J. Electrical Systems 20-2 (2024): 2616-2630

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A Study of Irrigation Management in Smart Farming and IoT for Greenhouse Tomato Production

Abstract: **-** In this study of the relevant literature, we look at the development of smart farming and precision agriculture in greenhouse tomato cultivation, paying particular attention to the role that the Internet of Things (IoT) and automated irrigation systems have played thus far. Five terms were used to compile this literature review: automated watering systems, greenhouses, the Internet of Things, tomatoes, and smart farming. This article summarizes recent advancements in smart farming tech, their impact on greenhouse tomato farming, and their potential to boost future crop yield and quality. The evaluation starts by introducing 'smart farming' and its significance in agriculture, followed by a review of the greenhouse sector and an overview of the Internet of Things (IoT) within it, with subsequent examination of the pros and cons of employing smart farming and IoT in greenhouse tomato cultivation through specific industry technology examples. The following overview section discusses the benefits of cultivating tomatoes in a smart greenhouse, techniques for achieving optimal results in greenhouse tomato farming, and includes case studies to demonstrate the advantages of automated irrigation for smart greenhouse tomato cultivation, while this literature review analyzes the current state of innovative farming technology and its effect on greenhouse tomato cultivation, covering smart farming, greenhouse cultivation, the Internet of Things, tomato cultivation, and automated irrigation, summarizing significant results and recommendations for future research, including promising increases in crop yield and quality.

Keywords: Greenhouse, Internet of Things, Irrigation automation, Smart farming, Tomato

I. INTRODUCTION

Smart farming, also known as precision agriculture, is an advanced approach that uses state-of-the-art technologies to increase crop yields, reduce resource loss, and maximize productivity [1]. Smart farming integrates advanced tools like detectors, unmanned aerial vehicles, and satellites to analyze factors impacting crop growth such as soil conditions, weather patterns, and plant maturation rates, allowing farmers to optimize resource allocation and utilization by collecting and scrutinizing diverse data points, ensuring each agricultural stage is executed at optimal times, and using insights to refine planting, fertilization, watering, and harvesting methods to unprecedented levels of precision and meticulousness, crucial for maximizing crop yields while minimizing resource waste and production costs [2], [3].

Smart farming aims to improve agricultural sustainability by reducing the harmful effects of agriculture on the ecosystem, achieved through the use of sensors and other tools to minimize fertilizer and water usage, thus mitigating pollution and waste while employing precision farming methods to optimize land use for crop production, thereby benefiting wildlife habitats and slowing deforestation [4]–[6]. Smart farming can significantly increase food yield and quality by enabling farmers to identify factors limiting crop output, such as weather patterns, soil conditions, and plant development; for instance, soil moisture sensors can alert farmers to the need to water their crops, thereby improving growth and yield, ultimately allowing farmers to produce more food with fewer resources, increase their earnings, and decrease food waste [7], [8].

Smart farming, an innovative approach utilizing advanced technology, enhances harvests, minimizes losses, and boosts productivity by allowing farmers to optimize planting, fertilizing, watering, and harvesting schedules through data gathered from sensors, drones, satellites, and other state-of-the-art tools, thereby promoting agricultural sustainability, increasing yield and quality, and mitigating waste and pollution [9], [10].

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A. Overview of the Greenhouse Sector

The greenhouse industry, a subset of agriculture, utilizes advanced techniques and inventions to produce high-quality fruits year-round by creating an artificial atmosphere that allows plants to thrive and grow food in harsh weather; vegetables, flowers, fruits, and herbs can all benefit from greenhouse cultivation, enabling farmers to control factors such as temperature, moisture, and luminosity, thereby facilitating continuous production of high-quality crops regardless of weather conditions, while also reducing water usage on crops, benefiting both the ecosystem and finances [11]–[13]. The greenhouse industry relies on cutting-edge technologies and automated processes, such as sensors, computer systems, and automation software, to monitor and adjust facility conditions, enabling farmers to immediately change growing conditions based on collected data [14]. Sustainable production practices such as solar and geothermal power are becoming more prominent in the greenhouse industry to minimize waste and pollution [15]. Farmers in greenhouses are also experimenting with hydroponics and vertical gardening as ways to boost productivity and reduce environmental impact [12].

Overall, the greenhouse sector is essential to modern-day agriculture because it permits the continuous, ecologically sound, and financially feasible growth of superior crops all year round [16]. Greenhouse farmers can optimize crop development and yield while curtailing squandering and undesirable environmental impacts using advanced technology and techniques. The greenhouse sector is well positioned to assume an even more crucial function in fulfilling the needs of global consumers as the request for locally grown, first-rate food surges [17].

