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TOPICAL REVIEW

A Systematic Review of Optimal and Practical Methods in Design, Construction, Control, Energy Management and Operation of Smart Greenhouses

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ABSTRACT In an era characterized by severe climate change, dwindling resources, and a growing world population, the agricultural industry is facing unprecedented challenges. On the other hand, overuse of natural resources has emerged as a major concern worldwide. Greenhouses (GHs) have been developed as central environments capable of growing a diverse range of high-quality agricultural products throughout the year, regardless of external weather conditions. However, conventional GHs often impose significant costs on energy resources for their heating and cooling operations, thus presenting sustainability challenges. To address these pressing concerns, using new smart technologies as well as the integration and development of renewable energy sources, including photovoltaics (PVs), wind turbines (WT), and geothermal systems, have gained momentum. This integration not only increases the ecological footprint of GHs but also reduces their dependence on conventional energy sources. Furthermore, the adoption of smart GH technologies, characterized by advanced control and automation systems, holds significant promise in energy optimization and efficiency. Hence, this systematic review attempts to carefully examine the optimal and practical methods that include the design, fabrication, control, energy management, and operation of smart GHs. This review includes an in-depth analysis of GH structures, building materials, cooling and heating systems, new dark GH concepts, and smart lighting systems. In addition, it addresses effective strategies to curb energy consumption in smart GHs. By synthesizing and synthesizing existing research and practical experiences, this paper seeks to provide valuable insights and recommendations to facilitate the efficient and sustainable design, construction, and operation of smart GHs. Ultimately, this work aims to promote resource-efficient and environmentally conscious practices in the agricultural energy sector.

INDEX TERMS Greenhouse, design, construction, control, energy management, operation.

NOMENCLATURES AND ABBREVIATIONS

AHU	Air-handling unit.
AVR	Automatic voltage regulator.
CO_2	Carbon dioxide.
GAA	Greenhouse azimuth angle.
GH	Greenhouse.
HVAC	heating, ventilation, and air conditioning.
IoTs	Internet of Things.
PLC	Program logic Controller.
PWM	Pulse width modulation.
PV	Photovoltaic.
SGHA	Smart Greenhouse Automation.
UV	Ultraviolet.
η_{conv}	efficiency.
ΔT	Temperature difference across the envelope.
A_{env}	Envelope surface area.
A_{solar}	Solar panel surface area.

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COP_{hp}	Heat pump coefficient.
E_{vent}	Ventilation energy.
E_{evap}	Evaporative cooling energy.
E_{heat}	Heating energy.
E_{output}	Output energy.
E_{input}	Input energy.
P_{lighting}	Power consumption of lighting fixtures.
t_{heat}	Heating duration.
t_{lighting}	Lighting duration.
t_{vent}	Ventilation duration.
Q_{heat}	Heat transfer rate.
U_{env}	Heat transfer coefficient.

I. INTRODUCTION

Smart greenhouses represent a significant leap in agricultural technology. These sophisticated structures are designed to optimize the growing conditions for plants, resulting in higher yields, better quality crops, and reduced environmental impact. In this article, every facet of smart greenhouses, from their inception to their practical applications will be explored.

A. BACKGROUND AND LITERATURE

One of the basic human needs is food. With the increase in population and decrease in agricultural land, the importance of sustainable production of agricultural products has become especially significant. The design, construction, and operation of suitable places where agricultural products can be produced in a controlled manner during the year with minimal energy consumption, has become one of the issues discussed by researchers [1]. To address this issue, GHs have been built and expanded. Over time, GHs evolve, but their purpose, which is to produce crops and grow plants, has not changed [2]. In different weather conditions from the cold parts of North America and Canada, Northern Europe, and Asia to the tropical and tropical regions of Africa, it is possible to create suitable environmental conditions for different plants can be produced throughout the year [3]. With the advancement of technology, recently, smart GHs with more optimal control, higher quality products, lower energy consumption, and higher efficiency are being built. Smart GHs support year-round crop production by creating a controlled environment [4].

