Integration of Geothermal Heating Technologies into Agricultural Structures: A Smart Greenhouse Approach

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Abstract— *The increasing global population, the impacts of climate change, and the rising energy costs are making it increasingly difficult to ensure sustainability in agricultural production systems. In particular, the greenhouse sector, despite offering significant advantages for year-round production, constitutes an energy-intensive production model due to its high heating requirements. The current heating systems based on fossil fuels lead to both increased production costs and higher carbon emissions. In this context, ensuring energy management in greenhouses through renewable sources has become a strategic necessity in terms of economic efficiency and environmental sustainability. The main objective of this study is to examine the potential use of geothermal energy resources in agricultural structures, particularly in smart greenhouse systems, from engineering, environmental, and economic perspectives. Within the scope of this study, the design principles of geothermal heating systems, their energy efficiency potential, heat transfer mechanisms, and integration processes with smart control systems (IoT sensors, automation, and artificial intelligence algorithms) were evaluated. In addition, comparative analyses were conducted based on Turkey's geothermal resource potential, application examples, and energy economy indicators. The significance of this study lies in the fact that renewable energy-based smart greenhouse applications enhance energy security in agricultural production, reduce carbon emissions, and ensure production continuity. The utilization of geothermal energy as a constant, domestic, and low-emission resource in the agricultural sector directly aligns with the goals of sustainable production. The literature review indicates that studies focusing on the integration of geothermal heating technologies with smart control infrastructures, particularly within the context of Turkey, remain limited. Existing research largely remains confined to energy analysis, while comprehensive engineering approaches that simultaneously address digital automation, system modeling, environmental impact, and policy interaction have not been sufficiently developed. This study aims to fill this gap by presenting a multidisciplinary assessment framework for the integration of geothermal energy and smart greenhouse technologies. In this review, studies published in international scientific databases such as Scopus, Web of Science, ScienceDirect, ProQuest, ResearchGate, MDPI, IEEE, and Google Scholar were examined to comprehensively analyze the integration of geothermal heating technologies into agricultural structures and their adaptation processes within the context of smart greenhouse systems.*

Keywords— ***Geothermal Energy, Smart Greenhouse, Energy Efficiency, Internet of Things (IoT), Sustainability, Carbon Emission.***

I. INTRODUCTION

The escalating global climate crisis driven by global warming, wars, mass migration movements, and rapid population growth has emerged as a fundamental threat to humanity's secure access to food. This process not only exerts increasing pressure on agricultural production systems but also poses a serious risk to the sustainable use of natural resources. According to the United Nations' World Population Prospects report, the global population is projected to reach 8.6 billion by 2030, 9.8 billion by 2050, and exceed 11.2 billion by 2100 [1]. This upward trend necessitates a re-evaluation of existing production and consumption models, the strengthening of food security policies, and the adoption of more sustainable approaches to natural resource management.

In Turkey, greenhouse cultivation stands out as a significant agricultural production area that reduces seasonal dependency and enhances crop diversity. The total area of greenhouse farming across the country amounts to 776,110 decares, of which 7.2%

consists of glass greenhouses (55,949 da), 58.4% of plastic greenhouses (452,907 da), 13.4% of high tunnels (103,978 da), and 21% of low tunnels (163,276 da) [2].

The Food and Agriculture Organization (FAO) of the United Nations projects that by 2050, the global population will reach approximately 9.1 billion, emphasizing that such demographic growth will exacerbate global challenges related to food access and adequate nutrition. According to FAO, mitigating the adverse effects of this trend requires countries to develop holistic, sustainable, and inclusive food policies. The organization further indicates that global food demand is expected to increase by more than 60% by 2050, necessitating a significant expansion of agricultural production capacity and food supply [3], [4].

These projections clearly demonstrate that the agricultural sector must not only increase production volumes but also enhance the efficiency, environmental sustainability, and energy performance of production processes. In this context, the effective utilization of geothermal energy resources in agricultural production particularly in greenhouse cultivation and rural heating applications emerges as a sustainable alternative solution. Geothermal energy holds strategic importance for the future of agricultural production systems due to its potential to reduce dependence on fossil fuels, lower production costs, and minimize carbon emissions. Consequently, achieving food security and addressing the climate crisis successfully depend on the integrated adoption of innovative agricultural technologies, climate-friendly production methods, and renewable energy sources such as geothermal energy within the agricultural sector.

Greenhouse cultivation, while being one of the most effective methods for maximizing agricultural productivity by increasing yield per unit area, is also considered one of the most energy-intensive subsectors within agricultural production systems due to its high energy demand, investment costs, and operational expenses [5]. In modern greenhouse enterprises, where environmental conditions are artificially controlled, energy consumption can account for up to 78% of total production costs. A substantial portion of this consumption approximately 65-85% of the primary energy requirement is directed toward heating and cooling processes aimed at maintaining the optimal temperature and humidity balance of the plant growth environment [6]. This situation underscores the importance of renewable energy solutions that enhance energy efficiency for the sustainability of greenhouse operations. In this context, the utilization of geothermal energy resources for heating in greenhouse cultivation presents a critical alternative that reduces dependence on fossil fuels while contributing to both economic and environmental sustainability.

