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PAPER

IoT-Enabled Smart Greenhouse for Robotic Enhancement of Tomato Production: Leveraging 5G and Edge Computing for Advanced Data-Driven Automation, Precision Irrigation, and Scalable Zoning Principles

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ABSTRACT

There are many difficulties in growing tomatoes, such as erratic weather patterns, variable yields, and short shelf lives. Tomatoes are a staple food that is grown all throughout the world, particularly in climate-friendly areas such as Morocco. These areas are not free from the difficulties that present major obstacles for farmers, though. Modern agricultural techniques are increasingly using cutting-edge technologies, such as Internet of Things (IoT)-enabled smart greenhouses, to address these problems. In order to improve tomato output, this study presents an enhanced smart greenhouse model that incorporates the zoning principle. The method provides optimal plant growth and resource efficiency by separating the greenhouse into various zones, each tailored for specific growth stages and environmental circumstances. Precision farming and sustainable practices are made possible by the suggested systems real-time monitoring and control, which integrates sensors, actuators, and data analytics. The automatic irrigation system of the intelligent greenhouse prototype is additionally set up to offer the best possible support for the growth of tomato plants. The functionality and efficacy of the prototype are investigated through extensive laboratory testing and experimentation, providing insight into its potential influence on agricultural practices and practical practicality. The greenhouse that has been created with the help of IoT capabilities and the zoning concept has proven to be an effective instrument in assisting farmers in their attempts to grow tomatoes in an efficient and sustainable manner. Our comprehensive testing yielded data that demonstrate the zoning principle-integrated IoT-enabled smart greenhouse greatly improves tomato quality and production. This system demonstrates the benefits and practical applicability of sophisticated data-driven automation in agriculture by providing a scalable and sustainable solution to the problems encountered by tomato producers.

KEYWORDS

Internet of Things (IoT), smart system, tracking system, sensor, agriculture greenhouse technology, tomato cultivation

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1 INTRODUCTION

Morocco is subject to a wide range of climatic conditions characterized by notable spatial and temporal fluctuations because of its diverse topography, which includes sweeping Saharan sands, lush valleys, desert oases, towering mountains, and expansive plateaus [1–5]. The nation faces a variety of difficulties as a result of its diversity, including unpredictable rainfall patterns, protracted cold spells, and growing heatwaves that worsen the frequency and intensity of droughts, which have a significant negative influence on the agricultural sector.

Morocco's agriculture industry holds a prominent position in the country's economic and social structure, serving as both a strategic cornerstone and a formidable challenge [6]. A vital component of Morocco's economic growth and social cohesion, agriculture employs 43% of the labor population, including 78% of rural residents, and contributes between 14 and 20% of the nation's GDP. Notwithstanding its importance, the industry faces a harsh reality: almost 40% of Morocco's arable land is located in desert or semi-arid areas, where a lack of water is a significant barrier to agricultural output [6]. The fact that just 15% of fertile land benefits from irrigation infrastructure emphasizes this mismatch even more and draws attention to the stark differences between more contemporary irrigation-based farming practices and ancient farming methods that depend on rainfall. This contrast between conventional and modern farming methods emphasizes how urgently creative solutions are needed to close the gap and strengthen agricultural resilience in the face of escalating environmental problems.

Smallholder farmers working in humid regions are the mainstay of Morocco's traditional agriculture. They raise cattle, vegetables, and staple cereals, which together make up the majority of the rural economy of the nation [5]. These farmers, who frequently labor on small parcels of land, mostly depend on rainfall patterns to guide their farming methods and establish crop yields. Their way of life is closely linked to the cycles of the natural world, as they must adjust to the unpredictable weather in order to maintain their animals and crops. Even with the difficulties brought about by climate change and a lack of water, these smallholder farmers are essential to maintaining traditional farming methods and guaranteeing food security for Moroccan communities. To strengthen their resilience and increase productivity in the face of changing agricultural landscapes, sustainable solutions are desperately needed, as demonstrated by their susceptibility to environmental influences.

Morocco's greenhouse vegetable production is rising at a rate that is faster than other regions of North Africa, particularly in important areas such as Kenitra and Larache [7]. This growth indicates the sector's increasing significance in the nation's agricultural landscape and a move toward more inventive and sustainable farming methods. Particularly notable is the spread of greenhouse agriculture in these areas, where between 2002 and the present the total cultivated area has increased from 2,975 hectares to over 1,500 hectares. This exponential growth is indicative of the growing awareness of the advantages of greenhouse farming, which include improved crop quality, production, and resource efficiency. It also shows how forward-thinking farmers and legislators have been in utilizing greenhouse technology to solve urgent issues such as water scarcity, climate variability, and market demands. Growing greenhouse vegetable production is expected to be crucial for Morocco's agricultural resilience and for promoting rural communities' economic growth.

A staple of Morocco's agricultural export portfolio, tomatoes are highly significant economically, especially when it comes to commerce with the European Union

(EU) [8]. Morocco's economy is largely dependent on the export of tomatoes, which also contributes significantly to the country's trade balance and export revenue. Morocco ranked as the world's fourth-largest tomato exporter in 2017 alone, having sent almost 527 million kg of tomatoes. This remarkable amount of exports represented 7% of the world's total tomato crop, underscoring the nation's key role in the worldwide tomato industry [8]. Moroccan tomatoes are in high demand, particularly from European markets, which supports their reputation for dependability, flavor, and quality. Additionally, the export of tomatoes boosts rural economies and supports livelihoods for countless farmers and agricultural businesses throughout Morocco. As a result, the tomato sector is vital to Morocco's overall economic development in addition to boosting the country's agricultural prosperity.

In the meantime, a new era of creativity and efficiency in a number of industries has been ushered in by the Internet of Things (IoT), which has emerged as a revolutionary force across numerous fields [9–11]. IoT technologies, in particular, have shown tremendous promise in transforming conventional farming methods and resolving long-standing challenges in the field of agriculture. IoT solutions provide farmers with real-time insights and control over crucial parts of agricultural operations by seamlessly combining sensors, actuators, and data analytics capabilities. Precision agriculture methods are made possible by these technologies, which enable more focused and effective use of resources such as herbicides, fertilizers, and water. Furthermore, early identification of insect infestations, crop diseases, and environmental stresses is made possible by IoT-enabled monitoring systems, which allows for proactive actions to reduce risks and maintain crop health. IoT solutions also make it easier to automate repetitive processes, which lowers the need for human labor and gives farmers more time to concentrate on innovation and strategic decision-making. Additionally, IoT platforms give farmers access to powerful data analytics and predictive modeling tools, which they can use to optimize market planning, crop rotation plans, and yield forecasting, all of which raise productivity and profitability levels overall. All things considered, IoT technologies have the potential to usher in a new era of smart agriculture that will be distinguished by increased resilience, sustainability, and profitability for farmers and agricultural communities around the world.

Strengthening current methods is essential to improving productivity and sustainability in Morocco's agricultural industry, given the diverse range of opportunities and problems it faces [9–11]. This study presents a novel approach to meet this need, which is the application of a smart greenhouse model designed for tomato production. This novel method optimizes tomato productivity, quality, and resource efficiency by utilizing embedded sensor technology and the IoT to create a transformative environment. The smart greenhouse continuously monitors and modifies important environmental parameters, including temperature, humidity, light levels, soil moisture, and nutrient concentrations, by combining sensors, actuators, and data analytics tools. With the help of this real-time monitoring and control, resources may be managed precisely, reducing waste and optimizing the use of electricity, water, and fertilizers. Furthermore, farmers may access real-time data, receive alerts, and remotely alter settings thanks to the remote monitoring and management capabilities offered by IoT technology. This allows for well-informed decision-making and quick responses to changing situations.

Furthermore, the smart greenhouse model is made even more effective by the addition of the zoning principle. The technology makes sure that each zone offers customized support for the many stages of tomato plant development by segmenting the greenhouse into several zones, each optimized for particular growth stages and environmental circumstances. In addition to optimizing resource efficiency, this zoning strategy greatly enhances plant output and health.

Essentially, the suggested smart greenhouse concept offers a revolutionary solution to Morocco's tomato farming problems by providing a route towards more productive and sustainable farming methods. The following is how this paper is organized: In order to establish the foundation for comprehending the background and importance of the suggested smart greenhouse model, the next part provides a thorough summary of relevant earlier research. The system's architecture, parts, and functions are then thoroughly explained in the third section, which offers a comprehensive grasp of the system's construction and functioning. The study's performance, effectiveness, and practical consequences are discussed in the fourth section, which also includes laboratory tests and testing that validated the smart greenhouse concept. The study concludes with a brief review of the most important conclusions and insights from our research, highlighting the importance and possible influence of the suggested strategy on promoting sustainable agricultural practices in Morocco and beyond.

Because it is essential to Morocco's export economy and contributes significantly to local consumption, tomato growing is an important part of the country's agricultural industry. Morocco's most lucrative agricultural export in recent years has been tomatoes, especially to the European Union, where Moroccan tomatoes are highly valued for their flavor and quality. Morocco exported almost 550 million kg of tomatoes as of 2023, bringing in a healthy sum of money and making a major contribution to the country's trade balance. But the industry has a lot of obstacles to overcome, including climate change, water shortages, and the requirement for increased yields to keep up with the world's expanding demand. The scarcity of arable land—nearly 40% of Morocco's arable land is situated in desert or semi-arid regions—exacerbates these problems. The severe environmental conditions in these places frequently make standard farming practices ineffective. The use of IoT technology offers a revolutionary answer to these problems. In spite of fluctuations in the outside climate, tomatoes may be produced under ideal circumstances thanks to the real-time monitoring and optimization of environmental variables that IoT-enabled smart greenhouses can provide. IoT technology may improve yields, decrease waste, and boost water usage efficiency by utilizing sensors, data analytics, and automated systems. This is especially crucial in a nation such as Morocco, where water supplies are getting harder to come by. Moreover, real-time data on soil moisture, temperature, and humidity may be obtained by farmers through the application of IoT in tomato growing, giving them exact control over irrigation and environmental conditions. This guarantees that the tomato industry stays competitive on the international market in addition to increasing the quality and quantity of tomato output. It is impossible to exaggerate the economic significance of Morocco's tomato industry. Through the integration of IoT technology, the industry may surmount present obstacles and sustain growth, therefore augmenting the regional economy and promoting global food security.