B. Exposition of the Internet of Things (IoT) in Agriculture

The Internet of Things (IoT) pertains to a framework of interlinked computing and perceiving nodes that can accumulate and transmit data through wireless means. IoT technologies are presently utilized in agribusiness to optimize productivity, decrease superfluousness, and intensify perpetual workability [18]. By assembling details concerning soil quality, climatic circumstances, vegetation growth, sundry, and other factors, farmers can make better judgments on when to sow, fertilize, irrigate, and harvest their crops. This enables them to make the necessary modifications for optimal growth and achieve more proficient and successful deployment of their resources [19].

IoT technologies in agriculture offer real-time data on crop progress and ecological conditions, enabling agriculturists to monitor soil moisture, temperature, and relative humidity using sensors and other instruments, thereby enhancing agricultural productivity, reducing waste, and optimizing resource utilization; precision farming techniques can further benefit from data analytics and machine learning systems, identifying trends and patterns in crop development and weather, thereby enabling plants to improve their resource management through optimal planting, fertilizing, irrigating, and harvesting [20], [21].

The use of Internet of Things technologies enhances the viability of farming by reducing the amount of water, fertilizer, and pesticides needed to grow crops. Farmers can improve sustainability and reduce their carbon footprint using renewable energy sources and sustainable practices. IoT technologies are increasingly important in agriculture for optimizing crop output, reducing waste, and increasing sustainability. As technology develops, enhanced IoT solutions for agriculture will likely emerge, boosting agricultural productivity and longevity [3], [14].

C. Overview of Tomato Cultivation and Irrigation Automation

The intricate process of tomato growth requires careful monitoring of soil moisture, temperature, sunlight, and nutrient levels, with irrigation playing a crucial role; consistent watering is essential for optimal plant development and can greatly influence the success and quality of the harvest. Traditionally, farmers have manually monitored soil moisture levels and adjusted irrigation systems during tomato cultivation, but in recent years, the widespread adoption of automated irrigation devices in agriculture has become increasingly prevalent, utilizing sensors and other technologies to automatically monitor soil moisture levels and make necessary adjustments [22], [23].

Automated watering systems provide significant benefits to tomato farms, including increased productivity, water conservation, and improved tomato quality, as farmers can save time and energy by installing computerized systems for routine monitoring and irrigation adjustment, which also enable more precise and practical water application than manual systems, thereby helping lower water consumption [24]. Tomato plants require a consistent water supply during growth and development, which automatic irrigation systems can provide by dispensing water appropriately, resulting in higher yields and better-quality tomatoes; monitoring various variables, including watering, is crucial for successful tomato growth. Moreover, irrigation automation technologies can increase productivity, decrease water consumption, and improve yields and product quality in tomato cultivation, with advancements in technology likely leading to the emergence of more sophisticated irrigation automation options for tomato cultivation, further boosting agricultural productivity and sustainability [22], [25].

D. Purpose of the Literature Review

This literature review offers a detailed examination of smart farming and precision agriculture for greenhouse tomatoes, emphasizing IoT and automated irrigation’s contributions to advancing agricultural technology and improving crop yield and quality.

Farmers are increasingly interested in smart and precision agriculture to maximize crop yield and minimize waste, and the combination of Internet of Things (IoT) technologies and automated irrigation systems has the potential to transform greenhouse tomato cultivation, allowing for high-quality crops year-round with minimal environmental impact; however, there is still much to learn about the advantages and disadvantages of these technologies in agriculture and their potential for growth and development, and this literature review aims to contribute to the ongoing discussion about smart farming and precision agriculture in greenhouse tomato cultivation by providing a comprehensive overview of the latest research in this field, assessing the latest breakthroughs in smart farming systems, covering their use in cultivating greenhouse tomatoes, their impact on crop production and excellence, and their capacity to curtail waste and improve sustainability, and also including recent investigations and revelations concerning Internet of Things (IoT) technologies and automated irrigation systems for tomato growth.

To create this literature review, we followed several essential methods: first, establishing core ideas including 'smart farming,' 'greenhouse,' 'IoT,' 'tomatoes,' and 'irrigation management' as keywords; second, reviewing scholarly literature through online databases such as Google Scholar and ScienceDirect, using keywords and associated terms to find relevant articles, papers, and reports, and narrowing the selection to papers from high-quality journals indexed by SCOPUS, with the most relevant and reliable options published between 2014 and 2023; third, reviewing abstracts and full texts of potential publications to include them in the literature review; fourth, building a foundation that made sense and was consistent with the literature by categorizing similar articles and extracting the most important themes and topics; and finally, composing an accessible and concise literature review by synthesizing the material gathered from relevant sources, proofreading and editing until complete, ensuring accuracy, clarity, and conciseness, and making necessary changes to enhance coherence and readability.