With technological advancements, recent years have witnessed the increasing adoption of smart greenhouses characterized by enhanced energy efficiency, high levels of automation, and precise monitoring of environmental parameters [7]. These new-generation greenhouse systems, through optimized control mechanisms, not only reduce energy consumption but also improve product quality and productivity. Smart greenhouses provide controlled agricultural production environments that ensure sustainable cultivation throughout the year by integrating sensor-based climate management, automated irrigation, and nutrient dosing systems.

These developments, in contrast to traditional greenhouse cultivation, highlight the growing importance of innovative approaches such as digital monitoring, data-driven decision-making, and renewable energy integration in production processes. In this context, smart greenhouse systems integrated with geothermal energy represent an innovative engineering approach that enhances energy efficiency in agricultural production, minimizes environmental impacts, and strengthens climate change adaptation capacity. The integration of Turkey's high geothermal potential with digitally monitored and automated greenhouse infrastructures is considered a strategic necessity for developing sustainable agricultural production models, enhancing food security, and promoting rural development. Through these systems, environmental variables can be monitored in real time, production processes can be managed through automation-based operations, and decision-making mechanisms can be executed more rapidly and with higher accuracy. For instance, in smart greenhouse systems integrated with sensor technologies, climate parameters such as temperature, humidity, light intensity, and carbon dioxide (CO_2) concentration are continuously monitored. Based on the analysis of the collected data, climate control systems are dynamically adjusted to ensure optimal growing conditions.

II. FUNDAMENTALS AND APPLICATIONS OF GEOTHERMAL ENERGY

2.1 Definition and Characteristics of Geothermal Energy:

A geothermal resource is defined as hot water or steam formed through the accumulation of heat at various depths within the Earth's crust, with a temperature consistently above the regional atmospheric average and a higher concentration of dissolved minerals, salts, and gases compared to surrounding groundwater or surface water [8]. Geothermal energy, on the other hand, refers to an environmentally friendly, renewable, and sustainable form of energy derived from the thermal energy stored in the deeper layers of the Earth's crust (Figure 1). This form of energy can be effectively utilized in agricultural production systems, particularly for greenhouse heating applications. Depending on the physical and chemical properties of the geothermal fluid, it can be employed for greenhouse climate control through direct heating systems, heat exchangers, or geothermal heat pumps, thereby reducing energy costs while enhancing environmental sustainability.

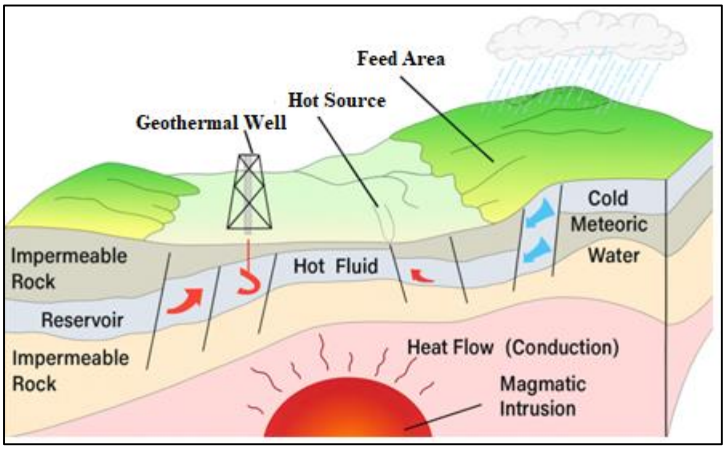

FIGURE 1. Schematic Representation of a Geothermal System [Modified from 9].

Geothermal energy is a renewable energy source derived from the thermal energy accumulated in the deeper layers of the Earth's crust, characterized by its environmental friendliness, sustainability, and high continuity. This form of energy is effectively utilized in agricultural production systems, particularly for greenhouse heating applications. In greenhouse operations, geothermal resources contribute to environmental sustainability by offering high energy efficiency and low carbon emissions. Notably, countries with substantial geothermal potential such as Iceland, the Netherlands, and Turkey have successfully implemented these systems in agricultural greenhouses. Depending on the system design, geothermal energy enables temperature regulation and the maintenance of optimal growing conditions within greenhouses through subsurface heat exchangers, water or antifreeze circulation loops, and geothermal heat pumps [10]. These integrated systems facilitate the establishment of controlled and sustainable production environments that operate independently of external climatic conditions, thereby reducing energy consumption, lowering operational costs, and supporting efficient year-round production.

Geothermal energy systems are classified into three main categories by [11] based on the physical state of the fluid within the reservoir: (1) Liquid-dominated systems contain fluid entirely in the liquid phase, where energy production is achieved directly by extracting hot water to the surface. (2) Two-phase systems feature reservoir conditions that allow the coexistence of both liquid and vapor phases; this results in complex fluid behaviors that influence thermodynamic efficiency during energy conversion processes. (3) Vapor-dominated systems occur when high-temperature and low-pressure conditions within the reservoir cause the fluid to exist entirely in the form of superheated steam.

Geothermal energy resources are generally categorized into three main groups based on the temperature levels of the reservoir fluids. This classification serves as a fundamental criterion for determining both the potential application areas of the resources and the selection of appropriate energy conversion technologies. Low-temperature fields, typically ranging between 20 °C and 70 °C, are primarily utilized for direct heating applications such as greenhouse heating, balneological (hot spring) uses, and industrial drying processes. Medium-temperature fields, with temperatures between 70 °C and 150 °C, can be employed for heating systems as well as secondary (binary cycle) power generation under suitable technological conditions. High-temperature fields, exceeding 150 °C, are usually associated with reservoirs used for electricity generation through steam turbine systems [8], [11], [12], [13], [14].