Overall, the intelligent section in the smart GH is the main controller of the GH, where various sensors have been connected to the automation software to measure the temperature, humidity, and temperature of the indoor and outdoor environment, as well as equipment such as shadow displays and LED lights. The controllers in the smart GH are the brain of the system, which can collect, control and monitor data remotely, and the GH system can be managed through a computer or smartphone [5]. The technology of smart GH and automation systems has grown a lot and has gained a lot of popularity all over the world. From smart lamps to security systems, cameras, smart heating, ventilation, and air conditioning (HVAC), etc. are gaining more and more fans nowadays [6]. Smartening the cooling and heating system is one of the most important parts of smart GH automation. This air conditioning system controls the heat and cold conditions of the GH, and by connecting to Wi-Fi and the Internet, it allows users to remotely manage and control this smart thermostat system through their tablets and smartphones. These systems are associated with features and benefits, among which can be mentioned the reduction of costs [7], [8]. Using smart technology and the Internet is an effective and practical solution. In addition, the use of the Internet in many cases helps people to make databased decisions [9].

In a smart GH, lights, dampers, plants, humidity, and other values can be controlled according to a predetermined schedule. By using a smart GH, more and faster productivity is achieved. Smart GH helps farmers to increase their productivity rate [10]. An important concern in the minds of GH growers is access to labor, profitability, and competition. Labor can be the biggest cost for GH businesses. Today, many GH owners seek to use methods that reduce the costs of maintaining and growing flowers and plants and bring the best productivity from them [11]. Hence, smart GH can provide such conditions for GH owners.

B. SPECIFICATIONS OF SMART GHS

Smart GH is a controlled environment with micro dust for optimal plant growth. The weather conditions inside the GH such as temperature, humidity, light, and soil moisture are continuously monitored and automatically controlled. Small changes in these weather conditions trigger automatic actions [12]. Automated actions assess changes and then take corrective actions, thus providing optimal conditions for plant growth. The control of temperature, humidity, irrigation, etc. in the smart GH is done automatically; it leads to the highest productivity and production, and it is even possible to monitor the smart GH remotely [13].

The price of GH automation may be a little expensive at first, but considering the benefits it has, it is completely cost-effective and economically justified. A smart GH provides a controlled environment to grow plants and sprouts that are destined to become consumer-friendly products. Traditionally, no matter how regular and precise we are in growing plants in a closed environment, there are still situations that are far from expected [14]. In the smart GH, proper ventilation and climate control are easier than the challenges of the smart GH, which can be fully controlled by making the GH intelligent. The use of the Internet of Things (IoTs) and other smart protocols have been considered for smart GH, along with other industries. Flowers and agricultural products are grown in a safe place with moment control, away from the disturbances that happen in the natural world [15]. Therefore, increasing the productivity of the GH and producing fresh produce with high quality and quantity at the same time is one of the things that gardeners welcome. Although the price of the intelligentization of the GH is high, in return the results obtained are very valuable and can make investors profitable in the shortest period [16].

FIGURE 1. The exterior of a modern industrial GH [17].

In the following, the advantages of smart GH and the difference between traditional GH and smart GH will be discussed. Figure 1 and Figure 2 show the exterior and interior of a modern industrial GH.

C. ADVANTAGES OF SMART GHS

Overall, the main purpose of every business can be the rate of profitability. The rate of profitability of using GH or indoor agricultural applications according to the type of facility based on the study conducted in 2017 in the United States is illustrated in Figure 3.

As can be seen from Figure 3, indoor deep-water culture (DWC) floating boats, and GH culture are more profitable than other types, whereas low-tech systems such as covered vertical farms and plastic houses are less profitable.

1) PERMANENT MONITORING OF PLANTS

One of the important benefits of making the GH smart is to equip it with sensors and advanced communication technologies. This modern equipment automatically provides information about the surrounding environment and the product to the user 24 hours a day. This collected data is entered into a platform provided by the IoTs protocol, and after processing, it is used to solve the problems and challenges of GH [17]. For example, the temperature settings in the smart ventilation system are up and down, with the intelligent lighting system of low and high artificial light, or go to the irrigation and spraying system and activate or deactivate them as needed. It is continuous monitoring that makes the smart GH stand out from the traditional GH.

2) OPTIMIZING AND MINIMAL USE OF ENERGY AND REDUCING COSTS

One of the hot topics discussed in GHs is the topic of energy minimization and optimization [20]. With the intelligentization of the GH, the IoTs take care of the GH using smart equipment twenty-four hours a day, and without interruption. The energy used for heating, cooling, humidity regulation and exposure, and other uses of GHs can be obtained from renewable sources and battery storage by using optimal energy management and considering the price of electricity [4], [21]. On the other hand, with proper investigation, it limits the purchase of resources and chemicals without the guesswork, exactly as needed. With such a precise process, the cost of human services, as well as the purchase of fertilizers and poisons based on guesswork, is minimized [22].

