using water, due to real-time environmental data monitoring (Indurthi *et al.*, 2024). Relying on sensor networks and automation algorithms, these systems dynamically adjust irrigation schedules according to soil moisture levels, rate of evapotranspiration, and climate forecasts, managing to stabilize yield regardless of climate stress volatility (Tzounis *et al.*, 2017).

Drone surveillance technologies have grown into great powerful tools in smart agriculture. They allow for real-time monitoring of the entire farm's pests, crops diseases, and irrigation efficiency (Atianashie *et al.*, 2025). Drones fitted with multispectral cameras and tanks, able to scan and monitor farmland, provide farmers with valuable insights using drone mounted cameras, allowing them to take swift measures which stand to avert possible crop losses (Madec *et al.*, 2017). Drones also take a big part in precision spraying and sowing, making the work of an agrochemical operator less labor reliant (Assimakopoulos *et al.*, 2025).

The application of robotics in harvesting is yet another modern innovation in protected growing environments. Examples like Agrobot and Octinion robots demonstrate how complex robotic systems are developed to automatically identify, pick, and process soft fruits and vegetables with minimal human involvement ensuring that harvesting quality is maintained and labor cost issues are addressed (Janbandhu *et al.*, 2024). These robots are equipped with highly advanced vision systems, and AI systems, which make it possible for the robots to navigate through greenhouse rows and harvest crops (Ahmad *et al.*, 2024). Furthermore, new developments in automated greenhouse robotics go beyond harvesting to include pruning, pollination, and disease surveillance, thereby improving overall farm management (Gupta & Gupta, 2024).

Not only do the integration of these technologies improve productivity, but the achievement of environmental sustainability via reduced greenhouse gas emissions and improved resource utilization is enhanced (Ayilara *et al.*, 2025). The growing automation and robotics will continue to be of utmost importance to managed agricultural systems, with climate variability in focus serving as a pointer to the shift needed in the approach to ensuring food security.

**Blockchain and Data Management**

The use of blockchain technology for improving traceability and security capabilities in protected agriculture is on the rise. As concerns related to food safety, sustainability, and supply chains transcend geographical boundaries, blockchain seeks to resolve these issues by providing a promise ledger that guarantees visibility throughout the agricultural supply chain (Polwaththa *et al.*, 2024). This trust increases consumer and stakeholder confidence, as well as improves the tracking of agricultural produce from farm to fork (Lin *et al.*, 2019). Through blockchain, the entire agricultural cycle including planting, harvesting, processing, packaging, and distribution can be recorded reducing risks of fraud and contamination (Tian, 2016).

In Protected Agriculture, the integration of blockchain systems with greenhouse management platforms enables the captured environmental data, production data and post-harvest handling data to be tracked in real-time (Shukla *et al.*, 2025). Data stream security guarantees that sensitive information about the farm such as crop state and resource consumption is safeguarded from unwanted intrusion while offering protection to the data (Ahmad *et al.*, 2025). Strong data management frameworks provided by enhanced encryption mechanisms and distributed data repositories allows farmers the confidence to share information with partners within the supply chain.

Furthermore, blockchain technology enables the use of automated smart contracts which facilitate transactions between producers, distributors, and retailers. Shipment and payment processes for services are automated for set procedures which makes business transactions more effective (Tripoli & Schmidhuber, 2018). Joining blockchain with IoT sensors makes data collection more accurate since the sensors capturing information about soil health, humidity, and temperature are stored and can be retrieved in a secure manner for audits or certifications (Tian, 2017).

Global studies have documented the use of blockchain technology to optimize logistic activities and curb waste in the supply chains as an effective means of reducing greenhouse gas emissions (Shukla *et al.*, 2025; Treiblmaier, 2019). Additionally, the automated tracking made possible by blockchain helps farmers respond faster to changes in factors such as climate, pest activities, and other supply chain related disruptions increasing overall climate adaptation (Bhattacharya & Bansal, 2025).

To conclude, blockchain technology with secure data management systems is essential in modern protected agriculture. This technology provides farmers in the industry with unquestionable proof for product safety and authenticity. Furthermore, strategic plans are made based on information that is certain and incapable of being altered which helps in developing farming systems that are environmentally sustainable and climate resilient.