2.2 The Potential of Geothermal Resources in the World and in Turkey:

Data from the period between 1995 and 2020 clearly demonstrate a significant global increase in the direct-use applications of geothermal energy, including residential and district heating, thermal tourism, greenhouse heating, and industrial process heating. As illustrated in Figure 2, both the installed global geothermal thermal capacity (MWt) and the total annual energy use (TJ/yr) exhibited a steady and substantial increase over the examined period. The global installed geothermal heating capacity, which was 8,664 MWt in 1995, reached 105,107 MWt by 2020. Similarly, the total annual energy use rose from 112,441 TJ/yr to 1,005,198 TJ/yr during the same period. These data indicate that over a period of approximately 25 years, the installed geothermal capacity increased by a factor of 12, while the annual energy use grew nearly ninefold. This remarkable growth demonstrates that the global expansion of geothermal energy has not only occurred in terms of capacity but also through the diversification of application areas and enhancements in technological efficiency. Overall, the graph reveals a significant broadening and dissemination of direct-use geothermal applications between 1995 and 2020. In particular, the notable rise in the use of geothermal heat pumps underscores the growing strategic importance of low-temperature geothermal resources in the global energy transition (Figure 3).

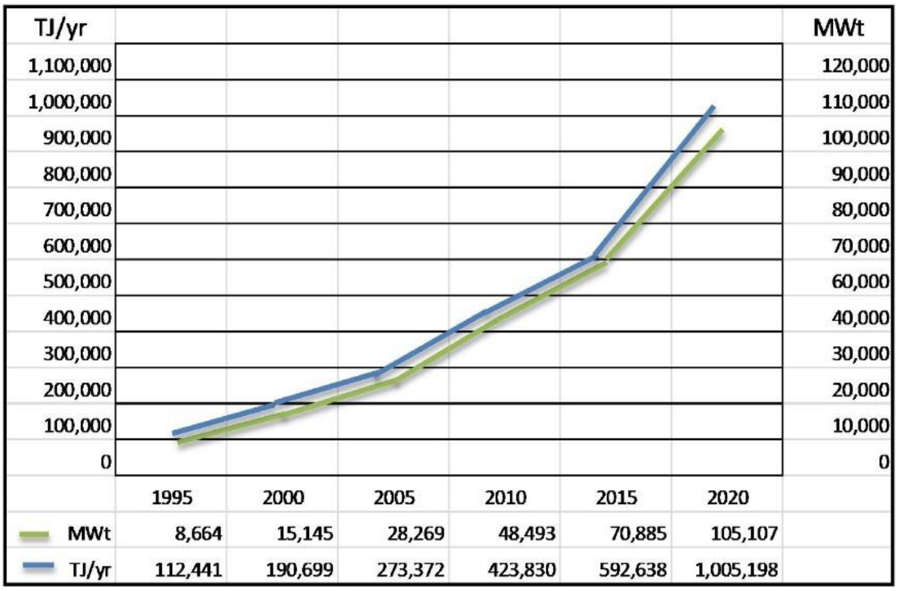

FIGURE 2: The installed direct-use geothermal capacity and annual utilization from 1995 to 2020 [15].

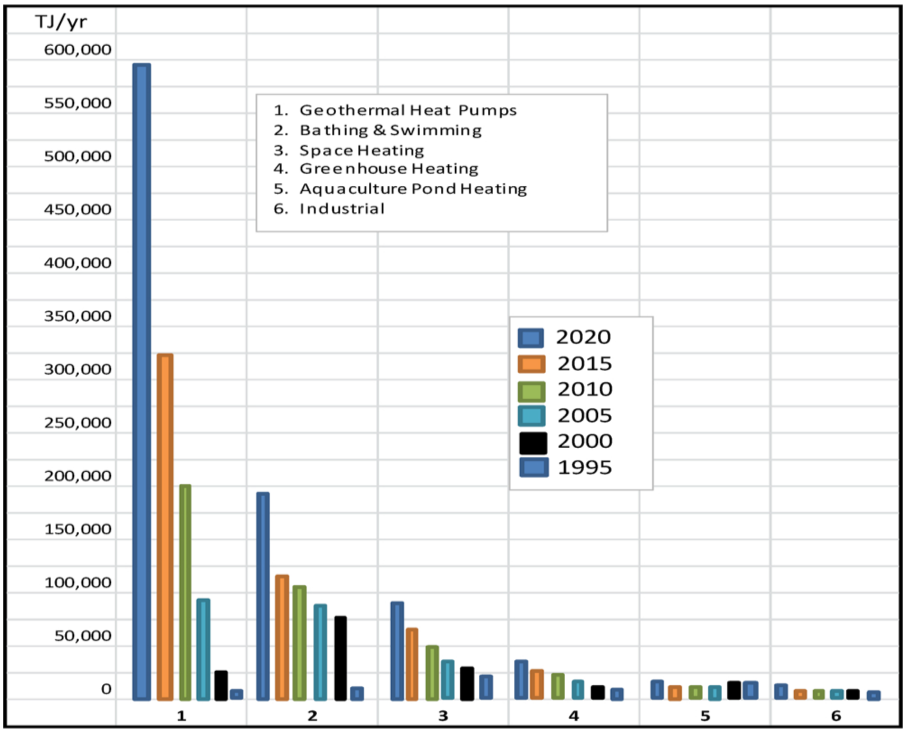

FIGURE 3. Comparison of worldwide direct-use of geothermal energy [15].