2 RELATED WORKS

The literature on smart greenhouse systems offers a number of methods for controlling and monitoring the environment. The study [19] describes how sensors interfaced with a microcontroller are used to monitor and control a greenhouse's environmental features. The collected parameters are displayed through an Android-based application, which also includes a water pump for controlling soil moisture, a misting device for managing humidity, a ventilator for controlling temperature, and an artificial lighting system for controlling light intensity.

A methodology for automatically controlling humidity and temperature is presented by "[20]" for the purpose of growing strawberries in solar-powered greenhouses that are climate-adapted to Malaysia. The system lacked fogging for humidity management, even with its sophisticated monitoring capabilities. Li created a smart greenhouse in 2017 using a three-layer IoT architecture [21]. Wireless connectivity, sensor technology, and configuration monitoring technologies are all included in this system [12–18]. Tests in the lab on information gathering precision, system coherence, and remote monitoring proved the system's resilience and secure network layer. A year later, an IoT-based automated greenhouse monitoring system was proposed by Danita et al. [22]. This system uses particular sensors to measure three primary parameters, and when thresholds are surpassed, actuators are activated. Additionally, the system allows for cloud-based data storage that is available anywhere, at any time. Maraveas et al. (2022) emphasized the need to integrate IoT technology in intelligent greenhouse environments while striking a balance between ecological sustainability, cost-effectiveness, and environmental preservation. They pointed out that significant infrastructure projects and rising energy usage could give rise to worries about potential climate effects in the future. Ahmad et al. (2023) suggested a novel smart greenhouse that makes use of a Raspberry Pi microcontroller [23]. The goal of their research was to create a clever system for controlling the microclimate in greenhouse crops. They used automatic control systems to establish temperature and humidity parameters, and they compared the agronomic and quantitative parameters of Roma and cherry tomatoes in both conventional and smart greenhouses. In many of the connected activities, water mismanagement is still a major problem in spite of these developments. In response, intelligent drip irrigation systems have been created, which maximize water usage by supplying it straight to the roots of the plants. Furthermore, sensors keep an eye on the storage unit's water levels all the time, warning operators when they drop. Precision farming requires efficient crop data monitoring. Fuzzy approaches help UAVs deal with ambiguity and vagueness, as shown by Morimoto et al. [26]. Artificial neural networks (ANN) were utilized by Habaragamuwa et al. [27] to assess strawberry maturity, overcoming the considerable difficulties involved in this process. For greenhouse green pepper detection, Ji et al. [28] used a least-squares support vector machine improved with particle swarm optimization (PSO), yielding accurate parameter estimations. Similar to this, Longo et al. [29] investigated GPS, artificial potential fields (APF), and a laser range finder for agricultural robot navigation in vines. Harik et al. [30] and Hou et al. [31] used autonomous vehicles with APF for a variety of agricultural chores in their other investigations. Using a mobile measuring device, Martinovic et al. [32] combined sensor-based technology with APF to regulate the greenhouse microclimate.

The zoning idea could be added to these smart greenhouse systems to increase their efficacy even more. Different plant development phases can receive specialized support by creating zones within the greenhouse, each optimized for certain growth stages and environmental circumstances. This method overcomes some of the shortcomings found in earlier research while also greatly enhancing plant health and productivity and optimizing resource efficiency.

3 PROPOSED SYSTEM

We have integrated a variety of hardware components (DHT11, soil moisture sensor, LDR, ultrasonic sensor) and built software solutions utilizing a variety of programming languages, including Arduino, C, and Matlab, in order to design a new intelligent greenhouse model that is optimal for tomato growing.

3.1 Arduino implementation

The main microcontroller used for data collection and real-time control is Arduino. It communicates with sensors and actuators to control greenhouse conditions and keep an eye on environmental elements. For example, Arduino controls the pump's operation based on predetermined criteria, regulates the water level in the basin, and opens the electric valve for drip irrigation. Furthermore, Arduino communicates with the climate control system's temperature and humidity sensors to initiate functions such as air conditioning and fog production.

3.2 C implementation

Performance-critical tasks and low-level hardware control are implemented in the C programming language. C code manages complex algorithms and system-level features in our implementation. For instance, C code controls the precise management of irrigation valves and the processing of sensor data in the irrigation system. Similar to this, complicated control logic for humidity and temperature management in the climate control system is handled by C code.

3.3 Matlab implementation

Matlab is used for algorithm creation, simulation, and data analysis. Matlab scripts are utilized in our greenhouse system to assess sensor-collected environmental data, optimize watering schedules, and model and simulate plant growth dynamics. Furthermore, Matlab makes it easier to create control algorithms iteratively and quickly for a variety of subsystems, including climate control and light control. By utilizing these programming languages, we are able to develop the intelligent greenhouse system in a thorough and reliable manner. Every language has a unique function that contributes to accurate control, effective operation, and data-driven decision-making.

3.4 System architecture

The general design of the greenhouse system, as seen in Figure 2, is made up of a number of parts, such as wireless modules, sensors, actuators, and monitoring apps that allow for remote measurement and control. Polycarbonate glass, used in the construction of the greenhouse, helps retain heat during the night and keeps leaves from being frostbitten, especially in arid and cold climates.

3.5 Comprehensive module explanation and comparison

The whole layout of the greenhouse system, which includes wireless modules, sensors, actuators, and monitoring apps for remote measurement and control, is shown in Figure 2. In this part, we offer a thorough analysis of the modules that are available and explain why we chose each one for our design.

a) **Wireless modules:**
   - **Wi-Fi modules:** Because of its wide range of IoT platform compatibility and fast data transmission speeds, Wi-Fi modules (such as the ESP8266) are employed. Applications needing constant data streaming and cloud service integration are best suited for them.

- **Zigbee modules:** Because of their mesh networking capabilities and low power consumption, Zigbee modules (such as XBee) are a good choice for locations where a lot of sensors are dispersed across a big area.
- **LoRa modules:** Low-power long-range communication is made possible with LoRa modules, which is advantageous for remote agricultural applications where power supplies could be scarce.

We selected Wi-Fi modules for our greenhouse system because they provide real-time monitoring and management, have fast data transmission rates, and are simple to integrate with current IoT systems.

b) Sensors:

- **Temperature sensors:** The precision and dependability of DHT11 and DS18B20 sensors make them popular choices for monitoring ambient temperature.
- **Humidity sensors:** The selection of DHT11 and AM2302 sensors is based on their precision in measuring humidity levels.
- **Soil moisture sensors:** Long-term usage is appropriate for capacitive soil moisture sensors since they offer accurate readings without corroding problems.
- **Light sensors:** For the purpose of maximizing the environment for plant development, light intensity is measured with BH1750 sensors and LDRs (light dependent resistors).

The precision, dependability, and compatibility of the chosen sensors—capacitive soil moisture sensors, DHT11 temperature and humidity sensors, and LDR light sensor—with the Arduino platform of our system are the reasons behind their selection.

c) Actuators:

- **Water pumps:** Submersible and peristaltic pumps are utilized to precisely distribute water to the plants.
- **Valves:** In order to provide accurate irrigation, solenoid valves regulate the water flow in the irrigation system.
- **Climate control devices:** The greenhouse is kept at the ideal temperature and humidity levels with the assistance of blowers, heaters, and foggers.

The capacity of the actuators to precisely regulate the greenhouse climate played a role in their selection. Propane heaters, fans, and foggers keep the right temperature, and solenoid valves and piston pumps guarantee precise water supply.

d) Monitoring apps:

- **Blynk:** Blynk is a well-liked Internet of Things platform that allows for remote monitoring and control. It is compatible with a wide range of hardware components and has an intuitive UI.
- **ThingSpeak:** An additional IoT platform that provides real-time data analytics and visualization is perfect for keeping and eye on the environment and making informed judgments.

Because of its simple setup process and user-friendly interface, Blynk is utilized for real-time greenhouse environment monitoring and control. ThingSpeak's strong data analytics capabilities are used to analyze and optimize greenhouse conditions in detail.

We hope to shed light on the selection of the parts in our smart greenhouse system and provide the reasoning behind our design decisions by offering this thorough comparison and explanation. Together, these elements guarantee the greenhouse's dependable and effective functioning, which maximizes tomato-growing conditions.

4 ZONING PRINCIPAL IMPLEMENTATION

The greenhouse is divided into several zones, each of which is optimized for particular growth stages and environmental circumstances, in order to implement the zoning principle. This methodology guarantees customized assistance for distinct phases of tomato plant growth, augmenting resource effectiveness and elevating plant well-being and productivity. In smart greenhouses, zoning entails partitioning the greenhouse into several discrete sections, each specifically designed to meet the requirements of plants at various growth phases, including seedling, vegetative, blooming, and fruiting stages. By offering exact environmental controls for temperature, humidity, light, and irrigation, this approach maximizes growing conditions. The physical layout of each zone is intended to support the growth stage for which it is intended: seedling zones need misting systems and shade cloths, higher humidity, and moderate light; vegetative zones require intense light and robust nutrient delivery; flowering zones concentrate on particular light spectra, lower humidity, and precise temperature control; and fruiting zones require stable temperatures, humidity, and balanced light conditions. Temperature sensors and heating/cooling systems, humidity sensors with misting or dehumidifying systems, drip or ebb-and-flow irrigation systems driven by soil moisture sensors, and LED grow lights with programmable spectra overseen by light sensors are some of the environmental control systems found in each zone. An IoT platform that processes and analyzes the data is linked with a network of sensors installed in the zones to gather data on temperature, humidity, soil moisture, and light levels in real-time. By automating the regulation of parameters to maintain ideal conditions in each zone, this integration enables real-time modifications to environmental circumstances. Optimized growing conditions, resource efficiency, higher crop quality, and flexibility in handling various crops or scaling operations are some of the advantages of zoning. The initial setup expenses, the intricacy of overseeing several zones, and the technological expertise needed to manage IoT systems and comprehend the requirements of plants at different growth stages are some of the hurdles, nevertheless. Notwithstanding these difficulties, zoning is a useful tactic because of its advantages, which include increased yields, superior produce, and economical resource usage.

5 SUBSYSTEMS

An overview of the smart greenhouse system is given by this graphic Figure 1, which also shows how its main parts interact. The Raspberry Pi microcontroller, at the heart of the system, serves as the primary processing unit for gathering and analyzing data from a variety of sensors and managing the actuators.

Sensors: The system has sensors for light, temperature, humidity, and soil moisture. These sensors keep an eye on the greenhouse's environmental conditions all the time, sending the information they gather to the microcontroller for evaluation.

Actuators: The microcontroller decides what to do and instructs the actuators based on information gathered from the sensors. These actuators, which are in charge of preserving ideal growth conditions by modifying the environmental parameters as necessary, include the heating, ventilation, and irrigation systems.