Fig. 1. Articles Distribution by SCOPUS Quartile

Fig. 1 reflects the distribution of articles used as references for the literature review on smart farming and precision agriculture for greenhouse tomatoes, categorized by the SCOPUS reputation article ranking quartile. The majority of the articles, totaling 35, originate from the highest-ranked journals in the first quartile (Q1), signifying a preference for highly reputable sources, followed by 16 articles from the second quartile (Q2), 11 from the third quartile (Q3), and 7 from the fourth quartile (Q4), with an additional 11 articles sourced from conference proceedings, known for presenting the latest research findings concisely, thereby indicating a comprehensive and high-quality selection of sources, ensuring a robust and credible literature review, grounded primarily in well-regarded and influential research, which can enhance the credibility and reliability of the review's findings and conclusions, highlighting the authors' prioritization of sourcing from reputable journals with rigorous peer-review processes and widely recognized work in the field.

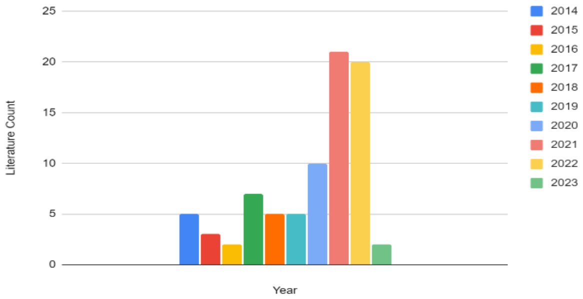

Fig. 2. Articles Distribution by Year Pubished

Fig. 2 illustrates the annual acquisition of SCOPUS-indexed articles for the literature review on smart farming and precision agriculture in greenhouse tomatoes, showing a gradual rise in research articles from 2014 (starting with 5 articles) to a peak of 21 articles in 2021, indicating increasing academic interest and development in IoT and automated irrigation systems to enhance tomato cultivation in greenhouses; the decline to 2 articles in 2023 may suggest a mature field with established research or a shift in focus to newer topics, underscoring a substantial body of research contributing to the literature review, emphasizing advancements and discussions surrounding smart farming systems and their impact on sustainability and crop production excellence.

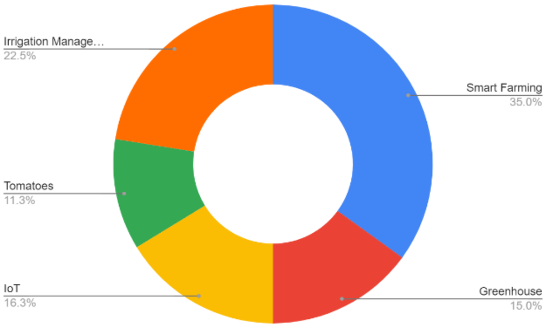

Fig. 3. Articles Distribution by Keywords

Fig. 3 reflects the number of articles acquired from SCOPUS-indexed journals used as references for the literature review on smart farming and precision agriculture for greenhouse tomatoes, with 'Smart Farming' yielding 28 articles, indicating a robust body of research; 'Greenhouse' associated with 12 articles, showing focused interest in this controlled environment; 'IoT' leading to 13 articles, highlighting the growing integration of Internet of Things technologies in agriculture; 'Tomatoes' resulting in 9 articles, pointing to specific research on this crop within the context of smart farming; and 'Irrigation Management' linked to 18 articles, underscoring the importance of water management in the pursuit of efficient and sustainable agriculture practices, collectively forming the foundation of the literature review and providing insights into the advancements and challenges of implementing IoT and automated irrigation systems in the cultivation of greenhouse tomatoes.

Table 1. Relationship between Articles Keywords and SCOPUS Quartile Rank

	Smart Farming	Greenhouse	IoT	Tomatoes	Irrigation Management
Q1	17	6	3	3	6
Q2	4	2	3	2	5
Q3	2	2	1	2	4
Q4	2	2	1	0	2
Proceeding	3	0	5	2	1
	28	12	13	9	18

Table 1 represents the number of articles acquired from SCOPUS-indexed journals, used as references for the literature review on smart farming and precision agriculture for greenhouse tomatoes, categorized based on keywords: 'Smart Farming,' 'Greenhouse,' 'IoT,' 'Tomatoes,' and 'Irrigation Management,' with the majority of articles in Q1 related to 'Smart Farming' (17 articles) and 'Irrigation Management' (6 articles), and a consistent presence of 'IoT' across all quarters, particularly in proceedings (5 articles). Overall, 'Smart Farming' had the highest number of articles (28), indicating a strong research focus, while 'Irrigation Management' had a significant number of articles (18), reflecting its importance in greenhouse tomato cultivation. 'Tomatoes' had fewer articles (9), suggesting a more specific research niche. The relationship between values for each cell reflects the distribution and focus of research articles across different themes related to smart farming and precision agriculture, indicating trends, sustained research interests, potential interdisciplinary connections, and areas most actively explored over time.