Systematic geothermal resource exploration in Türkiye was initiated by the General Directorate of Mineral Research and Exploration (MTA) in 1962. Since 2004, these efforts have accelerated, and significant progress has been achieved in geothermal energy applications due to the expansion of exploration activities, the promising results obtained, and improvements in legal and regulatory frameworks. Through geological, geophysical, and geochemical surveys conducted within this scope, numerous geothermal fields across different regions of the country have been identified, including high-temperature geothermal systems with temperatures reaching up to 287.5 °C. These findings demonstrate that Türkiye possesses substantial potential not only in low- and medium-temperature geothermal fields but also in high-enthalpy resources suitable for electricity generation [16].

Türkiye's location within an active tectonic belt contributes to its considerable geothermal wealth. There are approximately 1,000 natural geothermal discharge points nationwide, exhibiting a wide range of temperatures [17]. Türkiye ranks among the leading countries in Europe in terms of geothermal resource potential and is listed within the top five globally with respect to direct-use applications [18] Moreover, the country ranks fourth both in Europe and worldwide in terms of installed geothermal power capacity. As of June 2022, Türkiye's installed geothermal capacity had reached 1,686 MW [17].

2.3 Applications of Geothermal Energy in the Agricultural and Greenhouse Sectors:

As a renewable, domestic, and low-carbon energy source, geothermal energy holds strategic importance in meeting both heating and process energy demands within agricultural production systems. Among various agricultural applications, the greenhouse sector stands out as one of the most effective areas for the direct utilization of geothermal energy. On a global scale, the agricultural sector particularly greenhouse heating and agricultural drying represents a significant share of total geothermal energy used for direct purposes. According to Figure 4, approximately 3.5% of the total direct-use geothermal energy consumption is allocated to greenhouse heating, while 0.4% is utilized for agricultural product drying [19].

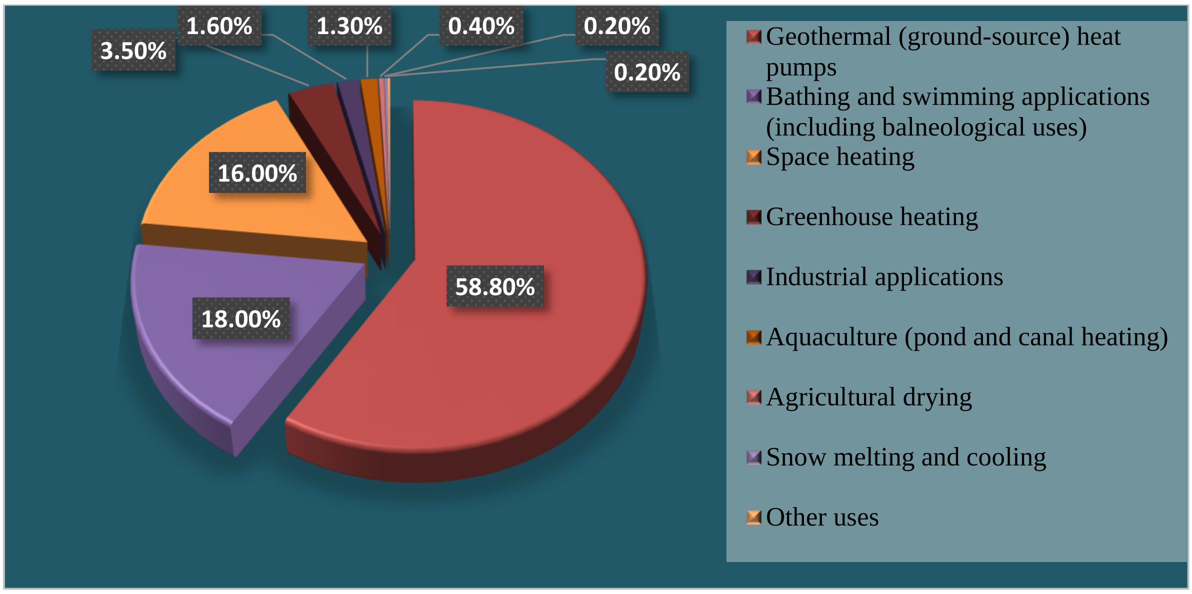

FIGURE 4: Direct-use distribution of geothermal energy by category [Modified from 19]

These proportions indicate that low- and medium-temperature geothermal resources possess substantial potential in agricultural production by reducing energy costs, shortening production periods, and enabling precise climate control. The use of geothermal energy in greenhouses provides a sustainable and economically viable production model, particularly in regions where heating expenses are high, while also contributing to carbon emission reduction. According to the World Geothermal Congress (WGC, 2015) data, this field has experienced a 24% increase in installed capacity and a 23% increase in energy utilization [20]. Similarly, the Turkey Geothermal Resources Strategy Report indicates that the total installed thermal capacity for direct-use applications in Turkey has reached 5,113 MWt, of which approximately 24.1% is allocated to greenhouse heating purposes [21].