Communication interfaces: The microcontroller has Zigbee and Wi-Fi modules installed, allowing for remote greenhouse management and monitoring. The system can communicate with external devices and receive orders from them thanks to these interfaces.

User interfaces: Users may access and control the system's data from anywhere using a mobile app or a web dashboard, giving them access to real-time information and the flexibility to manage the greenhouse environment.

This networked system makes sure the greenhouse runs smoothly, preserving the perfect environment for plant development and enabling automation and remote administration.

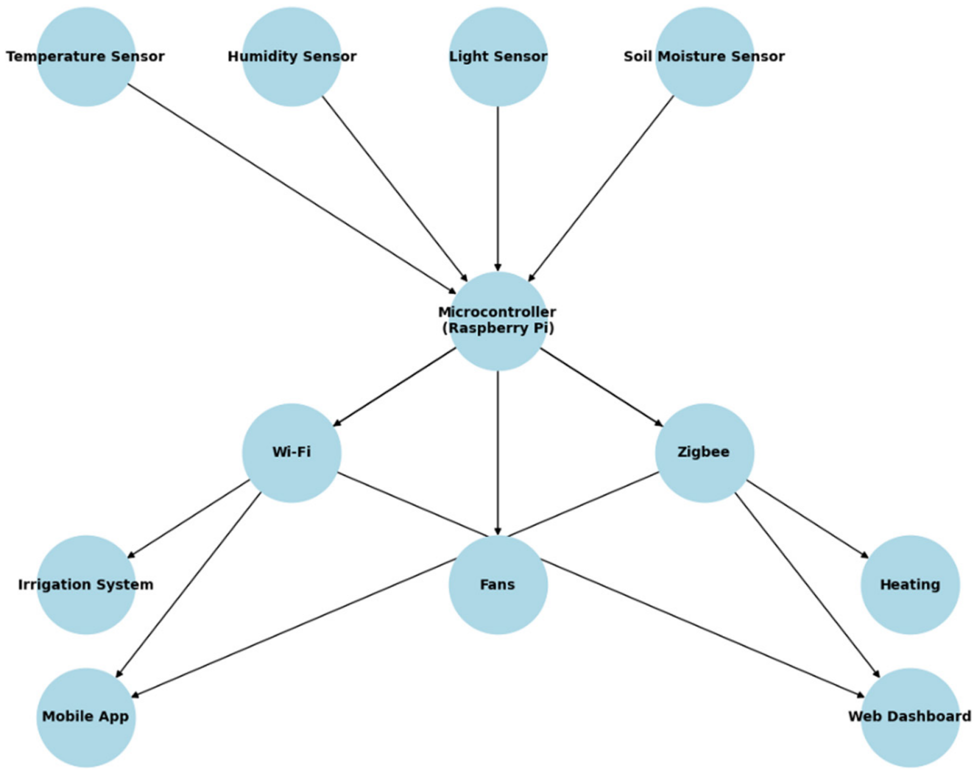

Fig. 1. Overview of the smart greenhouse system

5.1 Irrigation system

We employ the drip irrigation system, which sends water to the roots of the plants, to optimize water use. Water from a variety of sources, such as streams, rainfall, and tube wells, is gathered in a basin fitted with sensors to continuously check the water level. Based on water levels, the microcontroller turns the pump on or off, and an electronic valve manages the drip irrigation system. When moisture levels fall below the threshold, soil moisture sensors installed across the agricultural field activate the valve; when ideal levels are reached, the valve deactivates.

5.2 Light control system

LED grow lights are employed because they use less electricity and run at a lower temperature than traditional high-pressure sodium lights. Plants can be positioned closer to the lights as a result, increasing fruit-bearing areas and improving light persistence through the canopy [24]. Photoresistors (LDR) are used to control the lights; they measure light intensity and modify the lights as necessary [25].

5.3 Climate control system

Greenhouse conditions are monitored via temperature and humidity sensors. The Arduino triggers a fog generator to disperse tiny water droplets and lower the temperature when the temperature rises above a predetermined threshold. In a similar vein, the fog generator keeps the relative humidity (RH) constant when the atmospheric humidity falls below the predetermined threshold. When needed, Peltier modules that run on solar energy might provide more heat or air conditioning. The suggested smart greenhouse model provides a revolutionary approach for tomato cultivation, improving sustainability, efficiency, and productivity by fusing the zoning principle with cutting-edge IoT capabilities.

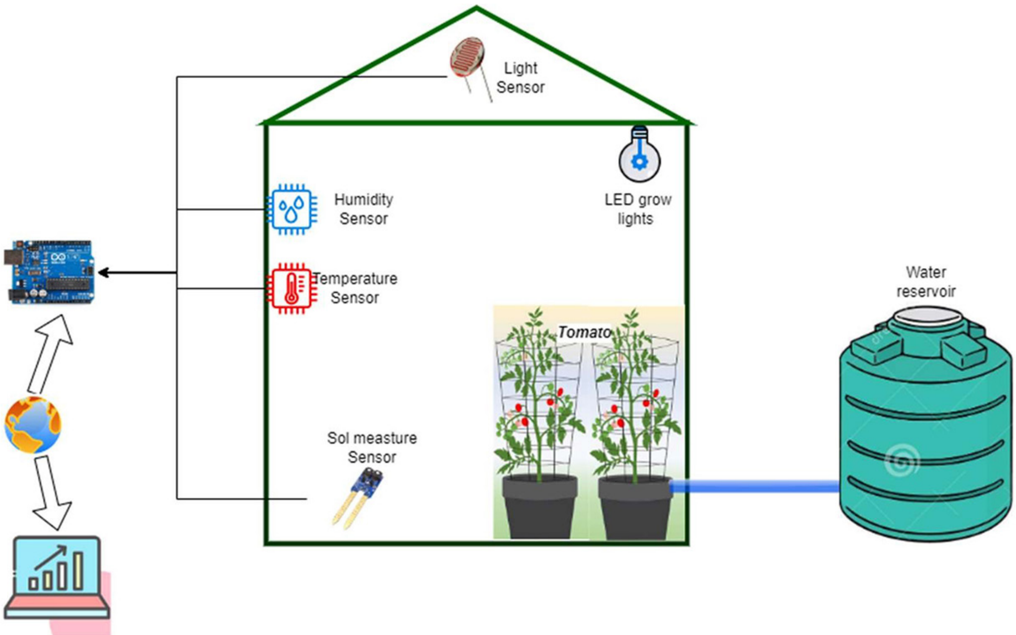

Fig. 2. Smart greenhouse designed for tomato cultivation

6 INTEGRATING ZONING EFFECTIVELY IN A SMART GREENHOUSE

The following procedures must be followed in order to properly include zoning in a smart greenhouse Figure 2 and guarantee that each zone is tailored for particular growth phases and environmental circumstances.

6.1 Define growth zones

- **Seedling zone:** A designated space for immature plants that need a certain amount of light, warmth, and humidity.
- **Vegetative zone:** With modified environmental conditions, it facilitates quick leaf and stem growth.

- **Flowering zone:** Preserves environmental factors that encourage pollination and flowering.
- **Fruiting zone:** Provides ideal circumstances for fruit growth and ripening.

6.2 Sensor deployment

- **Temperature sensors:** Place one in each zone to keep an eye on the outside temperature.
- **Humidity sensors:** Determine how humid the air is in each area.
- **Soil moisture sensors:** positioned to measure soil moisture at various depths.
- **Light sensors:** Place them such that each zone's light intensity and duration may be measured.

6.3 Actuator installation

- **Irrigation system:** Use drip irrigation with soil moisture sensors controlling the valves. There should be separate irrigation controls for each zone.
- **Lighting system:** Make use of intensity-adjustable LED grow lights. Using the feedback from light sensors, adjust the lighting.
- **Climate control:** Install fans, heaters, and foggers to control the climate. Utilizing data from humidity and temperature sensors, control them.

6.4 Data collection and analysis

- **IoT platform:** Gather and evaluate data in real time from all sensors using an IoT platform. Make sure it is capable of remote control and monitoring.
- **Data logging:** To monitor environmental conditions and make data-driven decisions, continuously log data.

6.5 Zoning control algorithms

- **Temperature control:** Using information from temperature sensors, implement algorithms to modify heating and cooling.
- **Humidity control:** To regulate dehumidifiers and foggers, utilize data obtained from humidity sensors.
- **Irrigation scheduling:** Developing algorithms to optimize irrigation schedules based on plant requirements and soil moisture data is the task of irrigation scheduling.
- **Light management:** Depending on the development stage and light sensor data, modify lighting schedules and intensity.

6.6 Monitoring and alerts

- **Real-time data monitoring:** To keep track of data in real-time from every zone, use a dashboard.
- **Notifications and notifications:** To ensure that quick action is taken, set up notifications for key conditions (such as temperature spikes and low soil moisture).

6.7 Automation and remote control

- **Automation:** Using preset parameters and sensor data, automate regular chores such as climate control, lighting adjustments, and irrigation.
- **Remote control:** To change settings and react to alarms from any location, enable remote control functionality.

6.8 Regular maintenance and calibration

- **Sensor calibration:** To guarantee reliable readings, calibrate sensors on a regular basis.
- **System maintenance:** To avoid issues, do regular maintenance on all of your equipment.

6.9 Continuous improvement

- **Data analysis:** Examine gathered data on a regular basis to spot trends and potential improvement areas.
- **Feedback loop:** Constantly improve zoning plans and control algorithms by drawing conclusions from data analysis.

7 EXAMPLE IMPLEMENTATION

7.1 Design layout

- Four zones should be established in the greenhouse: seedling, vegetative, flowering, and fruiting.
- Determine where the actuators and sensors should be placed in each zone.

7.2 Install sensors and actuators

- Install sensors for light, temperature, humidity, and soil moisture in each zone.
- Install solenoid valves in drip irrigation systems.
- Install LED grow lights with movable blades.
- Install climate control devices, such as heaters, fans, and foggers.

7.3 Develop control algorithms

- To read sensor data and operate actuators, write Arduino code.
- Use C code for applications that require high performance, such as precisely controlling irrigation valves.
- For data analysis, simulation, and the creation of optimization algorithms, use Matlab.

7.4 Set up IoT platform

- Link actuators and sensors to an IoT platform.
- Set up the platform so that data can be gathered, examined, and displayed.
- Turn on the features for remote control and monitoring.