3) IDEAL MICROCLIMATE CONDITIONS

One of the important topics in GHs is creating suitable weather conditions for plants during the year. The sensors provide the user with information such as temperature, humidity, light, carbon dioxide, and other such things from different points throughout the GH [23]. This data optimizes HVAC and lighting settings for healthy plant growth and maintenance, as well as optimal energy use. These conditions can change depending on the type of plant in different seasons with a suitable program. In addition, GHs that have different zones can provide more optimal management to prove that they have an ideal condition in that particular microclimate [24].

FIGURE 2. The interior of a modern industrial GH [18].

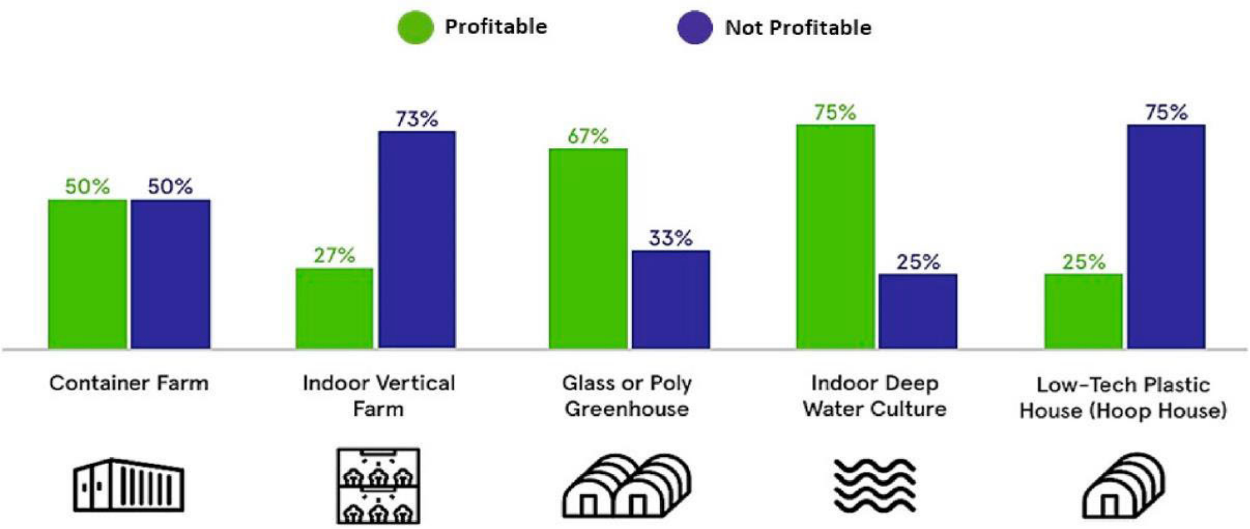

FIGURE 3. The rate of profitability of using a GH or indoor agricultural applications according to the type of facility is based on a study conducted in 2017 in the United States [19].

4) EQUIPPING PLANTS FOR FAST GROWTH

Equipping the smart GH with the right equipment with optimal controlled consumption can help plants grow faster. For example, with plant growth lamps, and artificial light, the speed of plant growth for greater efficiency, is significantly increased [25]. In addition to the temperature and humidity regulation system in the smart GH, there are other sensors called movement and acceleration sensors in the system that help to identify doors that are left open unintentionally and disrupt the stability of the atmospheric conditions [26].

5) STRENGTHENING IRRIGATION AND FERTILIZING METHODS

Making the GH smart, in addition to monitoring the environmental parameters, allows the farmers to check the conditions of the product. With this feature, the amount of irrigation and fertilization is met according to the other needs of the plants. For example, checking the volumetric water content of the soil shows whether the plant needs water or not. In the same way, soil salinity measurement, soil enrichment, and the need for what kind of fertilizer are determined. Under these conditions, it is easy to take over the intelligent management of the GH even through an intelligent system [27].

6) PREVENTING PLANT DISEASES

Another important issue can be product contamination and pest infestation, which is one of the constant problems of farmers and gardeners. With a simple disease of a plant and rapid spread, heavy losses are caused to crops. Of course, there are various methods and methods to eradicate plant

TABLE 1. Comparative assessment of review papers about smart GH.