III. HEATING STRATEGIES AND USE OF GEOTHERMAL ENERGY IN AGRICULTURAL GREENHOUSES

The growing global demand for food has made controlled-environment agriculture a strategic production model that enables year-round cultivation. Greenhouses, as the most widespread example of such systems, require maintaining environmental parameters such as carbon dioxide concentration, relative humidity, lighting, and temperature within optimal ranges to ensure healthy plant growth. However, due to their structural characteristics typically constructed from lightweight materials and exhibiting relatively low energy efficiency greenhouses consume significantly more fossil fuels and generate higher carbon emissions compared to other building types of similar scale. Consequently, greenhouses are regarded as one of the most energy-intensive systems within the agricultural production sector.

Among the various applications of geothermal energy, its use in agricultural production stands out as particularly significant. Greenhouses, depending on the climatic characteristics of the region in which they are located, require different levels of heating, ventilation, shading, and cooling throughout the year. The heating process, which plays a critical role in enhancing yield and quality in plant production, also represents one of the major factors contributing to the overall production costs in greenhouse operations. Acosta-Silva et al. [22] emphasize that energy consumption in greenhouse cultivation is one of the primary factors determining production expenses, accounting for up to 50% of total operational costs in many countries. In this context, heating and cooling processes constitute approximately 65-85% of the total energy demand, making them among the most critical components of energy management and sustainability in greenhouse operations [23].

In a study conducted by Çaylı et al. [24], the annual heating energy requirements of greenhouses located in different climatic regions of Turkey were comparatively analyzed. The results revealed that the highest annual heating energy demand was observed in Kahramanmaraş with 179.7 kWh m^{-2}, while the lowest was recorded in Mersin with 65.9 kWh m^{-2}. In addition, regarding the variability of average annual energy demand, the largest fluctuation was found in Antakya (-24.5%), whereas the smallest variation occurred in Osmaniye (-12.2%). These findings clearly indicate that regional climatic conditions play a decisive role in determining the heating energy requirements of greenhouses. Similarly, Baytorun et al. [25] reported that greenhouse heating costs vary between 20% and 60% of the total operating expenses, depending on factors such as structural characteristics, technological equipment used, and regional climatic differences. Energy balance analyses conducted by Kurpaska et al. [26] revealed that heat consumption in Venlo-type greenhouses varies significantly depending on sidewall height and local climatic conditions. According to the study findings, increasing the greenhouse height from 4 m to 6 m results in an approximately 13% increase in total heat consumption. This rise is associated with the larger air volume and greater heat losses due to the expanded surface area. Moreover, it was determined that around 50% of the total annual heat demand occurs during the winter months, 40% during spring and autumn, and 10% during the summer season. These results emphasize that greenhouse energy management strategies should be optimized based on regional climatic conditions and structural design parameters.

The use of geothermal energy in greenhouse heating systems can reduce primary energy consumption by more than 20%, thereby contributing significantly to the reduction of operational costs. It is estimated that if renewable energy sources are more widely adopted in greenhouse cultivation, fossil fuel consumption could decrease by approximately 40%, leading to a substantial reduction in greenhouse gas emissions [27]. In this context, Turkey, Iceland, Italy, and Japan are among the leading countries in geothermal energy-assisted greenhouse heating applications. In Turkey, particularly in the provinces of Afyon, Aydın, and Denizli, project reports indicate that the use of geothermal energy provides 25-40% energy savings compared to conventional heating systems [28]. Studies conducted by Bibbiani et al. [29] support these findings, revealing that maintaining an indoor greenhouse temperature between 15-20 °C requires an average of 5-6 kg/m² of fossil fuel consumption per year. The same study reported that the combustion of approximately 4 million tons of oil equivalent results in 11.3 million tons of CO_2 emissions, emphasizing the significant impact of fossil fuel use in greenhouse heating on total greenhouse gas emissions.

Similarly, Tomarov and Shipkov [20] highlighted the global environmental benefits of energy efficiency practices, reporting that such measures have prevented the consumption of approximately 596 million barrels (around 81.0 million tons) of oil equivalent per year. This conservation corresponds to an estimated reduction of 78.1 million tons of carbon and 252.6 million tons of CO_2 emissions released into the atmosphere. These values also encompass the energy efficiency gains achieved by geothermal heat pumps operating in cooling mode, which have increasingly replaced fuel-oil-based electricity generation. Collectively, these findings demonstrate that the utilization of geothermal and other renewable energy sources in greenhouse heating systems holds substantial potential in terms of both energy efficiency and carbon mitigation.

IV. ENERGY MANAGEMENT, DIGITAL INTEGRATION, AND SUSTAINABILITY IN SMART GREENHOUSES

In recent years, smart greenhouse technologies and automation-based control systems have become fundamental components of the digital transformation in controlled-environment agriculture. These systems are designed to enhance production efficiency, reduce energy and water consumption, and promote environmental sustainability. At the same time, the increasing cost of energy and the growing need to mitigate the environmental impacts of greenhouse operations have made the integration of renewable energy sources such as photovoltaic (PV) panels, wind turbines (WTs), and geothermal energy systems increasingly important. The use of these renewable systems significantly reduces the carbon footprint of greenhouses and decreases their dependence on fossil fuels. Integrating renewable energy technologies with advanced control, monitoring, and automation infrastructures holds great potential for optimizing energy management, enhancing production efficiency, and ensuring sustainability in resource utilization [30]. The model developed by Ghiasi et al. [30] presents a comprehensive approach to the integration of renewable energy sources into smart greenhouse systems. The overall structure of this integrated system is illustrated in Figure 5.