7.5 Calibration and testing

- To guarantee precise data gathering and efficient control, calibrate the sensors and test the system.
- Conduct preliminary experiments to optimize control algorithms and zoning plans.

You may successfully incorporate zoning into a smart greenhouse by following these procedures, which will guarantee ideal growing conditions for every stage of development and increase overall productivity and resource efficiency. The main goal of this project is to use cutting-edge IoT technology to create a smart greenhouse for tomato farming and show farmers the benefits and dependability of the smart greenhouse prototype. According to the study, the smart greenhouse's design promotes tomato development and offers ideal weather. IoT technology facilitates data-driven decision-making and higher yields by improving tracking, data collection, and the exact delivery of water, pesticides, and fertilizers. The zoning principle optimizes circumstances for seedlings, vegetative plants, blooming plants, and fruiting plants by allowing for customized environmental control for various growth stages. In spite of certain obstacles such as high startup costs, higher energy usage, and the requirement for specialized training, IoT in greenhouse agriculture offers advantages such as greater production, sustainability, and efficiency that make it a promising answer for contemporary agriculture.

8 IMPLEMENTATION AND TESTING OF THE SMART GREENHOUSE PROTOTYPE

Our endeavor started with the creation of a smart greenhouse prototype. We then put it into practice and used transparent light panels to confirm its efficacy in two different scenarios: an irrigation-free greenhouse and a greenhouse with controlled watering.

A network of sensors in our monitoring system gathers vital environmental data necessary for tomato plants to thrive to their full potential. This network consists of.

- **Temperature sensors:** Located thoughtfully throughout the greenhouse, these sensors offer a thorough picture of the surrounding air temperature, assisting in the maintenance of the ideal 24°C to 32°C range for tomato plants. While ideal temperatures promote effective photosynthetic activity, excessive heat can damage plants and impede photosynthesis Figure 3.
- **Humidity sensors:** Two varieties of humidity sensors are employed by us:
  - **Sensors for air humidity:** Determine how much moisture is in the air. Enough air humidity keeps plants from drying out and guarantees that their stomata stay open for gas exchange, which is necessary for photosynthesis Figure 4.
  - **Soil moisture sensors:** Keep an eye on the soil's water content to make sure it's sufficiently hydrated for plant health and nutrient uptake.
- **Light sensors:** These sensors are positioned within the greenhouse to measure solar radiation and make sure there is enough light for photosynthesis. To maximize light exposure, they assist in adjusting the transparency of light panels or artificial lighting.

– **Wind sensors:** Determine the greenhouse's interior wind speed. Recognizing wind patterns promotes a constant growing environment by assisting in the maintenance of stable humidity and temperature levels.

An IoT module that gathers and interprets data in real-time is attached to every sensor. With this configuration, the greenhouse atmosphere can be continuously monitored and controlled, guaranteeing ideal growing conditions for tomatoes. Monitoring apps are essential for remote management, data logging, and real-time observation in addition to the control systems used in the intelligent greenhouse. With the help of these programs, users can keep an eye on a variety of criteria, get notifications, and decide on greenhouse operations with knowledge.

Real-time observation: Monitoring programs give users access to real-time information about the temperature, humidity, water levels in the irrigation basin, light intensity, and soil moisture content. A user-friendly interface makes this information accessible to users, allowing them to quickly spot abnormalities and follow changes.

Data logging: Monitoring software provides continuous logging of sensor data in order to support data-driven decision-making. In order to help customers analyze past data trends, spot patterns, and modify greenhouse settings for better crop growth and resource management, this technology takes sensor readings at regular intervals and saves them in a database.

Alerting mechanisms: To inform users of important occurrences or departures from intended conditions, monitoring applications include alerting mechanisms. For instance, the program can notify users via email or SMS if the temperature is above a predetermined threshold or the soil moisture level falls below a specified number. This allows for early intervention to avert potential crop damage or system malfunctions.

Remote management: The ability to remotely manage a program is one of its main characteristics. The greenhouse system may be accessed and controlled remotely in a number of ways, including modifying light schedules, turning on irrigation cycles, and setting temperature setpoints. Greenhouse managers can now monitor operations from any location with an internet connection, giving them flexibility and convenience.

By offering thorough insights, data logging capabilities, real-time warnings, and remote management features, monitoring software improves the intelligent greenhouse system's functionality and usability. With the help of these apps, users may increase crop output, streamline greenhouse operations, and guarantee resource efficiency.

8.1 Data analytics and machine learning integration

Our solution maximizes the smart greenhouse's operating efficiency by utilizing modern data analytics. Real-time processing of the data gathered from several sensors, such as those that monitor temperature, humidity, soil moisture, and light levels, provides useful insights. Thanks to these insights, environmental elements can be precisely controlled, guaranteeing that the greenhouse's settings are always ideal for growing tomatoes. While real-time monitoring and control are the main emphasis of the implementation at this point, it's crucial to remember that the incorporation of machine learning (ML) techniques is a planned expansion of this effort. By examining past data to find trends and forecast future circumstances, ML algorithms may greatly improve the system's predictive power. Proactive modifications to the greenhouse environment made possible by this predictive study will increase production and resource efficiency even further. We are investigating the usage of cognitive networks that can adapt and learn from the data provided by the greenhouse in order to assist the possible inclusion of ML in subsequent versions. Deep learning algorithms combined with cognitive networks present a possible path toward creating next-generation IoT systems that operate not just reactively but also anticipatorily.

We recommend that readers peruse the thorough analysis of Buenrostro-Mariscal et al. "[34]," which covers the developments in deep learning applications for cognitive networks, for further background on the use of ML in data networks. This source offers insightful information about how ML may be included in data-driven systems to build environments that are more responsive and intelligent.

9 ENERGY COST AND OPTIMIZATION

A key consideration in the development and functioning of IoT-enabled smart greenhouses is energy consumption. Our system uses a number of techniques to maximize energy consumption while maintaining the effective operation of every part. Here, we offer an examination of the energy needs, optimization strategies, and related expenses.

a) Energy needs:
- **Actuators and sensors:** Each component in our system, such as pumps, valves, and climate control devices, has a unique power demand. The sensors in our system include temperature, humidity, soil moisture, and light. For example, a single DHT11 sensor uses roughly 2.5 mW, whereas irrigation peristaltic pumps need about 4 W.
- **Control systems:** The total energy usage is also influenced by microcontrollers and wireless communication modules (such as Arduino and Wi-Fi modules). Typically, an Arduino board uses about 0.5 W.

b) Optimization techniques:
- **Energy-efficient components:** Whenever feasible, we have chosen components that are energy-efficient. For instance, because LED grow lights are more efficient and need less electricity than traditional high-pressure sodium lights, they are utilized instead.
- **Dynamic power management:** When not in use, the system uses low-power modes or turns of sensors and actuators. These are examples of dynamic power management strategies.
- **Integration of solar energy:** We have incorporated solar panels to capture renewable energy in order to reduce our energy expenses. This encourage sustainability and lessens dependency on outside power sources.

c) Cost analysis:
- **Initial investment:** Compared to typical systems, the initial cost of installing energy-efficient components, such as solar panels, LED grow lights, and energy-efficient sensors, is greater. However, the long-term cost reductions on energy make this investment worthwhile.
- **Operating expenses:** Because the improved system uses less electricity, the operating expenses are greatly decreased. For instance, compared to conventional systems, the adoption of LED lighting and energy-efficient pumps decreases power expenses by about 30–40%.

- **Return on investment (ROI):** Because of the significant energy savings, the ROI is anticipated to be achieved in two to three years. By lowering reliance on outside energy sources, the incorporation of solar panels quickens the ROI even further.

d) Environmental impact and sustainability:
- **Reduced carbon footprint:** By optimizing energy use and integrating renewable energy sources, our system contributes to a reduced carbon footprint. This aligns with global sustainability goals and benefits the environment.

For our IoT-enabled smart greenhouse, this part offers a thorough description of the energy efficiency techniques and financial factors. We make sure the system is both commercially and ecologically sustainable by emphasizing energy efficiency.

10 IMPROVED READABILITY AND VISUAL REPRESENTATION

We have included a lot of charts and graphs in this work to make it easier to read and guarantee that our study findings are communicated clearly. These visual aids are intended to make difficult information easily understandable and accessible. To guarantee uniformity and clarity, we have given close consideration to the normalization and logicalness of fonts in our graphs. The following are some particular actions we have taken:

a) **Consistent typeface usage:** To keep the paper's visual appearance constant, all of the charts and graphs use the same typeface. This lessens the cognitive strain on readers and facilitates their comprehension of the information being given.

b) **Normalization of data:** To make comparison and comprehension easier, we have standardized the data in our charts. By ensuring that the scales of measurement are uniform, normalization facilitates the comparison of disparate data sets.

c) **Clear and descriptive labels:** Axes, legends, and data points are all labeled in concise and informative language on every chart and graph. This makes sure that readers won't have to keep going back to the main text to comprehend the context and significance of the data.

d) **Use of color and patterns:** Several data sets within the same graph have been distinguished from one another by the deliberate use of patterns and colors. In addition to highlighting important patterns and comparisons, this visual difference facilitates rapid comprehension.

e) **Logical data arrangement:** Our graphics' data is rationally presented, with an emphasis on readability and simplicity of understanding. Time-series data is arranged chronologically, for instance, while comparison data sets are logically categorized to emphasize differences and similarities.

f) **Incorporation of key findings:** Annotations and callouts inside the graphs themselves emphasize important conclusions and insights from the data. This aids in highlighting crucial details and guarantees that the reader's focus is brought to the most vital parts of the information.

We hope that these graphical and typographical improvements will make our paper easier to read and more accessible overall, helping to successfully convey our study findings to a wide audience.

11 DATA COLLECTION AND ANALYSIS

11.1 Without irrigation (control condition)

We ran studies in a non-irrigated greenhouse for 24 hours, from 6:00 AM to the same time the following day, to gather data on temperature and humidity. The maximum temperature of 35°C was recorded between 2:00 PM and 4:00 PM, as illustrated in Figure 3. Figure 4 shows that, albeit at different rates, both soil moisture content and air humidity dramatically dropped throughout the first portion of the day. Because tomato plants need optimal temperatures between 24°C and 32°C, the lack of irrigation resulted in higher temperatures and lower humidity levels.