Reference	Design	Construction	Control	Energy Management	Operation	Main objective
[30]	✓		✓			Sensor Network Technology
[31]				✓	✓	Solar Energy
[32]			✓			Artificial Neural Networks
[15, 33]				✓	✓	IoTs
[34]				✓		Reducing energy consumption
[35]					✓	Automation and monitoring
[36]		✓	✓		✓	Digital Twin applications
[37]	✓		✓	✓		Design, technology, and management
[38]				✓	✓	Energy efficiency and operational control
[39]	✓	✓				Solar and PV
Our study	✓	✓	✓	✓	✓	Various optimal and practical methods

diseases and pests, but the problem is that to fight the pest, preventive measures must be taken before it occurs [28].

7) PREVENTING THEFT AND UNEXPECTED EVENTS

Although it is common to think that stealing from a GH is a far-fetched thing, GHs can be the target of thieves despite the valuable products. Implementing traditional surveillance networks with CCTV cameras is expensive, and unfortunately, many manufacturers do not offer an effective security system. In this context, by intelligentizing the GH and sensors under the supervision of the IoTs protocol, they provide a cost-effective infrastructure for monitoring the condition of the door and identifying suspicious activities and unexpected events such as fire [29].

As can be seen, the recently published review articles in the field of smart GHs in Table 1 are presented. However, each of these review articles has studied a small area in terms of design, construction, control, energy management, and utilization. However, our review article studies and presents all of the above more ultimately from the perspective of optimal and practical methods.

D. MAIN CONTRIBUTIONS OF THIS REVIEW PAPER

The main contributions of the paper are classified as follows:

- Comprehensive Review: This paper provides a thorough and systematic review of optimal and practical methods in the design, construction, control, energy management, and operation of smart greenhouses, offering a consolidated resource for researchers and practitioners.
- Sustainability Enhancement: The paper emphasizes the significance of integrating renewable energy systems, such as photovoltaics, wind turbines, and geothermal technology, into smart greenhouses, contributing to sustainability by reducing reliance on conventional energy sources.
- Energy Efficiency Insights: It offers insights into energy-efficient technologies and strategies, including advanced climate control, LED lighting systems, precision irrigation, and ventilation management, to optimize energy consumption within smart greenhouses.
- Case Studies and Examples: The inclusion of case studies and practical examples highlights real-world implementations of energy-saving strategies, providing valuable lessons learned and success stories for the greenhouse industry.
- Decision Support: The paper discusses the role of data analytics and decision support systems in greenhouse operations, assisting stakeholders in making informed choices for energy-efficient practices.
- Holistic Approach: By addressing various aspects of greenhouse design, construction, and operation, this review paper takes a holistic approach to fostering resource-efficient and environmentally conscious agricultural practices.

E. PAPER STRUCTURE

The rest of the review article is organized as follows: In Section II, the most important GH structures and operation strategies will be presented. Section III will present smart GH features. In Section IV, intelligent lighting systems will be investigated. Energy management approaches in GHs will be given in Section V, and finally, in Section VI, the main conclusions of the review of smart GHs will be stated.

II. GH STRUCTURES AND OPERATION STRATEGIES

A. GH STRUCTURE AND TYPES

The first thing that plays an essential role in controlling energy consumption is the structure of the GH and the materials used in the windows, walls, and roofs of the GH. The type of material used in the structure varies depending on the location of the GH the climate of the region and the ambient temperature, and in general, it should be such that it keeps the heat inside the GH in winter and minimizes the heat energy loss with the external environment [40]. In addition, in the summer, to reduce the use of the cooling system and electricity consumption, it can transfer the heat inside the GH created by sunlight to the outside environment as much as possible. U value and G value.

GH structures are also different, but the nature of this difference is in terms of the principle and technicality of the

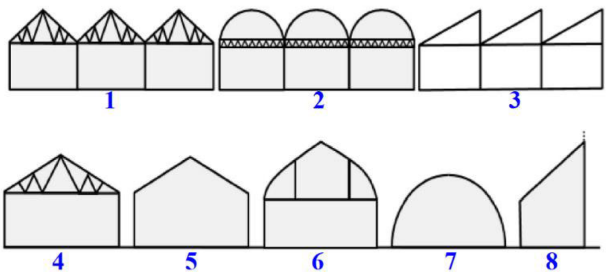

FIGURE 4. Different common types of GH shapes [44].

structure [41]. In other words, since the smart building is to optimize GH production, structures that are not optimal will not have optimal efficiency during smart building. It is a true statement that the efficiency of the GH will increase with the intelligentization; but, the amount of this improvement is different in various structures. In the past, the height of the structures was considered short to reduce energy consumption, but today, to increase the volume of air, to reduce the sudden changes in temperature and humidity due to temperature stress, the roofs of GHs are considered taller. GHs can be built in one or more zones or openings [42].