II. SMART FARMING IN GREENHOUSE CULTIVATION

Smart farming, a data-focused strategy, optimizes crop productivity and sustainability while minimizing waste, improving crop quality and output, thus proving to be a valuable approach wherein farmers can optimize planting, fertilization, irrigation, and harvesting operations timing through sensors, drones, satellites, and other advanced technologies that collect and scrutinize data on weather patterns, soil conditions, and other variables [14]. Smart farming enhances yield and quality by providing farmers with real-time statistics on crop growth and environmental conditions, allowing them to use sensors to monitor soil moisture and nutrient levels, adjust watering and fertilization plans accordingly, thereby increasing harvests and producing higher-quality crops [26].

Smart farming enables farmers to optimize planting schedules and crop interchanges using real-time information on atmospheric patterns and other environmental variables, thus improving soil health and crop yields by planting appropriate crops at the right time, while data analysis and machine learning algorithms can help identify patterns in crop growth and environmental conditions, leading to long-term benefits such as improved resource distribution and increased harvests [27]. Using innovative farming technologies, such as sensors and other monitoring tools, enables farmers to prevent and swiftly resolve crop issues like pests, disease, and nutrient deficiencies, thereby maintaining agricultural health, increasing yield, and enhancing harvest value and quality [28]. As technology advances, smart farming can enhance crop yields and quality by offering farmers real-time data on crop development and environmental conditions, fostering the development of more sophisticated and innovative farming solutions to further increase agricultural effectiveness and output [29].

A. Advantages and Disadvantages of Using Smart Farming in Greenhouse Cultivation

Smart farming, an advanced technique utilizing modern technology to increase yields, minimize resource waste, and optimize productivity, can enhance greenhouse cultivation by improving crop yield and quality, reducing waste, and using resources more efficiently, although it may also present drawbacks [30]. Innovative farming practices enable farmers to fine-tune greenhouse climates for optimal plant growth by utilizing data from sensors to determine the ideal timing for watering, fertilizing, and harvesting, thus maximizing resource efficiency and yields [31].

Greenhouse cultivation utilizing smart farming techniques not only offers additional benefits, such as waste reduction and minimized environmental impact, but also enables farmers to decrease water and fertilizer usage through sensor-based monitoring of soil moisture and other conditions, thereby benefiting the climate and reducing waste, while the integration of renewable energy sources and other eco-friendly practices can enhance long-term business viability and diminish environmental footprint [32]. Implementing innovative farming tools in greenhouses may have drawbacks due to the expense of introducing and maintaining these technologies, as farmers may face substantial initial costs and challenges in adopting and utilizing these complex, labor-intensive solutions, particularly if lacking the necessary skills or resources [33], [34].

Using smart farming in greenhouse cultivation has numerous benefits that outweigh the drawbacks of optimizing crop yield and reducing waste. However, farmers must carefully consider the costs and complexity of adopting these technologies and ensure that they have the necessary knowledge and resources to do so successfully. As science and engineering progress, they will likely create more sophisticated smart farming solutions for greenhouse cultivation. This will further boost agricultural productivity and sustainability [35].

B. Examples of Smart Farming Technologies in Greenhouse Cultivation

Rapid advances in precision agriculture are revolutionizing the greenhouse industry, allowing farmers to harvest healthy fruits year-round with minimal environmental impact. Greenhouse farming employs numerous forms of clever farming technology, each with benefits and advantages. Some innovative farming tools currently in use in greenhouses are listed below.

[36] utilized sensors linked to the Internet of Things (IoT) to assess and communicate details regarding factors such as temperature, humidity, and luminosity in a specific region. Adaptations to the evolving climate can subsequently be implemented based on these data. Farmers can optimize environmental conditions such as temperature and humidity by utilizing IoT contraptions to amplify crop output. [37] discovered the application of sensors in automated irrigation systems to monitor soil moisture levels and adjust watering schedules automatically. This can potentially lessen water consumption and boost agricultural output and quality.

LED lighting is frequently used in greenhouses to increase the luminosity required for plants to thrive, as indicated by [38]. Because LED lights can be adjusted to provide the precise spectrum of luminosity that plants need at various stages of growth, higher crop yields and higher quality crops are feasible. The greenhouse's ideal growing conditions are maintained with the help of climate control devices. [39] implemented systems that use sensors to monitor the surrounding environment and modify building heating, ventilation, air conditioning (HVAC), lighting, and temperature control.

Machine learning and artificial intelligence (AI): Algorithms created by [40] are trained on large amounts of data from instruments and other sources and are used to identify recurring patterns and trends in crop development and environmental conditions. By knowing this, farmers can better plan when to sow, fertilize, and harvest their products. Greenhouse farmers can use various clever farming technologies with potential benefits and uses. As science and engineering progress, more sophisticated smart farming solutions for greenhouse cultivation will likely be created, boosting agricultural productivity and sustainability even further.

III. INTERNET OF THINGS (IOT) IN AGRICULTURE

The Internet of Things (IoT) is a linked computing and sensing module structure that can compile and relay data wirelessly. The agribusiness sector is progressively adopting Internet of Things (IoT) technologies to increase yield efficacy, curtail waste, and reinforce environmental sustainability. By amassing information on soil circumstances, atmospheric models, vegetation expansion, and other parameters, farmers can make informed choices about planting timing, enriching, drenching, and cropping yields [41].