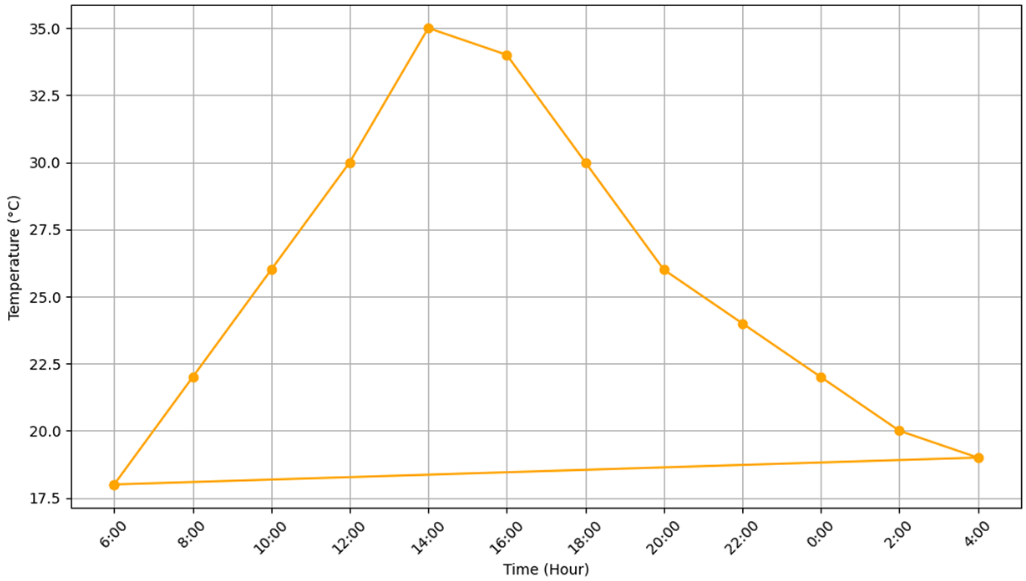

Fig. 3. Temperature monitoring on a non-irrigated day

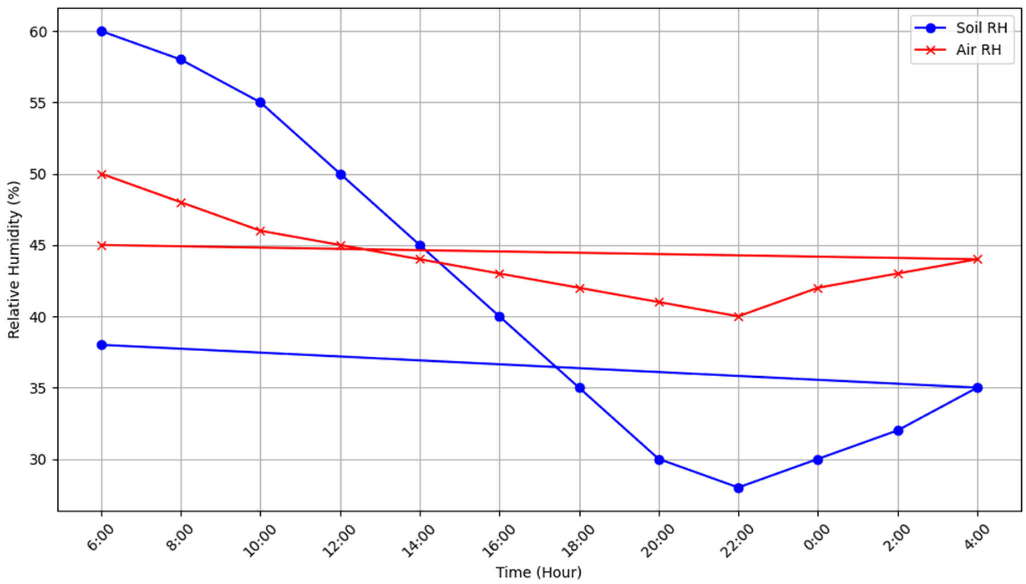

Fig. 4. Relative humidity monitoring on non-irrigated day

11.2 With controlled irrigation

Before the studies began in the irrigated greenhouse scenario, irrigation was done in the morning at 6:00 AM. The temperature in the early morning was a comfortable 26°C. Figure 5 shows that air humidity was 42% and soil moisture was 65%. Figure 6. The temperature reached 30 °C by midday, and by 1:30 PM, the soil moisture content dropped to 25%. The IoT module received a signal from the soil moisture sensor when the moisture content dropped below this minimal threshold. This signal activated the irrigation valve, which in turn lowered the temperature in the ensuing hours as a result of the increased moisture.

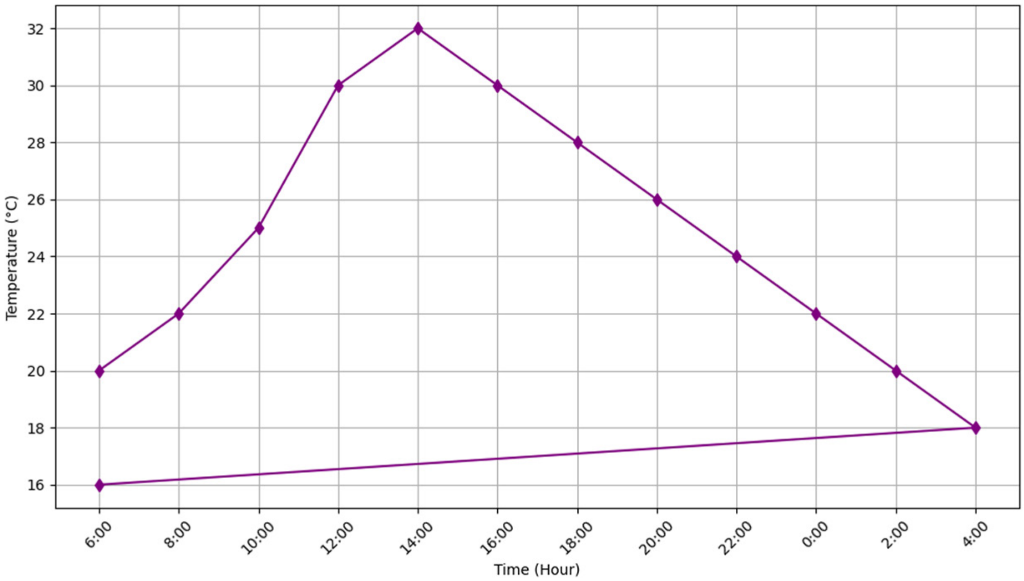

Fig. 5. Temperature monitoring on irrigated day

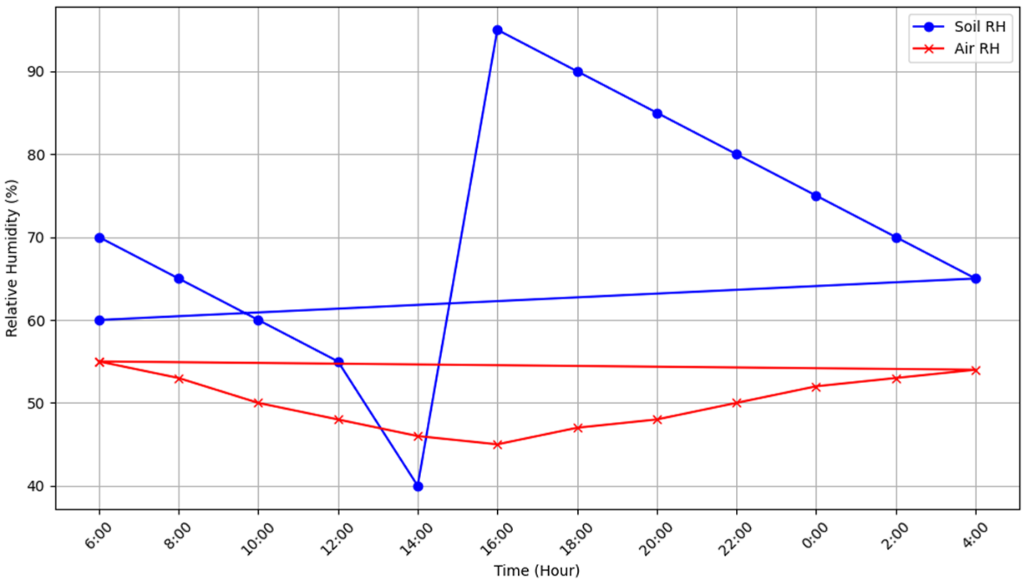

Fig. 6. Relative humidity monitoring on irrigated day

11.3 Impact on photosynthesis and growth

The growth of tomato plants and photosynthesis depend on maintaining ideal temperatures and humidity levels. By ensuring that these factors stay within the appropriate range, the IoT-enabled monitoring and management system improves photosynthesis and encourages healthy plant growth. The technology greatly increases greenhouse output and tomato yield quality by averting excessive temperature swings and maintaining uniform soil moisture. Our findings emphasize the significance of an automated irrigation control system by demonstrating that inadequate irrigation results in less-than-ideal growing conditions. The information gathered is used as a guide for putting these systems into place to successfully control humidity and temperature. Real-time modifications are made possible by the integration of IoT technology, guaranteeing that the greenhouse atmosphere is constantly tuned for the greatest growth conditions for tomato plants.

Plant growth and photosynthesis are significantly impacted by the smart greenhouse's ability to maintain ideal environmental conditions. The process by which plants transform light energy into chemical energy, known as photosynthesis, is essential to the growth and yield of fruits on plants. Photosynthesis is influenced by several elements such as temperature, humidity, light intensity, and carbon dioxide content. By optimizing these variables, the IoT-enabled smart greenhouse system aims to boost photosynthesis and encourage strong development.

An ideal range of light intensity is needed for photosynthesis in tomato plants. LED grow lights are used in the smart greenhouse, and they may be adjusted to produce the perfect light intensity and spectrum. This guarantees that the plants receive enough light on a regular basis, especially in the evenings and at night. The technology promotes continuous and effective photosynthetic activity, which results in healthier and more fruitful plants, by preserving ideal light conditions.

One important element influencing the rate of photosynthesis is temperature. The inside temperature of the smart greenhouse system is constantly monitored and adjusted to maintain tomato plants' ideal temperature range of 24°C to 32°C. Elevated temperatures may result in heat stress, which diminishes photosynthesis's effectiveness and reduces yields. On the other hand, by preserving the ideal temperature range, photosynthesis' enzymatic processes are able to function as efficiently as possible, which promotes plant development and yield.

Stomatal conductance, which is crucial for gas exchange during photosynthesis, is influenced by humidity levels. To keep RH at ideal levels, the smart greenhouse system makes use of humidity sensors and control devices such as foggers and dehumidifiers. By preventing excessive transpiration and water loss, proper humidity control keeps the stomata open and facilitates the effective uptake of carbon dioxide, which is essential for photosynthesis.