In multi-span GHs, energy losses are lower than in simple GHs. For example, a multi-span GH that covers an area of 5,000 square meters has 15-25% of the coverage area and, as a result, lower energy losses than several simple GHs that cover the same area. In multi-span GHs, the ratio of the surface of the GH cover to the surface of the GH floor is equal to or less than 1.5, but this ratio is 1.7-1.8 in single-span GHs. The surface of the GH cover shows the contact surface of a GH with its surrounding environment. The lower the surface of the cover is compared to the area of the GH, the less the heat exchange with the outside environment, therefore, the geometrical shape of the GH and its appropriate design are very important according to the conditions of each region [43]. In the spherical geometric shape, the ratio of the coverage area to the area of the GH is the lowest, but in this design, the costs are high and it also creates limitations in the production of GH products. After the hemisphere, the cubic shape has the smallest area compared to the surface of the cover. Therefore, the closer the surface of the GH floor is to the square, the lower the heat loss. In Figure 4, different common types of GH shapes are displayed

These shapes include: 1- Gable roof; 2- Arch roof; 3- Saw tooth roof; 4- Trussed roof; 5- Gable frame or even span; 6- Gothic house; 7- Hoop house or Quonset; and 8- Lean-to house.

1) TYPES OF STRUCTURES OF ADVANCED GHs

Today, the most prominent feature of the standard multi-span and advanced GHs in the world is their high height and wide width (multi-span and high technology). Because the higher the GH is, the volume of air inside the GH will increase, and this will not only reduce the energy consumption of heating and cooling the GH but also reduce excess humidity and the accumulation of undesirable air above the GH and make available air. The large volume of air in the GH makes it possible to keep the temperature inside the GH stable [45].

As a result, the dangers caused by the stress on the plant and due to a sudden change in the temperature outside the GH are eliminated. In the paper [46], with similar fuel consumption and production management conditions, it was observed that the average production performance of GHs with a tunnel model metal structure is 20 kg per square meter, and the average performance of GHs in metal structure model is 25 kg per square meter. Therefore, a comprehensive evaluation is needed to construct a GH, e.g., structure with new technologies, optimal energy management and product management.

2) MULTI-WALL COVERING SYSTEM

Today, to reduce the heat loss in the environment of the GH, a double-walled plastic system and compressed air between them are used, and it will significantly reduce the fuel cost. Compressed air separates two layers of plastic. The outer layer of plastic can be 0.152mm thick to reduce ultraviolet (UV) light, while the inner layer only needs to be 0.102mm thick because the UV light is less in this place. Semi-cylindrical GHs are suitable for double-layered covers [47]. Double-glazed plastic covers also play an effective role in reducing fuel costs by a third.

B. ORIENTATION OF THE GH

Many studies have shown that in northern latitudes single-room GHs should be oriented east-west to allow maximum light in late fall, winter, and early spring. However, in multi-room GHs, the direction can be north-south so that the direction of the studs is from east to west in the direction of the product and their shading is not in the same parts of the GH throughout the day [48]. But in both cases, the rows of crops must be in the north-south direction so that enough light reaches the crop during the day and the bushes have the least shading on top of each other [49]. Usually, the azimuth or the direction of the GH is called the angle between the north-south direction and the vertical normal horizontal elevation of the surface. To better represent the orientation in different GHs, the concept of GH azimuth angle (GAA) is proposed in [50], which is shown in (Figure 5). The GAA angle in this figure varies from 0° to 90°.

C. WINDBREAKER

A wind with a speed of 24 km/h doubles the heat loss of a GH because the wind causes the hot air inside the GH to be sucked out faster than when the surrounding air is still. Therefore, by constructing a windbreak, the wind speed on the GH cover can be reduced, and as a result, the heat exchange between the outside and the inside of the GH can be reduced through leakage and convection [51]. The windbreak can be designed as a fence, planting trees constructing a building, etc. In general, windbreaks reduce 5 to 10% of heat loss from inside the GH. In windy areas, the windbreaker should be built in the direction of the prevailing winter wind.