**Remote Sensing and Precision Farming**

The use of satellites for remote sensing has advanced precision agriculture by offering high-definition images and real-time information on crops, soil, and environmental stressors. Satellite platforms through multispectral and hyperspectral imaging can detect small variations in vegetation indices which helps in early detection of nutrient deficiency, pest damage, and disease outbreaks (Petrovic & Csambalik, 2025). This approach based on data is improving protected agriculture decision making by allowing timely action to be taken thus lowering resource expenditure (Assimakopoulos *et al.*, 2025).

Besides, incorporating satellite imaging into greenhouse monitoring systems improves remote diagnostics. Farmers, for example, can monitor soil moisture, canopy temperature, and chlorophyll content throughout extensive greenhouse complexes, even multi-site geographically dispersed operations (Indurthi *et al.*, 2024). This capability not only provides cost-effective spatial response mitigations but also reduces operational expenditures by alleviating the need for manual inspections (Shaari *et al.*, 2024).

Alongside remote sensing, Variable Rate Technology (VRT) allows for the precise application of water, fertilizers, and pesticides according to specific site requirements. VRT systems utilize geospatial data obtained through remote sensing to produce prescription maps that direct machinery to apply inputs only where necessary, thereby increasing resource use efficiency and environmental sustainability (Wang *et al.*, 2025). Studies prove the adoption of VRT can cut input costs by as much as 30%, and additionally reduce greenhouse gas emissions resulting from the over-application of agrochemicals (Keskin & Sekerli, 2024).

Emerging applications of VRT for protected agriculture include automated fertigation systems, which adjust nutrient delivery based on real-time soil analyses and plant health indicators. Also, remote sensing drones equipped with VRT capabilities allow for precision spraying in closed environments such as greenhouses, further enhancing operational efficiency (Mahmood *et al.*, 2025).

Future developments anticipate deeper integration AI with remote sensing and VRT technologies, creating more advanced systems capable of performing predictive analytics and autonomous farm management (Hayat *et al.*, 2025). This merging promises to transform protected agriculture into a highly accurate, secure, and enduring climate adaptive practice.

**Benefits of Smart Technologies for Climate Resilience**

The application of smart technologies for protected agriculture is one of the most notable innovations that improve climate adaptability while improving sustainability and economic returns of agricultural systems. One of the most notable advantages is related to the drastic enhancement of water-use efficiency with sensor-based irrigation systems. These systems apply water directly to the crop's root zone, using real-time data from soil moisture sensors, weather predictions, and evapotranspiration models (Dileep & Kavitha, 2025). In water scarce regions like most of the Middle East and North Africa, smart irrigation has been shown to decrease water use by up to 40% while maintaining yield (Ali & Benlamri, 2025). IoT-enabled irrigation controllers preemptively modify irrigation schedules dynamically, enabling the alignment of water delivery to the irrigation schedule with the crop water requirement, eliminating overwatering, and minimizing nutrient leaching (Yadav *et al.*, 2025).

Simultaneously, smart agriculture technologies play a remarkable role in lowering greenhouse gas emissions. Modern practices of precision agriculture allow for the selective application of fertilizers and herbicides, hence reducing emissions of nitrous oxide, one of the greenhouse gases, which is also a byproduct of excessive use of fertilizers (Akhil *et al.*, 2025). Also, solar greenhouses utilize climatic automation systems that dynamically adjust ventilation, heating, and lighting to control energy use and to improve greenhouse productivity (Qureshi *et al.*, 2025). This energy efficiency results in diminished carbon footprints throughout carbon-capturing farming operations. In addition, the use of integrated artificial intelligence (AI) and the IoT with solar irrigation systems further aids in the decarbonization of agriculture (Valov *et al.*, 2025).

Another crucial advantage of smart technologies is enhanced productivity under climate stress. AI-enabled climate management systems include greenhouses and mitigate the effects of temperature extremes, droughts, and unseasonal rainfall (Qureshi *et al.*, 2025). Such systems monitor environmental parameters and dynamically adjust the internal conditions of the greenhouse, which includes providing crops with adequate light, humidity, and $CO_2$ for photosynthesis, even during adverse weather phenomena. This enables farmers to maintain higher and more consistent yields despite the increasing variability of climate conditions (Paul & Bhatia, 2025). In particular, Controlled Environment Agriculture (CEA) technologies enable off-season production, thereby decoupling crop cycles from seasonal dependency and stabilizing food supply chains (Hrustek, 2020).