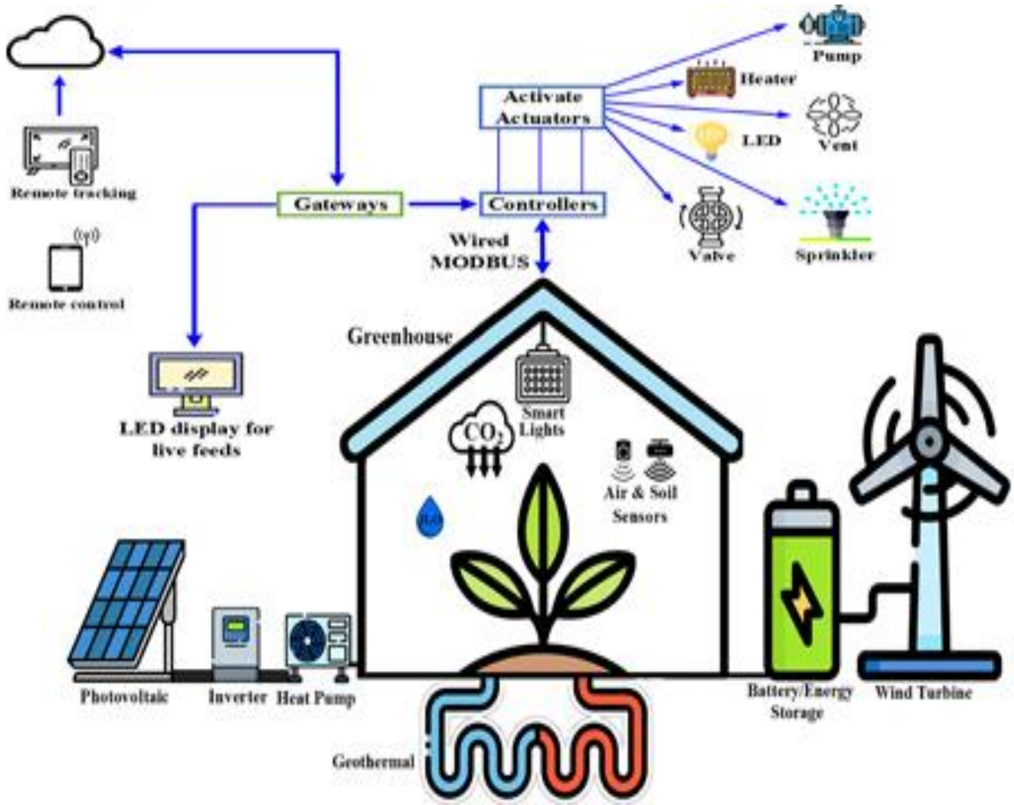

FIGURE 5: Conceptual model of the integration of renewable energy sources into smart greenhouse systems [30].

Automation-based heating and cooling systems, which constitute one of the fundamental components of climate control in smart greenhouses, automatically regulate the indoor temperature using data obtained from sensors and allow remote access through internet connectivity. With Wi-Fi-based control modules, users can monitor and manage the system via tablets or smartphones. This approach offers significant advantages in terms of optimizing energy consumption, reducing operational costs, and enhancing production efficiency [31], [32]. Consequently, smart automation systems emerge as an effective technology that supports both economic sustainability and energy efficiency in modern greenhouse production.

The integration of Internet of Things (IoT) technology into agricultural production systems has fundamentally transformed the operational principles of traditional greenhouses, paving the way for data-driven, automated, and interactive production environments. IoT-based greenhouse systems rely on sensor networks that continuously monitor key environmental variables such as temperature, relative humidity, carbon dioxide (CO_2) concentration, pH, light intensity, and water usage. Data collected from these sensors are analyzed by central control units, enabling irrigation, fertilization, ventilation, and heating operations to be activated automatically and only when required. This intelligent control mechanism reduces energy and water consumption, optimizes resource utilization, and lowers operational costs. Furthermore, IoT-enabled automation systems minimize pesticide use, thereby mitigating environmental impacts and contributing to the protection of plant health against sudden climatic fluctuations. In this regard, IoT technology plays a strategic role in the development of sustainable, energy-efficient, and environmentally friendly agricultural production models [33].

The schematic representation of the IoT-based smart greenhouse model developed by Rayhana et al. [34] is presented in Figure 6. This model represents an intelligent energy management system in which sensor-based monitoring, data collection infrastructure, control algorithms, and artificial intelligence (AI)-driven decision-making mechanisms operate in an integrated framework. The digitalization of energy management in greenhouses through such systems enables the continuous monitoring of environmental variables including temperature, humidity, solar radiation, CO_2 concentration, and soil moisture and allows the analysis of collected data to optimize energy consumption patterns. Consequently, heaters, fans, pumps, and other energy-consuming devices are activated only, when necessary, thereby minimizing energy losses [35].