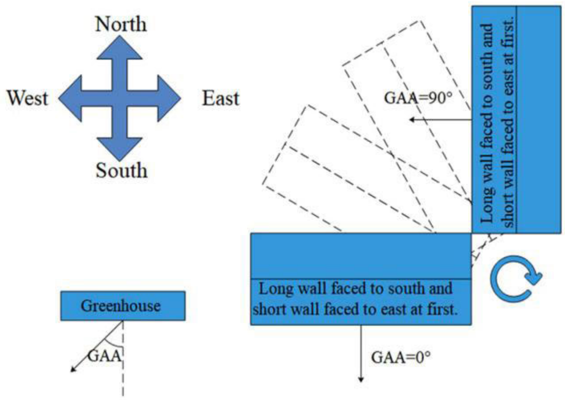

FIGURE 5. The orientation of the GH.

To protect a GH with a normal height of 3.3 to 4.7 meters, a temporary windbreak can be built utilizing a fence with a height of 3 to 4 meters at a distance of 12 to 18 meters from the GH. Permanent windbreaks are also built by planting coniferous and evergreen trees. In this situation, 4 to 5 rows of trees are needed, and 4 to 6 trees in each row [52], [53].

D. DIVISION OF THE GH IN TERMS OF PLANTING CROP

Based on the type of cultivation of agricultural products, the smart GH is divided into the following two categories:

1) SMART HYDROPONIC GH

Based on the most basic definition, hydroponics can be identified as a production methodology in which plants are grown in a nutrient solution instead of soil. In recent years, various changes have been made to the base system. To run a smart hydroponic GH, it is necessary to have enough information about the structure technology, equipment, and technical knowledge of the production and operation of smart hydroponic GHs [15]. Knowledge of how to set up GH biological condition control devices along with technical supervision improves production qualitatively and quantitatively. The smallest GHs, gardens, and even plant collections at home can benefit from smart technology to achieve better results. Automatic irrigation systems allow more flexibility to take better care of plants. Smart GHs control critical factors that affect crop performance, such as temperature, ventilation, exposure, and humidity. Farmers can adjust key factors that affect crop performance through a smart GH [54].

It is necessary to be aware of the needs of the plants for the weather conditions in the smart hydroponic GH and plan for each of them so that there is no disruption in the growth of the plants. For instance, paper [55] provided a strategy to address thermal energy issues in hydroponic GHs. In the construction of a smart hydroponic GH, agricultural engineers or specialists in this field can be used for this work. Paying attention to the necessary instructions of agricultural engineers in the field of GH construction can help in saving capital effectively. A freestanding GH can be a great opportunity to create a completely new space with few restrictions.

To start the process of building a smart hydroponic GH, it is always necessary to follow the standard recommendations in the design of the structure, especially the control and operation equipment. Beyond all the strategies, it should be used optimally at certain intervals to enrich the GH with organic materials [56].

The intelligent hydroponic GH is built to grow crops, so it is possible to ensure the quality of the food program by growing plants such as tomatoes, eggplants, potatoes, and vegetables and monitoring their growth. In general, with traditional GHs, farmers can usually control environmental parameters through experimental control mechanisms and manual intervention. This traditional control method often causes loss of production, increased labor costs, and wasted energy [57]. However, the existence of a smart hydroponic GH for growing plants allows GH owners to benefit from the characteristics of food all year round and produce high-quality plants, it also significantly reduces labor costs, and ultimately, high profitability for It will have a GH [58].

2) NON-HYDROPONIC SMART GH

A non-hydroponic GH is conventionally defined as a traditional methodology in which farmers plant crops in soil. However, in GH, the environmental control system is the same whether the plants are grown hydroponically or conventionally. The difference can be in the support system as well as the methodology of supplying water and nutrients, so the equipment for hydroponic or traditional is not much different [59].

However, there may be differences in processing and commands for optimization. Non-hydroponic smart GHs have the greatest growth potential in the global market. Smart non-hydroponic GHs dominate the market and provide the greatest growth potential for plants. The key technologies used in smart GHs, such as pressurized irrigation systems, valves, pumps, etc., have provided the basis for the growth and production of products in terms of quantity and quality [60].

E. OPERATION OF THE GH

Generally, GHs work in a semi-closed state, so that the inlet air must be cool in summer and warm in winter. We can classify the key features in the procedure as follows:

- **Semi-Closed System:** The greenhouse operates in a semi-closed state, implying that the structure allows for some control over the internal environment. This is essential for managing temperature and humidity for optimal plant growth.
- **Seasonal Adaptation:** The greenhouse should have a control system that can adaptively manage the climate to suit different months of the year. This ensures that the conditions inside the greenhouse are suitable for agriculture throughout the changing seasons.
- **Air Circulation:** Various feeding ducts inside the greenhouse supply air evenly to the field area. This helps in maintaining a consistent climate for the plants.