Above all, smart technologies enhance the quality and market appeal of crops. For instance, farmers can improve the sensory and nutritional value of produce foods by increasing the precision with which nutrients and microclimates are controlled within production ecosystems (Ali & Benlamri, 2025). With smart farming systems, set attributes of uniformity of size, color, and texture that are appreciated by retailers and consumers can be achieved with ease (Yadav *et al.*, 2025). Additionally, the use of integrated blockchains and traceability tools strengthens buyer confidence by offering easy, non-falsified evidence of production practices, environmental practices, and even the product itself (Valov *et al*., 2025). This transparency increases the market competitiveness of crops from smart farms towards premium markets that demand verified sustainable practices which enhances their competitive edge.

As stated, increased environmental resiliency of protected agriculture, smart technologies introduce economic value from increased efficiency of operations, cost savings, and reduction in service expenditure due to enhanced product quality. Moreover, such advancements make smart farming a pillar of climate resilient agriculture that is future ready.

**Challenges and Barriers to Adoption**

The potential of smart technologies in revolutionizing protected agriculture is undeniable, but there are still some barriers in middle and low-income countries associated with systemic issues that prevent wide adoption.

The foremost hurdle, out of all the barriers, is the high initial investment cost of the advanced integrating technologies IoT devices, precision irrigation systems, automated machinery, and climate control systems powered by AI. These technologies involve not just costing out equipment, but also incurring installation, integration, and ongoing maintenance costs, which are quite overwhelming for smallholder farmers and medium-sized enterprises (Klerkx *et al*., 2019; Kimani, 2024). Furthermore, the lack of subsidized credit, low-interest loans, and agricultural support adds to this strain, especially in developing regions. Farmers, especially in volatile agricultural markets, are reluctant to invest in uncertain returns, regardless of how efficient the farming practices will be in the long run (Piot-Lepetit, 2025).

Beyond the financial obstacles, the digital illiteracy associated with rural communities poses a dire threat. Smart farming technologies, such as precision irrigation and yield monitoring systems, require not only specialized knowledge for proper use but also advanced maintenance capabilities. Many of these agricultural workers have little to no experience with smart farming tools. Understanding complex interfaces with steep learning curves often inhibits people from adopting new technologies (Bronson, 2019). There are some training courses and agricultural extension programs, but they frequently lack the depth or sustained intensity that would allow farmers to fully harness these technologies (Piot-Lepetit, 2025). The advanced technologies are continuously evolving, and these need to be integrated with new and existing tools, which requires farmers to constantly reskill (Rose & Chilvers, 2018).

In particular, infrastructure issues pertaining to unreliable rural electrification alongside limited connectivity stand out as additional barriers. The dependable supply of electricity is critical for the operation of sensor networks, automated irrigation systems, and the environmental control units in protected agriculture settings (Malhotra *et al*., 2024; Atif, 2024). Unfortunately, numerous rural regions across Asia and Africa deal with power outages or complete grid disconnection. Moreover, connectivity problems worsen the situation, in the absence of a dependable internet connection, the advantages of monitoring and analyzing data in real-time are mostly out of reach. There is evidence that insufficient broadband infrastructure can stall the deployment of data-driven agricultural practices, or worse, completely disable it (Deichmann *et al*., 2016). While mobile networks and satellite internet technologies are advancing, these options are still out of reach for many farmers.

Data privacy and cybersecurity issues are equally important. A farm's automation level directly corresponds to the amount of sensitive information such as production capacity, crop schedules, and environmental data which is created and communicated across networks. It is strategically important information for improving agricultural efficiency, and, if proper cybersecurity precautions are not in place, it can also be abused (Ahmad, 2025). Agribusinesses and farmers have valid reasons to hesitate incorporating IoT and Cloud-based systems to their operations if there are no safeguards that guarantee data protection from breaches and unauthorized access (Rose & Chilvers, 2018). In addition, agriculture data privacy laws are still in development and not consistently enforced in different territories which increases uncertainty and risk aversion among stakeholders (Bronson, 2019).

These sets of issues should be addressed with techniques that are more holistic. Educating farmers and other stakeholders on modern technologies is just as crucial as improving rural infrastructure and lowering the citizens' health costs. Farmers and other stakeholders have a misconception that advanced smart technology requires advanced skills; thus, it is necessary to provide them with a technical literacy boost. Furthermore, fostering a safe digital agricultural ecosystem will require establishing strong standards for data protection as well as clear policies for data governance.

When tackling these obstacles one after the other, it becomes easier to embrace digitally empowered and climate resilient agriculture.