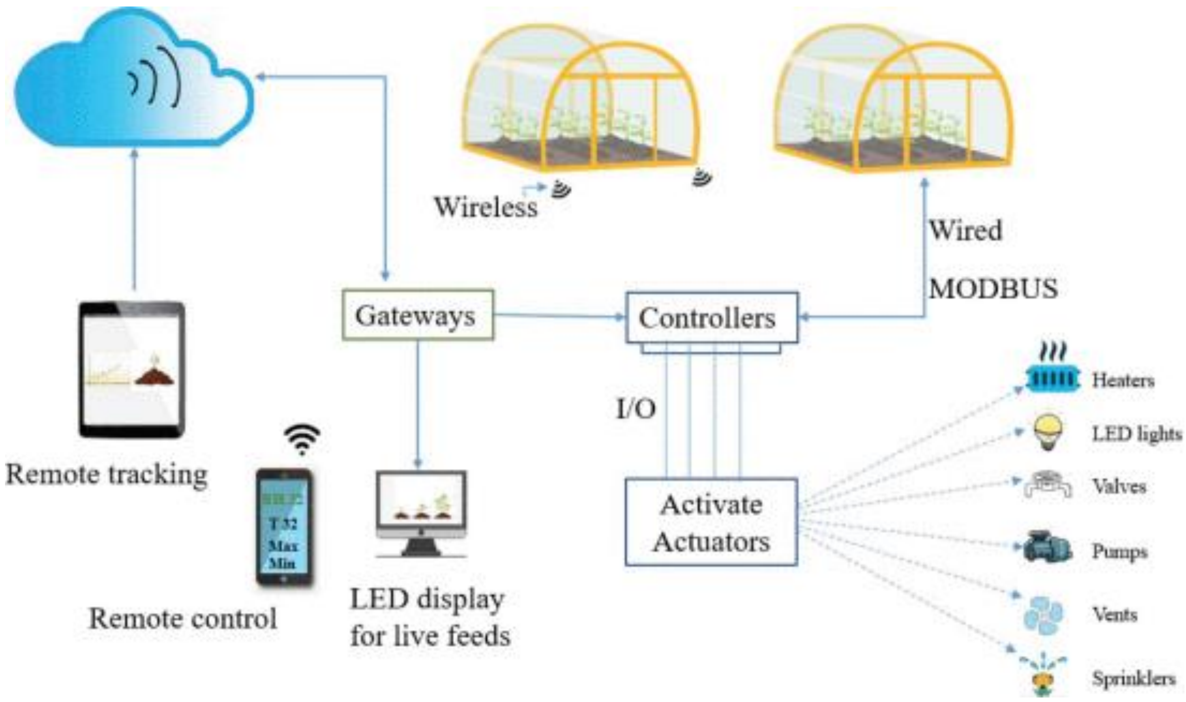

FIGURE 6: IoT-enabled smart greenhouse model [34].

When supported by artificial intelligence (AI) algorithms, this digital transformation process is expected to give rise to highly autonomous and self-learning smart greenhouse systems. The next generation of smart greenhouses will operate through the seamless integration of IoT-based sensor networks and AI-driven analytical systems, enabling the real-time monitoring and analysis of environmental parameters such as light intensity, temperature, relative humidity, carbon dioxide (CO_2) concentration, soil moisture, and wind speed. This integrated structure will not only optimize energy consumption but also ensure that plant growth is maintained under the most favorable microclimatic conditions [36], [37].

In addition, the integration of digital twin technology enables the creation of a virtual model parallel to the physical greenhouse environment, establishing a bidirectional data flow between the physical and digital systems. This dynamic interaction not only enhances energy efficiency but also allows for the predictive identification of potential system failures and the implementation of more planned and proactive maintenance processes [38]. Therefore, the holistic integration of Internet of Things (IoT), artificial intelligence (AI), and digital twin technologies in smart greenhouse systems not only enhances production efficiency and resource management, but also establishes the foundation for an innovative production paradigm centered on sustainability, environmental awareness, and energy efficiency in agricultural production. This integrated approach unites the goals of energy optimization, climate adaptation, and resource conservation within the broader context of agriculture's digital transformation, thereby introducing a new framework for the smart farming ecosystems of the future.

Azaza et al. [39] developed a fuzzy logic-based control (FLC) system aimed at optimizing temperature and humidity balance within greenhouse environments. In this system, ventilation and heating rates were used as control variables, resulting in a 22% reduction in energy consumption and a 33% reduction in water use. Similarly, studies conducted by Bevilacqua [40] reported that smart energy management systems can reduce energy consumption in greenhouse applications by 20-40%, while significantly improving overall system efficiency.

Azaizia et al. [41] reported that in such smart systems, energy conversion efficiency is approximately 35-45% higher compared to traditional climate control methods. In line with these findings, research conducted by Mohamed et al. [42] demonstrated that the implementation of IoT-based energy management systems led to a 35% reduction in energy consumption and a 12% increase in crop yield in greenhouse operations. These results clearly demonstrate the potential of digital and intelligent control-based energy management approaches in greenhouses to simultaneously enhance energy efficiency and improve production performance. In another study conducted by Asibeluo and Ekruyota [43], it was determined that the integration of sensor-based systems with Internet of Things (IoT) technology enabled greenhouse automation units to operate with high accuracy levels. According to the research findings, the accuracy rates were measured as 85% for the irrigation unit, 90% for the heating unit, 90% for the cooling unit, and 85% for the fertigation (nutrient solution application) unit. These findings indicate that IoT-assisted control systems possess significant potential in greenhouse management, both for enhancing energy efficiency and for the precise regulation of environmental parameters.