Another important component for photosynthesis is the concentration of carbon dioxide (CO_2) in the greenhouse environment, which is not specifically examined in this study. CO_2 enrichment devices may be included in smart greenhouses in the future to maintain greater CO_2 levels, which would improve photosynthetic rates and accelerate plant development.

The smart greenhouse system produces the best possible circumstances for photosynthesis by maximizing various environmental elements, which promotes tomato plant growth and development. Real-time modifications are made possible by the data gathered from sensors, guaranteeing that the plants receive the finest care possible at every stage of their growth. Higher yields, higher-quality fruits, and more economical use of resources are the results of the ensuing improvements in photosynthesis, which highlight the significant advantages of combining IoT with cutting-edge control systems in greenhouse farming.

12 RESULTS AND DISCUSSION

Crop output has increased significantly after the smart greenhouse with IoT technologies was put into place. As mentioned in Table 1, the average tomato production prior to the adoption of this technology was around 2.5 kg/m^2. The yield rose to 3.8 kg/m^2 when the smart greenhouse was put into place, a 52% rise. The system's capacity to sustain ideal environmental conditions throughout the growth cycle is largely responsible for this gain.

Table 1. Comparing crop yield and water consumption before and after the implementation of the smart greenhouse

Parameter	Before Implementation	After Implementation	Improvement (%)
Yield (kg/m^2)	2.5	3.8	+52%
Water Consumption (L/m^2)	30	18	–40%

The growth and health of plants were directly affected by automated watering, temperature, and humidity control systems. Plant stress was decreased and growing conditions were optimized thanks to the IoT system's real-time monitoring and quick modifications. For instance, based on the moisture content of the soil, smart irrigation changes increased plant growth while consuming 40% less water.

Utilizing energy-saving devices such as controlled fans and LED lights drastically decreased the greenhouse's overall energy usage. Through the integration of this technology, the greenhouse was able to maintain ideal conditions for tomato growing while operating in a more sustainable manner.

The findings show that crop yields may be raised and resource consumption can be greatly decreased by using IoT technology in greenhouse management. This study demonstrates how smart greenhouse systems, which increase output while reducing environmental impact, provide a workable answer to today's agricultural problems.

13 TALK AND RESTRICTIONS

The application of an IoT-enabled smart greenhouse system has been shown to significantly increase agricultural productivity and resource efficiency, according to the study's findings. These results are consistent with other studies in the industry that have also shown the advantages of incorporating IoT technology into farming operations. For instance, employing automated irrigation systems was associated with comparable output gains [19, 22, 26].

But this study adds to the body of knowledge already in existence by offering a thorough examination of the ways in which particular IOT elements, such as soil moisture sensors and climate control systems, may be successfully incorporated into a greenhouse setting. This study takes a comprehensive strategy, integrating several technologies to produce ideal growth circumstances, in contrast to other earlier studies that concentrated on certain areas of IoT integration.

The results of this study will have a significant impact on precision agriculture going forward. Through the presentation of concrete advantages of smart greenhouses, this study encourages a wider use of IoT technology in the agricultural sector. By using less energy and water, the increased control over environmental elements promotes more sustainable agricultural techniques in addition to increasing crop yields.

Furthermore, the findings imply that smart greenhouses, particularly in areas with limited arable land and water resources, might play a critical role in addressing global food security concerns by allowing more efficient production systems. This is in line with the objectives of sustainable development and the requirement for creative answers to fulfill the needs of an expanding world population.

It is important to recognize the many limitations of this study, even in light of the encouraging outcomes. Initially, the studies were carried out in a controlled setting, which might not accurately reflect the unpredictability of actual farming circumstances. The lack of consideration given to variables such as illnesses, pests, and harsh weather in this study may have limited the applicability of the findings.

Secondly, this study did not cover the economic analysis of the implementation costs versus the long-term advantages. Even though the study shows the possibility for higher yield and efficiency, more investigation is required to determine whether using smart greenhouses on a larger scale would be financially advantageous.

Lastly, the study placed more of an emphasis on the technological components of IoT integration than on the social and economic issues that may affect farmers' acceptance of these technologies. These aspects should be considered in future research to offer a more thorough grasp of the potential and difficulties related to smart agriculture.

14 NEW CONTRIBUTION WITH ZONING PRINCIPLE

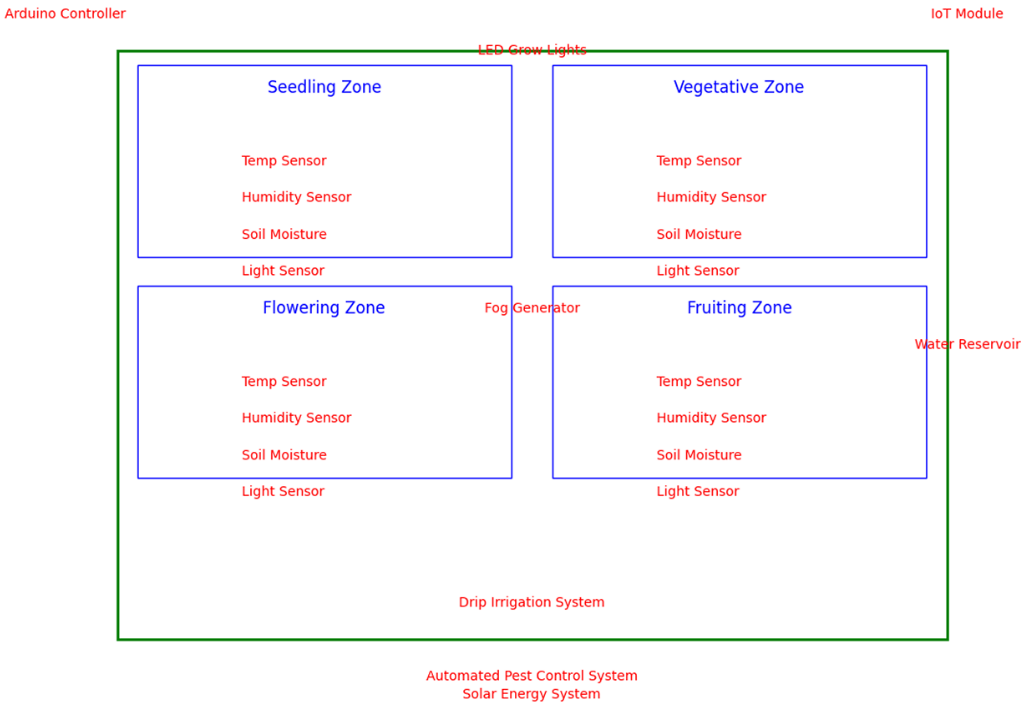

Fig. 7. Smart greenhouse with zoning for tomato cultivation

We present the zoning principle in Figure 7, which divides the greenhouse into several zones, each tailored for particular growth stages and environmental conditions needed by tomato plants, in order to further increase the production and efficiency of the smart greenhouse. With this strategy, every zone can be precisely controlled and managed to perfection, guaranteeing ideal conditions for each stage of growth.

14.1 Zoning implementation

- Growth zones: Set aside distinct areas in the greenhouse for the vegetative, blooming, fruiting, and seedling periods. The individual requirements of the plants at each stage will determine the temperature, humidity, light intensity, and watering parameters for each zone.
- Environmental control: To monitor and modify the environmental factors, install specific sensors and actuators for each zone. Utilize IoT modules to gather information from every zone and provide real-time actuator control.
- Resource management: Make the most use of your resources by modifying the climate control, lighting, and irrigation systems in response to real-time information from each zone. This method guarantees effective utilization of nutrients, energy, and water.
- Data-driven decisions: Examine the information gathered from each zone using ML and data analytics tools. With the use of this analysis, decision-makers will be able to gain a better understanding of plant development patterns and increase overall productivity.

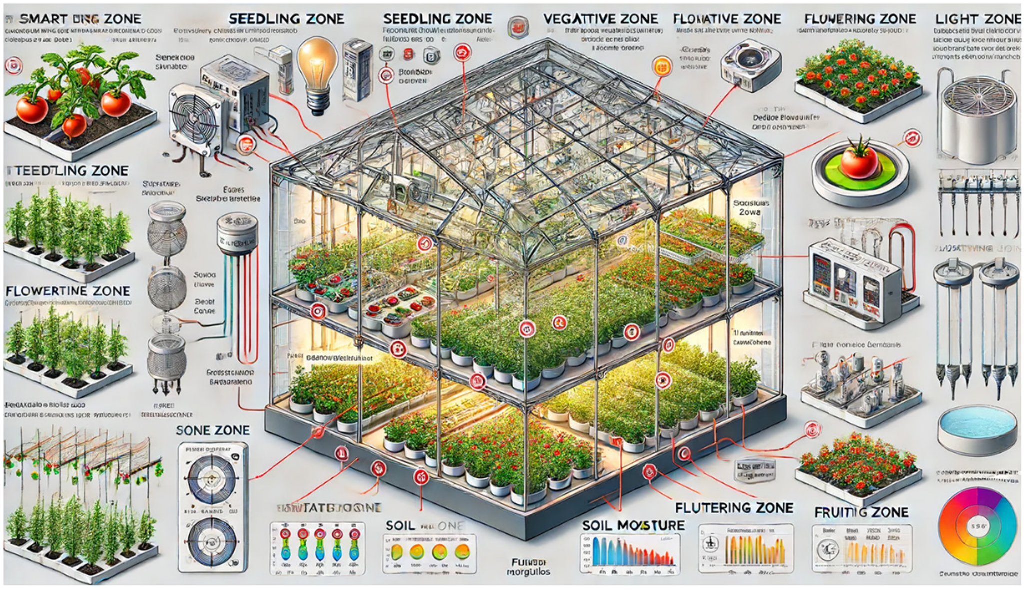

Fig. 8. Comprehensive schematic of a smart greenhouse with zoning integration for tomato cultivation

Higher yields and higher-quality food can be achieved by cultivating tomatoes in a more regulated and efficient environment within the smart greenhouse by implementing the zoning principle.