## MATERIALS AND METHODS

This review paper used a systematic literature review approach to capture the extent of available integration of smart technologies in protected agriculture for climate-resilient farming, and the synthesis of literature addressing the state of knowledge on the same integration. A predetermined process of database searching, the establishment of selection criteria, and data synthesis was followed in order to depict available research, mapping trends and gaps in the area of study.

The literature search was directed toward well-known academic databases with protected smart agriculture technologies publications like ScienceDirect, SpringerLink, IEEE Xplore, and ResearchGate. These platforms have relevance due to their focus in interdisciplinary fields like agriculture, engineering, environmental sciences, and smart technologies. The search period was confined to a ten-year window from 2015 to 2025 to ensure that the review reflects the most contemporary developments and technological advancements relevant to protected agriculture systems and climate resilience.

A set of strategic keywords such as "IoT agriculture," "AI farming," "smart greenhouses," "climate resilience," "precision agriculture," and "automation in protected farming" was developed to facilitate the search. The use of this combination allowed for the capturing of a larger variety of research studies dealing with technological and methodological innovations and climate adaptation approaches in controlled-environment agriculture systems.

In total, over 70 high-quality research papers, peer-reviewed articles, and academic books were reviewed and included based on the inclusion criteria. Within the scope of the review, studies related to protected agriculture, smart technologies, climate resilience in agriculture systems and their protected frameworks were evaluated based on determined relevance, methodological rigor, and contributions towards the understanding of the broader framework of protected agriculture. Considered outside the scope of the review were studies lacking empirical evidence, those published outside the date limits mentioned, and publications neglecting the focus on the integration of smart technologies within protected agriculture.

The categorization of the thematic orientation of the study as including but not limited to advancements in sensor technologies, automation tools, AI applications, and precision farming techniques was utilized in data extraction. Emphasis was placed on the literature concerned with the real-world agricultural contexts and the challenge towards the integration of modern agricultural technologies. In addition, the review identified foundational concepts and emerging concepts in the literature through cross-referencing with the goal of enhancing the coverage on the literature review and capturing both core literature and foreground innovations. The results of the review conducted in this document are compiled within the technology snapshot framework provided in the following sections of the document where these gaps, barriers, and prospects for sustaining protected agriculture systems while facing climate change are critically examined.

## RESULTS AND DISCUSSION

The adoption of smart technologies in protected agriculture practices shifts the farming systems towards sustainable intensification as well as climate smart farming. Escalating concerns to global food systems owing to the impacts of climate change, resource scarcity, and rising food needs put IoT, AI, blockchain, and automation technologies under great consideration (Ahmad *et al.*, 2024; Atianashie *et al.*, 2025). Recent findings suggest that the innovation of technologies into advanced protected agricultural systems not only protects the crops from external stressors, but also optimize resource consumption, productivity, and food safety (Mmbando, 2025; Tiwari *et al.*, 2025).

Incorporating technological innovation such as IoT in environmental sensors and automation tools play an important role in the real-time remote managing and monitoring of greenhouses adaptive systems. Computerized systems permit the real-time modulation of irrigation, nutrient delivery, and ventilation and these enable significant savings in water and energy (Kumar *et al.*, 2025). Integration with solar-powered systems further aids in the advancement towards off grid carbon-neutral farming systems (Ahmad *et al.*, 2024; Atianashie *et al.*, 2025).

The possibilities of predictive agriculture are being advanced by AI and ML. Predictive analytics now provide advanced warning of the presence of pests and diseases which enhances response time while reducing the use of chemical pesticides (Assimakopoulos *et al.*, 2025; Tiwari *et al.*, 2025). Moreover, microclimate automation systems powered by AI underline protected agriculture by ensuring optimal growth conditions of the plants despite weather conditions prevailing outside (Ferrández-Pastor *et al.*, 2016).

Blockchain technology as an innovation for the management of agricultural data due to its offers an incorruptible and transparent ledger, increasing the traceability as well as the food safety of the supply chain (Herrera & Orjuela-Castro, 2021). In conjunction with IoT networks, blockchain improves farm data security and consumer confidence through the authentic documentation of sustainable practices (Kumar *et al.*, 2025). This is important for high value export oriented crops which are cultivated in controlled environments.

Precision agriculture tools such as VRT and remote sensing platforms have reshaped resource management in protected systems. These advanced technologies enable controlled application of inputs which minimizes resource wastage alongside the reduction of greenhouse gas emissions associated with over-fertilization and excessive water use (Nayak *et al.*, 2024; Rani *et al.*, 2025).