Sensors and other instruments are extensively utilized in farming as an element of the Internet of Things to monitor everything from soil dampness to ecological situations to agricultural growth. Farmers can use real-time data from IoT technologies to make informed decisions at the right time, optimize crop growth and reduce waste [14], [42]. These technologies provide information on crop expansion and environmental conditions, allowing farmers to monitor ground moisture, temperature, and other factors and make necessary adjustments for optimal growth [43]. IoT technologies have the potential to increase agricultural productivity, decrease excess usage, and maximize the availability of accessible resources, facilitating precision farming techniques that enable farms to benefit from data analytics and machine learning systems for spotting trends and patterns in crop development and weather, ultimately improving resource management by planting, fertilizing, irrigating, and harvesting at optimal times [44].

The integration of Internet of Things (IoT) technologies in farming enhances viability by reducing water, fertilizer, and pesticide usage, enabling farmers to enhance sustainability and diminish their carbon footprint through renewable energy sources and sustainable practices, thereby transforming the agriculture industry towards more efficient and ecological crop cultivation. [45]. As technology progresses, refined IoT solutions for agriculture are expected to improve agricultural output and durability.

A. Advantages and Disadvantages of Using the IoT in Agriculture

The IoT revolutionizes farming by providing producers real-time information on crop development and weather patterns, guiding farmers toward optimal planting, fertilization, irrigation, and harvesting times, thus improving resource utilization, yield, and quality; however, the benefits of IoT technologies in agriculture are not without possible drawbacks, as implementing IoT can maximize crop development while decreasing waste through the utilization of sensors and other instruments to collect information about soil conditions, weather patterns, and other factors, ultimately leading to increased harvests of higher-quality produce [46]–[48].

Additionally, implementing IoT in farming can result in more productive use of resources, as farmers can improve crop growth by using sensors to monitor soil moisture and temperature, thereby reducing the time and effort required to adjust growing conditions physically [49]. However, despite potential disadvantages such as high implementation and maintenance costs, as well as the technical challenges requiring extensive knowledge, the benefits of integrating Internet of Things (IoT) devices in farming, including enhanced crop productivity and reduced losses, outweigh these concerns, necessitating farmers to carefully consider the associated time, effort, and expenses before adoption [33], [50], [51].

B. Examples of IoT in Greenhouse Cultivation

Farmers now have access to real-time information on crop development and environmental circumstances due to the proliferation of Internet-of-Things (IoT) devices in greenhouses, which can improve resource utilization, yield, and quality by guiding farmers toward optimal planting, fertilization, irrigation, and harvesting times; for instance, sensors developed to measure soil moisture are used in devices to track the moisture content of a field in real time, enabling farmers to fine-tune their irrigation systems for optimal water usage and agricultural growth.

Greenhouse temperature, humidity, and luminosity may be monitored using a climate control mechanism devised by [52]. Using this information to fine-tune environmental settings, we can maximize resource utilization and boost crop quality and output. [53] highlighted the use of sensors in automated irrigation systems to assess soil moisture levels and adjust watering schedules automatically. This can potentially lessen water consumption and boost agricultural output and quality.

Luminosity often increases the luminosity of plants, which need to flourish in a greenhouse. Higher crop yields and higher quality crops are possible because LED lights can be adjusted to provide the precise spectrum of luminosity that plants require at various stages of development, which has been studied by [54]. Many various types of Internet of Things technologies are currently being used in greenhouse farming, each of which offers specific advantages. Growing greenhouses could benefit from even more cutting-edge Internet of Things (IoT) answers in the future, increasing productivity and minimizing environmental impact.

IV. TOMATO CULTIVATION IN A SMART GREENHOUSE ENVIRONMENT

Growing tomatoes is difficult and time-consuming because variables such as humidity, temperature, and luminosity intensity must be controlled. Innovative greenhouse environments are being increasingly implemented for tomato cultivation to maximize yield while decreasing waste and increasing sustainability [22], [55]. Some of the upsides of growing tomatoes in a high-tech garden are as follows:

According to [56], increased harvest success and food safety are made possible by real-time monitoring of environmental factors such as temperature, humidity, and luminosity levels in an smart greenhouse setting. This information is used to fine-tune the growth environment, which increases resource efficiency and enhances the quality and quantity of the crops produced. [57] surveyed an smart greenhouse equipped with sensors and other technologies to monitor soil moisture, plant development, and other variables, utilizing the gathered information to optimize resource utilization, minimize waste, and maximize yield by adjusting the amount of water, fertilizer, and other inputs given to the crop. Greenhouses are becoming more eco-friendly by utilizing renewable energy sources such as solar and wind power, while also reducing energy consumption through innovative environments that employ sensors and other technologies to optimize growing conditions. Smart greenhouse cultivation of tomatoes minimizes environmental impact through the use of renewable energy and sustainable methods, while also boosting productivity and reducing waste [22], [58].