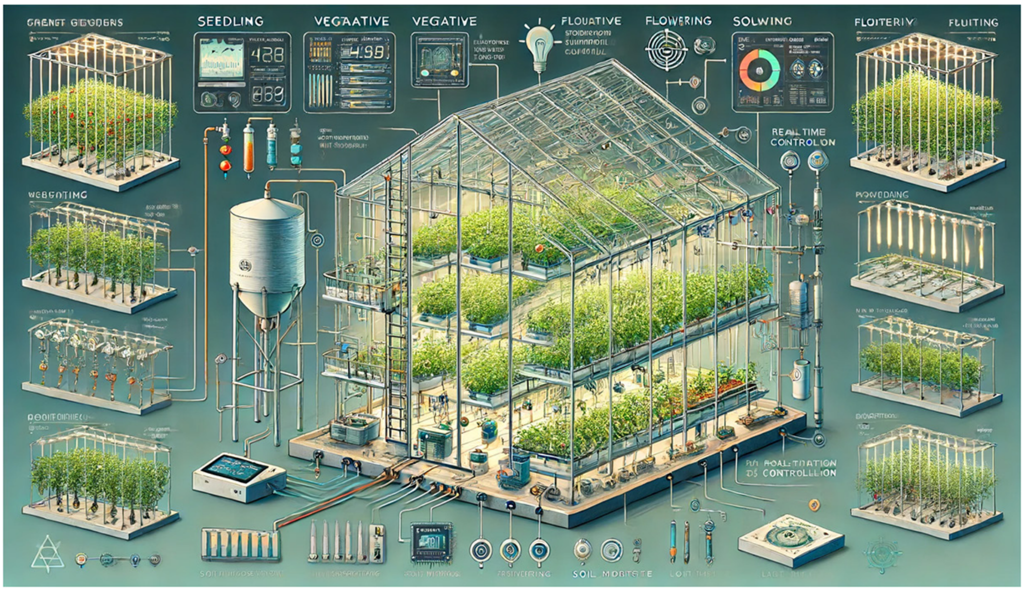

Fig. 9. Detailed schematic of an AI-enhanced Internet of Things-enabled smart greenhouse for tomato cultivation with zoning principles

15 IMPROVING SMART GREENHOUSE PERFORMANCE BY INTEGRATING 5G NETWORKS AND EDGE COMPUTING

Building on the research and ideas offered in the study [33], we address the advantages of 5G and edge computing in this part to enhance the speed, scalability, and efficiency of our smart greenhouse system.

For IoT systems, 5G networks and edge computing represent significant technological advancements. 5G, or fifth generation mobile networks, may transmit data at up to 10 Gbps, have latency as low as a few milliseconds, and have more connection capacity to accommodate several devices connecting at once. These characteristics are crucial for IoT applications that need to transport data in real time and provide effective connections between several sensors and devices. Edge computing reduces latency and power consumption by processing data locally, at the point of production, and enhances data security by limiting the amount of data that is exposed on the network. IoT systems may attain previously unheard-of levels of performance, scalability, and energy efficiency by fusing the speed and capacity of 5G with the responsiveness and efficiency of edge computing. As a result, these technologies are essential for enhancing smart greenhouse habitats.

5G provides a huge increase in data transfer speed, reaching up to 10 Gbps, much above the capabilities of 4G [33]. This speed makes it feasible to transfer enormous volumes of data in real time, which is vital for smart greenhouse systems. Higher transmission rates increase responsiveness and overall system efficiency by enabling real-time modifications to irrigation systems and environmental variables. For instance, greenhouse sensors have the ability to transmit data to control modules instantaneously, allowing for quick modifications to optimize watering, humidity, and temperature. By managing resources more quickly and precisely, photosynthesis and plant development are enhanced, which raises yields and improves the quality of tomato produce.

With 5G, connectivity capacity is much higher, and devices may be linked to several different networks at once. This is especially crucial for smart greenhouse systems, as they require smooth communication between a large number of sensors, robotic equipment, and control modules. Future system expansion is made possible by 5G, which makes it simple to add more devices without sacrificing performance. For instance, a smart greenhouse can incorporate robotic equipment to automate more farming chores or new sensors to monitor more environmental conditions. Because of its scalability, the system can adapt to changing production demands and technological advancements while preserving effective, real-time communication between all of its connected components. 5G facilitates the expansion and optimization of smart greenhouse operations by allowing for the constant addition of new devices and technologies, which raise and sustain agricultural yields.

Edge computing offers local data processing near sensors and devices, lowering latency and enhancing system responsiveness. Without sending data to a centralized data center, critical information may be processed at the source and used right away to modify greenhouse conditions. This makes it possible to react to changes in the environment almost instantly, which optimizes procedures such as climate control and watering. Additionally, edge computing adds to system resilience by making sure that critical functions carry on even in the case of network connectivity issues.

The continual improvement of greenhouse operations depends on the real-time analysis of huge amounts of data, which is made possible by the combination of 5G and edge computing. 5G makes it possible to gather large amounts of data quickly from multiple sensors, and edge computing analyzes this data locally for instantaneous analysis. This capacity optimizes plant development and resource management by making it possible to see patterns and anomalies fast and make decisions based on reliable data. ML algorithms, for instance, may be used to forecast the need for irrigation and automatically modify systems based on the situation at hand.

Significant energy savings are made possible by 5G and edge computing, which enable effective data management and lower connected device energy consumption. Edge computing reduces the quantity of data that must be transferred across long distances, which lowers energy consumption and the price of network connectivity by processing data locally. What's more, 5G optimizes the performance of connected devices, enabling more efficient use of energy. This energy efficiency is vital to the sustainability of smart greenhouse systems, where cutting operational costs and improving the ecological impact are top priorities. In summary, the integration of these technologies guarantees more economical and environmentally friendly greenhouse operations.

The smart greenhouse system's use of edge computing and 5G technology is drastically increasing tomato yield and revolutionizing farming practices. With 5G's fast data transfer speeds and numerous device connections, it is possible to regulate the many environmental factors that impact plant development in real time and with great responsiveness. This maximizes resource efficiency and increases yields through accurate irrigation and climatic changes based on continually updated data. By processing data as close to the source as feasible, edge computing helps to reduce the expenses and delays that come with transferring large amounts of data. This method also lessens latency, which is necessary for urgent interventions that must be performed right away to preserve ideal circumstances for plant development. Then, with the help of these technologies, massive data analysis makes it possible to revise growth models and obtain insightful knowledge, and higher energy efficiency makes agriculture more economically and sustainably feasible. As a result, smart greenhouses outfitted with these technologies are more able to handle the demands of contemporary agriculture, maximizing output while reducing negative environmental effects.

In fact, edge computing and 5G are more than simply advancements in technology; they are revolutionary forces for smart greenhouses, increasing the efficiency, productivity, and environmental friendliness of tomato cultivation. Precision agriculture has advanced significantly in terms of automation and optimization thanks to these technologies.

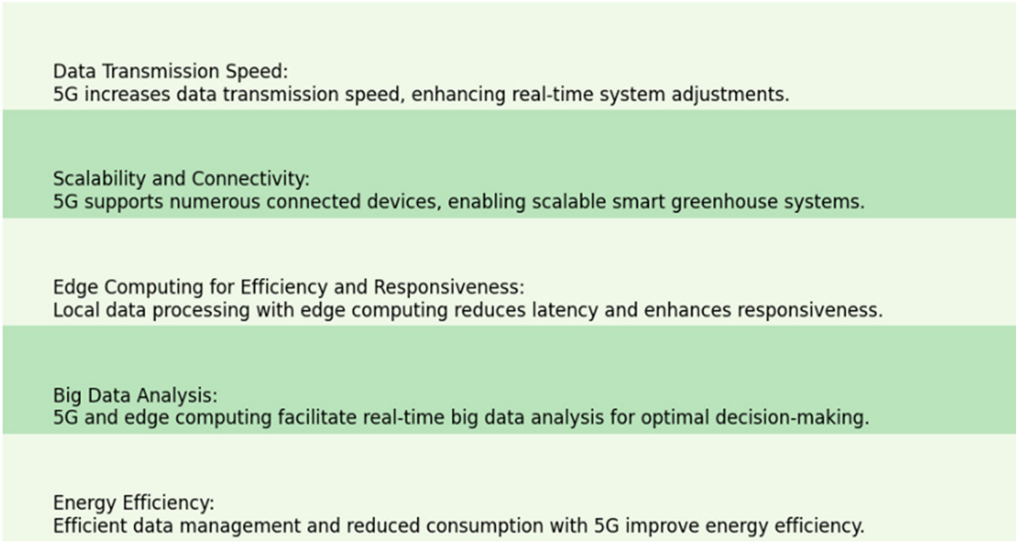

Fig. 10. Using edge computing and 5G to optimize intelligent greenhouses: a visual overview

16 CONCLUSION

The main goals of this project are to use cutting-edge IoT technology to create a smart greenhouse for tomato farming and to show farmers the benefits and dependability of the smart greenhouse prototype. According to this study, the smart greenhouse's design successfully promotes tomato growth and offers the ideal climate for various growth phases. IoT technology greatly improves data collection, monitoring, and accurate distribution of vital resources such as water, pesticides, and nutrients. Data-driven decision-making is made easier by this technology, which boosts yields and resource efficiency. The smart greenhouse's zoning principle, which optimizes conditions at every growth stage, enables customized environmental control for seedlings, vegetative plants, blooming plants, and fruiting plants.

Furthermore, incorporating artificial intelligence (AI) offers an additional degree of accuracy and efficiency. Within the smart greenhouse, AI algorithms may simulate a variety of climatic situations, predicting the ideal conditions for plant growth and automatically modifying the equipment accordingly. Figures 8 and 9, which illustrate these simulation capabilities, show how the AI models evaluate and adjust the environmental factors to guarantee ideal development conditions constantly. Additionally, in order to maintain the ideal conditions for tomato cultivation, the smart greenhouse makes use of real-time data from a variety of sensors to monitor temperature, humidity, soil moisture, and light levels. Healthy plant growth and increased yields are encouraged by the automatic irrigation system, fog generators, and LED grow lights, which all help to maintain constant and optimal conditions.

The benefits of these technologies in greenhouse farming are significant, even with possible drawbacks including higher initial investment costs, increased energy usage, and the requirement for technical expertise to maintain the IoT and AI systems. These advantages, which include higher output, increased sustainability, and improved efficiency, make IoT and AI-enabled greenhouses a viable option for contemporary agriculture. Farmers may increase yields, improve the quality of their produce, and use resources more efficiently by implementing such technology, which will ultimately increase agricultural practices' profitability and sustainability.