Regardless of the transformative possibilities, multiple setbacks still exist. For instance, the inadequate digital literacy possessed by farmers, insufficient electricity and internet access in rural areas, and high initial capital investments continue to restrain widespread adoption (Klerkx *et al.*, 2019; Nayak *et al.*, 2024). Moreover, other important issues such as the data privacy and cybersecurity concerns are still prominent threats, especially with the increasing digitization of farming practices which makes sensitive data easily accessible for breaches (Herrera & Orjuela-Castro, 2021; Mmbando, 2025).

Looking ahead, the focus of future innovations needs to be on low-cost smart devices that can be easily operated by smallholder farmers in developing areas (Ferrández-

Pastor *et al*., 2016). Adoption efforts may be eased through raising public-private partnerships and providing government subsidies to remove some initial financial barriers alongside aiding in skill-building programs. Moreover, integrating research on climate-resilient crop genetics into smarter farming systems will also augment agricultural resilience (Saad *et al*., 2022; Rani *et al*., 2025).

Smart technologies paired with protected agriculture systems offer boundless opportunities for building advanced climate-proof farming solutions, even when obstacles exist. Multifaceted support systems need to be put in place to encourage innovation supporting the mitigation of global food insecurity driven by unpredictable climate changes.

## Future Perspectives

Considering the impact current smart technologies have on protected agriculture, the future foresees farming systems to be more sustainable, resilient, and accessible. The integration of rechargeable energy sources, particularly solar power, is one of the most promising approaches due to its potential to ensure energy independence and lower carbon emissions. Solar-powered environmental control systems and irrigation systems can sustainably energize greenhouses in off-grid or economically constrained areas (Shukla *et al*., 2025; Kunlere, 2025). The distributed nature of these energy resources enhances the overall productivity and resilience against power outages, which is particularly important for maintaining the optimal conditions needed in controlled environment agriculture (Adamu *et al*., 2025).

Also key is the creation of inexpensive precision devices aimed towards smallholder farmers. Innovations in sensor and IoT have focused on making them more economical and easy to operate for people which enhances the case even in constrained environments (Malabadi *et al*., 2024). Such changes lower the barrier to technology and allow farmers to take advantage of precision agriculture techniques that were impossible before (Van Deursen, 2018). The ability of these technologies to serve a large portion of the population is important in making the food security aims achievable.

From the governance perspective, the suggestions made to aid the integration of smart agriculture technologies are of great importance. Policymakers are becoming more receptive to providing incentives such as hardware subsidies, tax exemptions on renewable energy use, and even allocating funds for educational programs aimed at upskilling rural farmers (Steiner *et al*., 2020). Additionally, the development of public-private collaborations is able to facilitate innovation systems aimed at smart agriculture by start-up and research institution participants (Baumüller *et al*., 2025).

Finally, the combination of cutting-edge research on climate-resilient crop genetic engineering with smart farming systems is expected to result in synergistic advantages. The integration of precise environmental monitoring and data-driven management systems will bolster the cultivation of climate-resilient crops and endurance toward drought, heat, and pest; thus stabilizing yield under volatile climate conditions (Angom & Viswanathan, 2023; Bevan *et al*., 2017). This integrated approach not only secures food supply but also improves economics of farming bolstered by global environmental changes.

Overall, these approaches will enhance the flexibility and sustainability of protected agriculture while expanding its reach to farmers around the world.

## CONCLUSION

The integration of smart technologies with protected agriculture offers a promising solution to withstand increasing climate pressures, and transform farming into a sustainable, climate-resilient practice. The combination of controlled environments with IoT networks enable AI-driven analytics, automation, and blockchain solutions improving resource allocation, yield increase, and supply chain transparency. Technological advancement optimizes operational efficiency and provides proactive insight to farmers, making data available even amid unpredictable weather. Still, there is a long way to go before widespread acceptance is achieved. The reduced access to infrastructure, data security, untapped regions of farming, and immense technical capacity still limit the smallholder farmers. Solving these issues needs concerted actions including policies, strategic assistance, and affordable technologically advanced solutions. Strategically placed agriculture is likely to be revolutionized into a low carbon emission, high efficiency process by integrating renewable energy with intelligence, adaptive farming techniques, and blending them with climate resilient crop genetics. The role of diverse stakeholder cooperation will be vital in solving issues and assuring that innovations benefit farmers and food systems considering the future climate uncertainties.

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