Today's smart greenhouses equip farmers with data for informed decision-making on sowing, fertilizing, irrigating, and harvesting crops, allowing them to enhance resource allocation by discerning trends and patterns in crop growth and environmental conditions via data analytics and machine learning algorithms [1], [47]. Growing tomatoes in an smart greenhouse can increase yield and quality, reduce waste, and improve sustainability, with an innovative greenhouse already having increased crop yields and efficiency, while future innovations in this area are expected to achieve even higher levels of success [16], [59].

A. Techniques for Optimizing Tomato Growth in an Smart Greenhouse Environment

Successful tomato cultivation in an smart greenhouse setting requires careful management of environmental variables such as temperature, humidity, and luminosity, wherein sensors and other technologies track these factors in real time, empowering farmers to make educated choices about maximizing crop growth [23]. Tomato plants thrive at warm temperatures, but excessive heat can stunt their development; according to [60] and [61], temperature sensors can be used to fine-tune the atmosphere of an smart greenhouse for optimal plant growth, thus helping maintain a steady temperature for plant development.

Additionally, controlling humidity levels is crucial for growing tomatoes as low humidity can cause plants to dry, while high humidity can encourage the development of fungal diseases; thus, an smart greenhouse utilizes humidity sensors to monitor and adjust climate conditions as needed [61]. [62] showed that tomatoes require different intensities of luminosity at various stages of development. In an innovative greenhouse, LED lights can be adjusted to emit the precise wavelengths of luminosity necessary for different phases of development. To aid in plant development, it is essential to ensure that plants receive the ideal amount and quality of light.

Tomato plants are sensitive to water, and over- or underwatering can hinder their growth. Soil moisture sensors in an smart greenhouse enable constant monitoring of soil moisture levels and automatic watering as needed. As a result, plants may obtain the ideal quantity of water required for maximum growth [61], [63]. The prudent regulation of ecological elements such as temperature, humidity, and luminosity is imperative for optimal tomato development in smart greenhouses. Farmers can heighten the output and sustained practicality of their tomato harvests by employing sensors and other apparatuses to trace these variables in real time and implement rectifying actions as needed.

B. Case Studies on Tomato Cultivation in an Smart Greenhouse Environment

Tomato production in an smart greenhouse setting has been the subject of numerous case studies highlighting how technological advancements can enhance yields and decrease environmental impacts. We can see this in the following instances:

According to a [64] study, innovative technological options, such as dynamic smart greenhouses, the Internet of Things (IoT), and precision farming, along with alternative water and energy resources, can help Qatar achieve its National Vision 2030, especially given the difficulties related to ensuring food security, preserving the environment, and promoting sustainability. Smart farming can help modernize and transition to precision agriculture by using technological methods such as hydroponics, aquaponics, and vertical farming for food production; novel cooling systems enable year-round crop cultivation, particularly in summer, with reduced water consumption.

An investigation by [65] identified enhanced greenhouse efficiency as one of the essential aims of advanced agriculture. Managing the greenhouse climate is a critical challenge in industrial agriculture. The effectiveness of greenhouse efficiency and crop cultivation can be considerably improved by controlling and adjusting greenhouse characteristics such as artificial luminosity. Therefore, determining the optimal supplemental luminosity and managing greenhouse lighting can enhance economic efficiency. The results show that the profit in the case study can be approximately doubled by using electrical lighting at the right time.

The smart greenhouse described by [66] and [67] is suitable for various crops, including tomatoes, and has shown positive effects on the growth of begonia, tomatoes, and peppers. During the observation period, the system used only 2800 mL of water when needed, indicating efficient water usage. Although the study is a prototype, it has the potential to be scaled up into a large-scale innovative greenhouse system. Smart greenhouses are advantageous because they help reduce resource consumption by utilizing resources most efficiently. Additionally, specialists suggest that the study can be easily adapted to different plants by defining the system's characteristics based on the plants grown in the greenhouse.

The research described by [68] centers on digitizing and presenting potted greenhouse tomato plants under indoor conditions. The objective is to create a "standard" digital tomato plant that can reflect the growth conditions of the entire group of tomato plants by generating a particular actual tomato plant in 3D. Future investigations will concentrate on digitizing the complete plant growth process in a controlled greenhouse environment without limitations on cultivation techniques. Consequently, the connection between crop growth and accurate plant growth models will be studied, and plant models derived from data will be established to replicate and anticipate actual climatic data for simulating plant growth and predicting accurate data.

These studies show how smart greenhouse settings can boost the efficiency, productivity, and sustainability of tomato cultivation. Growing tomatoes in a clever greenhouse has already increased crop yields and efficiency; future innovations in this area are only expected to take this to an even higher level.