The existing IoT smart greenhouse system may be substantially transformed by integrating the principles of speed, scalability, and edge computing with the developments in 5G networks, as described in paper [33] and Figure 10. This will enable more connected devices, boost data transfer speed, and raise the system's overall efficiency and scalability. These improvements will provide more accurate regulation and optimization of tomato production processes, leading to higher yields and more efficient use of available resources in the long run. Subsequent studies need to concentrate on utilizing 5G technology in intelligent greenhouses, investigating its capacity to facilitate increasingly complex artificial intelligence models and all-encompassing real-time surveillance systems. Furthermore, researching the financial effects of these integrations will offer important new perspectives on the viability and long-term advantages for farmers. The smart greenhouse idea may develop further by utilizing these cutting-edge technologies, offering even more accurate and effective answers to the problems facing contemporary agriculture.

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18 REFERENCES

[1] A. Irhza, L. Nassiri, M. El Jarroudi, F. Rachidi, R. Lahlali, and G. Echchgadda, "Description of the gap between local agricultural practices and agroecological soil management tools in Zerhoun and in the Middle Atlas Areas of Morocco," *Land*, vol. 12, no. 2, p. 268, 2023. https://doi.org/10.3390/land12020268

[2] S. Gorjian *et al.*, "A review on opportunities for implementation of solar energy technologies in agricultural greenhouses," *J. Clean. Prod.*, vol. 285, p. 124807, 2021. https://doi.org/10.1016/j.jclepro.2020.124807

[3] L. Gourdo *et al.*, "Solar energy storing rock-bed to heat an agricultural greenhouse," *Energy*, vol. 169, pp. 206–212, 2019. https://doi.org/10.1016/j.energy.2018.12.036

[4] A. Allouhi, N. Choab, A. Hamrani, and S. Saadeddine, "Machine learning algorithms to assess the thermal behavior of a Moroccan agriculture greenhouse," *Clean. Eng. Technol.*, vol. 5, p. 100346, 2021. https://doi.org/10.1016/j.clet.2021.100346

[5] K. Benabderrazik *et al.*, "Climate resilience and the human-water dynamics. The case of tomato production in Morocco," *Sci. Total Environ.*, vol. 849, p. 157597, 2022. https://doi.org/10.1016/j.scitotenv.2022.157597

[6] T. E. Epule *et al.*, "A systematic national stocktake of crop models in Morocco," *Ecol. Model.*, vol. 470, p. 110036, 2022. https://doi.org/10.1016/j.ecolmodel.2022.110036

[7] T. Bazza, "Morocco's greenhouse cultivation grows faster than Spain's," *Morocco World News*, 2023. Available Online: www.moroccoworldnews.com/2018/12/260332/moroccos-greenhouse-cultivation-spain/ [Accessed: Dec. 13, 2018].

[8] K. Benabderrazik, B. Kopainsky, L. Tazi, J. Jörin, and J. Six, "Agricultural intensification can no longer ignore water conservation–A systemic modelling approach to the case of tomato producers in Morocco," *Agric. Water Manag.*, vol. 256, p. 107082, 2021. https://doi.org/10.1016/j.agwat.2021.107082

[9] J. Mabrouki, M. Azrour, and S. E. Hajjaji, "Use of internet of things for monitoring and evaluating water's quality: A comparative study," *Int. J. Cloud Comput.*, vol. 10, nos. 5–6, pp. 633–644, 2021. https://doi.org/10.1504/IJCC.2021.120399

[10] J. Mabrouki *et al.*, "Smart system for monitoring and controlling of agricultural production by the IoT," in *IoT and Smart Devices for Sustainable Environment*, Springer, pp. 103–115, 2022. https://doi.org/10.1007/978-3-030-90083-0_8

[11] S. Khan and L. AlSuwaidan, "Agricultural monitoring system in video surveillance object detection using feature extraction and classification by deep learning techniques," *Comput. Electr. Eng.*, vol. 102, p. 108201, 2022. https://doi.org/10.1016/j.compeleceng.2022.108201

[12] F. Behrendt, "Why cycling matters for smart cities. Internet of bicycles for intelligent transport," *Journal of Transport Geography*, vol. 56, pp. 157–164, 2016. https://doi.org/10.1016/j.jtrangeo.2016.08.018

[13] A. U. Haq *et al.*, "IIMFCBM: Intelligent integrated model for feature extraction and classification of brain tumors using MRI clinical imaging data in IoT-healthcare," *IEEE J. Biomed. Health Inform.*, vol. 26, no. 10, pp. 5004–5012, 2022. https://doi.org/10.1109/JBHI.2022.3171663

[14] M. Azrour, J. Mabrouki, A. Guezzaz, and A. Kanwal, "Internet of Things security: Challenges and key issues," *Secur. Commun. Netw.*, vol. 2021, no. 1, pp. 1–11, 2021. https://doi.org/10.1155/2021/5533843

[15] M. Azrour, M. Ouanan, Y. Farhaoui, and A. Guezzaz, "Security analysis of Ye et al. authentication protocol for Internet of Things," in *Big Data and Smart Digital Environment*, *ICBDSDE 2018. Studies in Big Data,* Y. Farhaoui and L. Moussaid, Eds., 2019, vol. 53, pp. 67–74. https://doi.org/10.1007/978-3-030-12048-1_9

[16] S. Dargaoui *et al.*, "An overview of the security challenges in IoT environment," in *Advanced Technology for Smart Environment and Energy*, Springer, Cham, pp. 151–160, 2023. https://doi.org/10.1007/978-3-031-25662-2_13

[17] S. Ahmad *et al.*, "Deep learning enabled disease diagnosis for secure internet of medical things," *Computers, Materials and Continua,* vol. 73, no. 1, pp. 965–979, 2022.

[18] J. Khan *et al.,* "Secure smart healthcare monitoring in Industrial Internet of Things (IIoT) ecosystem with cosine function hybrid chaotic map encryption," *Sci. Program.*, vol. 2022, no. 1, 2022. https://doi.org/10.1155/2022/8853448

[19] M. H. Shankarrao and V. R. Pawar, "Automatic greenhouse parameters monitoring and controlling using Arduino and Internet of Things," in *Innovative Data Communication Technologies and Application*, Cham, 2020, pp. 676–683. https://doi.org/10.1007/978-3-030-38040-3_77

[20] A. D. J. Carlos *et al.*, "Monitoring system of environmental variables for a strawberry crop using IoT tools," *Procedia Comput. Sci.*, vol. 170, pp. 1083–1089, 2020. https://doi.org/10.1016/j.procs.2020.03.067

[21] J. Li, "Design and realization of greenhouse sensor intelligent management system based on Internet of Things," *Int. J. Online Eng. (IJOE)*, vol. 13, no. 5, pp. 80–96, 2017. https://doi.org/10.3991/ijoe.v13i05.7051

[22] M. Danita, B. Mathew, N. Shereen, N. Sharon, and J. J. Paul, "IoT based automated greenhouse monitoring system," in *2018 Second International Conference on Intelligent Computing and Control Systems (ICICCS)*, Madurai, India, 2018, pp. 1933–1937. https://doi.org/10.1109/ICCONS.2018.8662911

[23] B. Ahmad *et al.*, "Evaluation of smart greenhouse monitoring system using Raspberry-Pi microcontroller for the production of tomato crop," *J. Appl. Res. Plant Sci.*, vol. 4, no. 1, pp. 452–458, 2023. https://doi.org/10.38211/joarps.2023.04.01.54

[24] S. Javed, L. Issaoui, S. Cho, and H. Chun, "Utilization of led grow lights for optical wireless communication-based rf-free smart-farming system," *Sensors*, vol. 21, no. 20, p. 6833, 2021. https://doi.org/10.3390/s21206833

[25] N. B. Jensen, M. R. Clausen, and K. H. Kjaer, "Spectral quality of supplemental LED grow light permanently alters stomatal functioning and chilling tolerance in basil (*Ocimum basilicum* L.)," *Sci. Hortic.*, vol. 227, no. 3, pp. 38–47, 2018. https://doi.org/10.1016/j.scienta.2017.09.011

[26] T. Morimoto and Y. Hashimoto, "An intelligent control technique based on fuzzy controls, neural networks and genetic algorithms for greenhouse automation," *IFAC Proceedings Volumes*, vol. 31, no. 5, pp. 61–66, 1998. https://doi.org/10.1016/S1474-6670(17)42098-2

[27] H. Habaragamuwa *et al.*, "Detecting greenhouse strawberries (mature and immature), using deep convolutional neural network," *Engineering in Agriculture, Environment and Food*, vol. 11, no. 3, pp. 127–138, 2018. https://doi.org/10.1016/j.eaef.2018.03.001

[28] Ji, Wei *et al.*, "Recognition method of green pepper in greenhouse based on least-squares support vector machine optimized by the improved particle swarm optimization," *IEEE Access,* vol. 7, pp. 119742–119754, 2019. https://doi.org/10.1109/ACCESS.2019.2937326

[29] D. Longo *et al.,* "A multifunctional tracked vehicle able to operate in vineyards using GPS and Laser Range-Finder technology," in *International Conference Ragusa SHWA2010*, September 16–18, 2010, Ragusa Ibla Campus, Italy, 2010, pp. 487–492.

[30] E. H. Harik and A. Korsaeth, "Combining hector slam and artificial potential field for autonomous navigation inside a greenhouse," *Robotics,* vol. 7, no. 2, p. 22, 2018. https://doi.org/10.3390/robotics7020022

[31] S. Q. Hou *et al.*, "Force chain characteristics and effects of a dense granular flow system in a third body interface during the shear dilatancy process," *Journal of Applied Mechanics and Technical Physics*, vol. 59, pp. 153–162, 2018. https://doi.org/10.1134/S0021894418010194

[32] G. Martinovic and J. Simon, "Greenhouse microclimatic environment controlled by a mobile measuring station. Njas-Wagening," *J. Life Sci.*, vols. 70–71, no. 1, pp. 61–70, 2014. https://doi.org/10.1016/j.njas.2014.05.007

[33] A. Ariss, I. Ennejjai, M. Benchrifa, J. Mabrouki, and S. Ziti, "Analytic performance between 4 and 5G networks using big data," in *Advanced Systems for Environmental Monitoring, IoT and the Application of Artificial Intelligence*, Cham: Springer Nature Switzerland, 2024, pp. 313–327. https://doi.org/10.1007/978-3-031-50860-8_19

[34] R. Buenrostro-Mariscal, P. C. Santana-Mancilla, O. A. Montesinos-López, J. I. Nieto Hipolito, and L. E. Anido-Rifon, "A review of deep learning applications for the next generation of cognitive networks," *Applied Sciences*, vol. 12, no. 12, p. 6262, 2022. https://doi.org/10.3390/app12126262

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