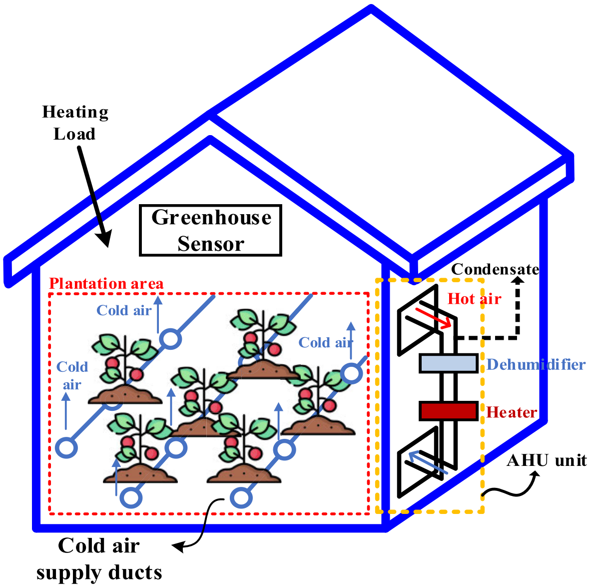

FIGURE 6. A schematic of GH operation [61].

- **Water Chiller:** To reduce the temperature of circulating air, a water chiller is used. Cold water is supplied to the air-handling unit (AHU) for this purpose.
- **Air-Handling Unit (AHU):** The AHU plays a crucial role in the system. It humidifies hot air, reducing the temperature to around 14 degrees Celsius. Freshwater condensate can be recovered from this process.
- **HVAC System:** The cooled and humidified air from the AHU is then passed through an HVAC system. This system raises the temperature of the air to a desired set point within the greenhouse.
- **Solar Radiation Utilization:** The greenhouse is designed to utilize solar radiation for photosynthesis. This involves managing the amount of sunlight entering the greenhouse to provide optimal conditions for plant growth.
- **Condensate Recovery:** The system is designed to recover freshwater as condensate from the humidification process, contributing to water efficiency.
- **Control System:** The greenhouse is equipped with a control system that likely includes sensors and automation to monitor and adjust environmental parameters such as temperature, humidity, and light levels.

A schematic of the GH operation is provided in Figure 6, which illustrates the flow and interaction of the various components mentioned above.

F. DARK GREENHOUSE

A dark GH is an innovative agricultural structure designed for the cultivation of plants with meticulous control over light and temperature conditions. Unlike traditional greenhouses that rely on natural sunlight and may exchange heat with the external environment, dark greenhouses are constructed with specific features to isolate the interior from external temperature fluctuations [62], [63]. The most important characteristics of this type of greenhouse include the following items:

1) LIGHT CONTROL

The term ‘‘dark’’ in dark greenhouse suggests a controlled or reduced exposure to natural sunlight. This is achieved through advanced shading systems or technologies that can selectively limit the amount of sunlight entering the greenhouse. This feature is particularly beneficial for crops that either require lower light conditions or benefit from specific light exposure during different stages of growth.

2) ISOLATION FOR TEMPERATURE CONTROL

Dark greenhouses are designed to minimize heat exchange with the external environment. This isolation helps in maintaining a stable and controlled temperature inside the greenhouse. Builders may use insulating materials and employ energy-efficient technologies to regulate the internal climate without relying on external heating or cooling sources.

3) PRECISION AGRICULTURE

The controlled environment within a dark greenhouse allows for precision agriculture. This means that factors like light intensity, duration, and temperature can be fine-tuned to meet the exact requirements of the cultivated crops. This level of precision can lead to improved yields and better-quality produce.

4) YEAR-ROUND CULTIVATION

With the ability to regulate both light and temperature independently of external conditions, dark greenhouses enable year-round cultivation. This is particularly advantageous in regions with extreme climates or where seasonal changes limit traditional outdoor farming.

5) ENERGY EFFICIENCY

The insulation and self-contained nature of dark greenhouses contribute to energy efficiency. These structures can potentially reduce the need for external heating or cooling, making them more sustainable and cost-effective in the long run.

A dark greenhouse represents a cutting-edge approach to controlled environment agriculture. By manipulating light exposure and maintaining strict isolation from external temperature fluctuations, these structures provide an optimal environment for plant growth, offering advantages in terms of productivity, quality, and energy efficiency.

III. GH FEATURES

Smart GHs can be divided from different perspectives. In this section, smart GHs from the perspectives of equipment and control strategies are classified.