V. IRRIGATION AUTOMATION IN SMART GREENHOUSE SYSTEMS

In an smart greenhouse, sensors and other technologies track soil moisture levels and automatically change irrigation systems. With automated irrigation, farmers can avoid over- or underwatering their crops while still providing them with the proper quantity of moisture [24], [67]. Automated irrigation is crucial to smart greenhouse systems because it significantly impacts productivity and environmental sustainability, offering better control over water usage by using sensors to track soil moisture levels and make necessary adjustments, thereby decreasing water and resource usage, minimizing pollution, and improving precision gardening [14], [63], [65].

By employing data analytics and machine learning algorithms, farmers can monitor soil hydration levels over time, enabling them to make informed decisions about watering schedules and application rates, ultimately resulting in better resource management and higher quality and quantity harvests, while mechanizing irrigation systems not only enhances workforce productivity but also saves time and energy typically spent on manual watering system monitoring and adjustments, potentially increasing productivity in the tomato industry while diminishing the reliance on manual labor; as technology advances, automated irrigation becomes increasingly crucial for smart greenhouse systems, aiding farmers in boosting agricultural yields, reducing resource consumption, and prioritizing ecological sustainability, with further advancements expected to lead to more sophisticated irrigation automation solutions for tomato cultivation, thereby enhancing farming efficiency and output [36], [44], [69], [70].

A. Advantages and Disadvantages of Irrigation Automation in Smart Greenhouse Systems

Equipped with sensors and control mechanisms, irrigation automation is a transformative technology that has the potential to revolutionize agricultural practices by monitoring and adjusting soil moisture levels in real time, ensuring optimal plant growth, offering precision in water management crucial in regions where water is scarce or expensive, reducing waste and preventing over-irrigation by delivering the exact amount of water needed for each plant, thus preventing soil degradation and nutrient leaching, and maximizing water use efficiency by watering plants at the most effective times of day [44], [65].

The integration of data analytics and machine learning into irrigation systems represents a significant advancement in agricultural technology, enabling analysis of vast amounts of data to determine efficient irrigation schedules, predict future water needs based on weather forecasts, and detect plant diseases early, thus improving yields, resource efficiency, and reducing manual labor. However, challenges include the high initial cost, limiting access for small-scale farmers and those in developing countries, the need for expertise to operate and maintain the technology, which may not be readily available in all farming communities, and susceptibility to malfunctions and breakdowns, potentially leading to reduced yields and lower quality produce when crops are left without water. [67], [71], [72].

Despite the challenges, the benefits of irrigation automation in smart greenhouse systems are evident, offering a sustainable solution to food production demands while conserving water and reducing environmental impact, as technology progresses and becomes more affordable, making these systems increasingly accessible to farmers worldwide, thereby ensuring food security for future generations; although there are disadvantages, the advantages of irrigation automation systems in smart greenhouses are compelling, representing a significant step forward in sustainable agriculture and holding great promise for improving crop production and resource management in the years to come, as the global population grows and climate change effects intensify, technologies like these will be vital in feeding the world without depleting its natural resources.[14], [65], [73].

With respect to optimizing water usage and improving the efficiency and sustainability of tomato cultivation practices, the benefits of using irrigation automation in innovative greenhouse systems exceed the potential drawbacks. However, farmers should weigh the benefits against the costs and complexity of adopting these technologies and ensure they have the know-how and resources to do so successfully.

B. Case Studies on Irrigation Automation in Innovative Greenhouse Systems for Tomato Cultivation

Numerous case studies have shown how automated irrigation in clever greenhouse systems can reduce water consumption, increase yields, and lessen environmental impacts when growing tomatoes. We can see this in the following instances:

Automated irrigation instruments are crucial for the future improvement of irrigation agriculture. [74] investigated a synthetic irrigation method that combines autonomous irrigation with a water-saving irrigation decision technique. In a greenhouse tomato growth experiment, an autonomous trickle irrigation system with moisture sensors and control nodes was configured wirelessly, and a central irrigation controller was used to accomplish irrigation events. Unlike earlier irrigation decision techniques, the designed irrigation depth was established at each irrigation result using various irrigation depths predicted from real-time soil moisture data.

The research presented by [75], [76] aims to create a novel approach to irrigation that utilizes zoning irrigation, fuzzy control, wireless sensor network (WSN) communication, and IoT to monitor irrigation and maintain optimal soil moisture levels for plant growth while minimizing water and energy usage, successfully meeting its objectives and outperforming other methods for reducing water and energy consumption by combining the zoning strategy with a fuzzy logic controller, resulting in the creation of a system with various advantages, including a simple setup, the option to include separate nodes for more areas, real-time monitoring using the IoT and WSN, and cost savings through reduced water and energy consumption.