Castaneda-Miranda and Castano [44] employed a multi-layer perceptron (MLP) model to accurately predict frost conditions inside greenhouses and reported that the system could forecast temperature variations with 95% accuracy. Similarly, a study conducted by Tzounis et al. [45] demonstrated that the implementation of IoT-based climate control systems could reduce greenhouse energy consumption by up to 30%. Collectively, these studies highlight the substantial potential of digital technologies and AI-assisted control systems in greenhouse climate management to optimize energy and water use, enhance production efficiency, and strengthen environmental sustainability.

V. RESULT AND DISCUSSION

In this study, the potential use of geothermal energy in agricultural greenhouses, as well as its advantages in terms of energy efficiency and sustainable production, have been comprehensively evaluated. The findings indicate that global dynamics such as climate change, population growth, and rising energy costs are rapidly increasing the need for renewable energy solutions in agricultural production systems. Particularly, greenhouse cultivation has become a strategic production model due to its ability to enable year-round production; however, it is also one of the most energy-intensive agricultural activities in terms of energy consumption and carbon emissions. Therefore, the importance of geothermal-based heating systems that enhance energy efficiency and reduce environmental impacts is increasingly emphasized.

Geothermal energy can reduce primary energy consumption in greenhouses by more than 20%, leading to significant reductions in operating costs. Geothermal greenhouse applications implemented particularly in the Turkish provinces of Afyon, Aydın, and Denizli have demonstrated energy savings of between 25% and 40% compared to conventional heating systems. This provides substantial benefits in terms of both economic sustainability and the reduction of carbon emissions. Furthermore, energy analyses have shown that greenhouse design parameters (such as sidewall height) and local climatic conditions have a direct impact on energy requirements. These findings highlight the necessity of planning energy management strategies in accordance with regional conditions.

With the integration of digital transformation into agricultural production systems, smart greenhouse technologies have ushered in a new era of energy management. Internet of Things (IoT), Artificial Intelligence (AI), and digital twin-based systems monitor in real time the internal climate parameters of greenhouses (such as temperature, humidity, light, CO_2 concentration, and soil moisture), thereby optimizing energy and water consumption. Research has shown that through the integration of these technologies, energy consumption can be reduced by 20-40%, water use by up to 30%, and system accuracy rates can reach 85-90% [39], [40], [42], [43]. Moreover, these systems enhance production performance by increasing crop yield by approximately 10-15%.

The findings indicate that greenhouse systems based on digital and renewable energy technologies possess a high potential not only in terms of energy savings but also regarding environmental sustainability, resource efficiency, and climate change adaptation capacity. Smart greenhouse models that holistically integrate geothermal energy with IoT and artificial intelligence technologies constitute key components of both economic and ecological sustainability in the agricultural systems of the future. Consequently, the integrated utilization of Türkiye’s geothermal energy potential with digital technologies will reduce energy dependency in agricultural production, lower the carbon footprint, and strengthen food security. In this context, the widespread adoption of geothermal energy-supported smart greenhouse systems should be regarded as a strategic priority for implementing sustainable agricultural development policies at the national level.

Geothermal energy resources are among the most prominent renewable energy options for greenhouse heating applications due to their high energy efficiency and low carbon emissions. By directly utilizing heat extracted from underground, these resources reduce fossil fuel consumption, thereby lowering greenhouse gas emissions and achieving significant savings in operating costs. In addition, the stable and reliable heat supply provided by geothermal systems supports continuous year-round production, contributing to the energy sustainability of modern greenhouse cultivation. However, the regional variability of geothermal resources, the high costs associated with drilling and infrastructure investment, and issues such as corrosion and mineral precipitation caused by the chemical composition of geothermal fluids are considered major technical and economic constraints limiting the widespread adoption of these technologies.

VI. CONCLUSION

Geothermal energy-integrated smart greenhouse systems represent an innovative approach that enhances energy efficiency, reduces carbon emissions, and supports the sustainable use of resources in agricultural production. Through the integration of IoT, artificial intelligence (AI), and digital twin technologies, these systems optimize energy and water consumption, leading to significant improvements in production efficiency. However, high drilling and infrastructure costs, technical challenges arising from the chemical properties of geothermal fluids, and limited financial resources remain the main factors constraining the widespread adoption of these technologies.

Therefore, establishing organized geothermal greenhouse zones in regions with high geothermal potential, increasing investment incentives, and promoting the development of domestic technologies are of great importance. The hybrid use of geothermal energy with photovoltaic and biomass systems, along with the widespread adoption of heat storage and recovery technologies, offers effective solutions for strengthening energy supply security.

In conclusion, geothermal energy-supported smart greenhouse systems represent a significant opportunity and a forward-looking strategic engineering approach for Türkiye to achieve its goals of sustainable agriculture, energy independence, and low-carbon production.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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