In their study [5], an autocalibrated smart pH sensor was introduced to collect data for monitoring and adjusting nutrient solution quality in precision agriculture, alerting the farmer when pH values cross a specific threshold and prompting corrective measures, while a wireless sensor network (WSN) gathers the data and presents it on a web-based interface, easily accessible from any device with a browser and an Internet connection, such as a computer, tablet, or smartphone.

Research by [77], [78] explained that the soil moisture sensors effectiveness to conserve water is contingent upon the threshold value of volumetric moisture capacity configured by farmers. Rain, soil moisture, and evapotranspiration sensors have been demonstrated to preserve up to 92%, 71%, and 50% of water, respectively, while maintaining crop growth and quality. In comparison, the optical sensor-based system surpassed on-site measurements in evaluating soil and crop limitations in the field. The conventional deficit irrigation approach was established to reduce crop yield by no more than 25% while conserving up to 13% of water.

According to [79], [80], although water and nutrient recirculation and reduction measures were implemented for tomato plants, there was no reduction in yield. However, these measures help minimize the adverse effects of nutrient discharge and improve water use efficiency. This paper discusses the environmental impact of food production and how it can be mitigated by implementing a recirculation system. Mass-balanced fertilization plans that consider soil nutrient availability and crop removal can be valuable methods for addressing the effects of open systems. Among recirculation management practices, irrigation reduction improved water-use efficiency by 7%.

Case studies show that using irrigation technology in innovative greenhouse systems for tomato cultivation improves water management, cuts waste, and makes the process more sustainable. More sophisticated irrigation automation solutions for tomato cultivation will likely be developed as technology advances, increasing farming efficiency and output.

VI. CONCLUSION

This study explored smart farming and IoT technologies for tomato production in greenhouses. The findings showed that these technologies, including smart greenhouses capable of regulating crucial growth conditions such as temperature, humidity, and luminosity to improve tomato yields, can simultaneously enhance crop yield and quality, reduce waste, and improve sustainability by enabling farmers to track crop growth factors in real-time using sensors and other technologies and make informed decisions, while also benefiting from automated irrigation systems to save water and increase crop yields. The implementation of smart farming and IoT technologies in tomato production has numerous benefits. Nevertheless, there are also some potential drawbacks. Overall, growing tomatoes with these technologies will be more beneficial, especially regarding productivity and longevity, than conventional methods. The advantages of using technology to optimize crop growth and minimize waste were demonstrated through case studies of tomato cultivation in innovative greenhouse environments. Pure Harvest Smart Farms, Green Sense Farms, and Proefstation Voor de Groenteteelt were just a few examples. This article emphasizes the significance of using smart farming and IoT technologies in smart greenhouses for tomato production. Increased crop yield and quality, decreased waste, and greater sustainability are some of these tools that help farmers. Growing tomatoes in a clever greenhouse has already increased crop yields and efficiency; future innovations in this area are only expected to take this to an even higher level.

A. Future Research Directions in Smart Farming

There is much room for growth and development in smart farming, greenhouse farming, the Internet of Things, tomato farming, and automated watering systems. A few possible prospective lines of inquiry in these fields are as follows:

Machine learning and AI can transform smart farming and greenhouse cultivation by allowing farmers to optimize crop growth with real-time data analytics. Machine learning and AI could be applied to improve air quality and maximize efficiency in using scarce resources.

Cutting-edge sensor technologies that offer real-time insights into crop environments and plant health is crucial in smart farming and the Internet of Things, while researchers may enhance data measurement precision and reliability through advanced sensor technologies development like nanosensors and biosensors for smart farming and greenhouse cultivation.

Vertical farming and urban farming, two promising new areas, could significantly enhance the efficiency and sustainability of a food system if allowed to flourish, with a forthcoming closer examination of smart farming, the Internet of Things, and alternative technologies aimed at optimizing resource utilization efficiency and improving crop quantity and quality.

B. Development of Sustainable Irrigation Techniques

Future studies should concentrate on sustainable irrigation methods that minimize water consumption and waste, which are critical for successful smart farming and greenhouse cultivation, such as precision irrigation methods that optimize water usage according to plant needs and utilize alternative water sources like rainwater harvesting and wastewater recycling; additionally, advanced nutrient management techniques that maximize nutrient utilization and minimize waste could be a focus of future research. This is especially relevant as smart farming and greenhouse cultivation gain momentum. This may involve the creation of biofertilizers and other long-term nutrient sources and the use of precision fertilization methods that transport nutrients directly to plant roots.

Smart farming, greenhouses, the Internet of Things (IoT), tomato farming, and automatic irrigation are promising sectors for impending inquiry that could extensively intensify the efficacy and sustainability of sustenance production. It is plausible that we will encounter even more state-of-the-art resolutions established in these domains as technology progresses, supplementarily augmenting the effectiveness and output of agricultural methodologies.

ACKNOWLEDGMENT

Sincere appreciation is extended to Universitas Padjadjaran's Directorate of Research and Community Service and Directorate of Finance and Treasury for facilitating the authors' research.

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