A. SMART GH EQUIPMENT

Different equipment can be used in the smart GH, but the most important ones are:

- HVAC system including fans, air, and soil humidity control system, dehumidifiers, heating and cooling system
- Smart GH temperature regulation system
- GH intelligent energy system
- Smart irrigation system
- Intelligent GH climate control system
- Valves and pumps
- Control and automation system

To implement a smart GH, several basic factors should be considered:

- Low-consumption sensors and batteries to record different weather, agricultural, and security points
- Wireless connection is one of the economical and reliable communication methods. This connection is used to transfer the data from the intelligent GH cross-sensors to the remote data portal.
- Using a diagnostic machine learning system to obtain information from different points of the GH and the data received from the sensor to convert those data into interpretable data. This information is used to predict and make informed decisions about agricultural activities in smart GH.

A database can be used in existing control systems at GH to automate the actions of various equipment such as air conditioning, lighting, and GH sprinkler networks. Also, commercial-scale GH complexes deployed and used in large geographic areas require a wireless connection and long-range connection with high reliability and penetration [64].

In addition to providing more reliable data transfer, using this method allows the port to be installed closer to the power source, which can also reduce wire usage. Another factor to consider is scalability, in that it can minimize the number of gateways needed to save on hardware costs, as well as installation and management.

Also, the connections in the information transmission network must be very efficient so that the sensors can work for years with minimal cost and maintenance. Considering the number of investments and research that is being done. Based on the study [65], the global GH industry was worth approximately USD 31.58 billion in 2022, whereas, it is predicted to increase about USD 54.14 billion in 2030. Therefore, smart GHs can undoubtedly be one of the main trends in agriculture to be an investment [66]. A smart GH can bring together conventional systems of farming and novel IoT technologies to have complete visibility and automation. This can notably help to identify inefficiencies and address issues that have long been a concern for crop protection and crop maximization [67]. A typical schematic of a smart GH based on the IoTs is presented in Figure 7.

B. SMART GH AUTOMATION AND CONTROL

The smart GH market was about \$1.4 billion in 2020, but it is projected to reach \$2.1 billion in 2025 [68]. Therefore, automatic and permanent monitoring and control of this system have attracted the attention of researchers and investors. With constant monitoring by Smart GH Automation (SGHA), as well as its intelligent platform with high learning capabilities, pest, and fungal risks are reported very quickly [56]. In the GH smart system like smart home, all equipment can be monitored and controlled remotely.

Certainly, the automatic control system is a crucial aspect of smart GHs. The control requirements for GHs are typically complex and non-linear, with variations occurring throughout the day, week, month, and year due to changes in weather conditions. Intelligent control methods are essential to cultivate healthy plants while minimizing energy consumption, thereby maximizing profitability. Figure 8 illustrates a schematic of the control system for the greenhouse.

This intelligent control system likely involves sophisticated algorithms and sensors to monitor and adjust various parameters such as temperature, humidity, light levels, and possibly nutrient delivery. The adaptability of the system is crucial for responding to dynamic environmental changes and ensuring optimal growing conditions for the plants. The goal of such a control system is to create a responsive and efficient environment that promotes plant health and growth while minimizing resource usage. This is particularly important in the context of maximizing profitability in greenhouse operations.

In addition, the control systems that have been used and are being developed include the following categories:

1) SMART GH WITH PROGRAM LOGIC CONTROLLER (PLC)

Currently, the GH intelligentization project is being offered in various cases such as irrigation time, temperature settings, the best fertilization time, etc. Among them, the most popular is the smart GH with PLC, which also can define the scenario of the smart GH [69].

2) SMART GH WITH ARDUINO

Arduino is an open-source hardware and software platform that can be used to factor in expensive designs. The smart GH with Arduino can measure temperature, humidity, and CO_2 [70]. With these three capabilities, all vital factors in the GH can be controlled.

3) SMART GH WITH AUTOMATIC VOLTAGE REGULATOR (AVR)

Another low-cost and affordable method is to provide a smart GH with an AVR. The GH control system is done using an AVR microcontroller and with the help of LabView software. The AVR microcontroller can adjust the temperature, air humidity, and soil humidity and measure the amount of gas in the GH environment [70].

C. THE COST OF A SMART GH

The cost of a GH automation system is completely variable depending on the modern smart equipment that is used and to what extent they cover the GH [11] The GH temperature regulation system and the intelligent GH feeding system, which

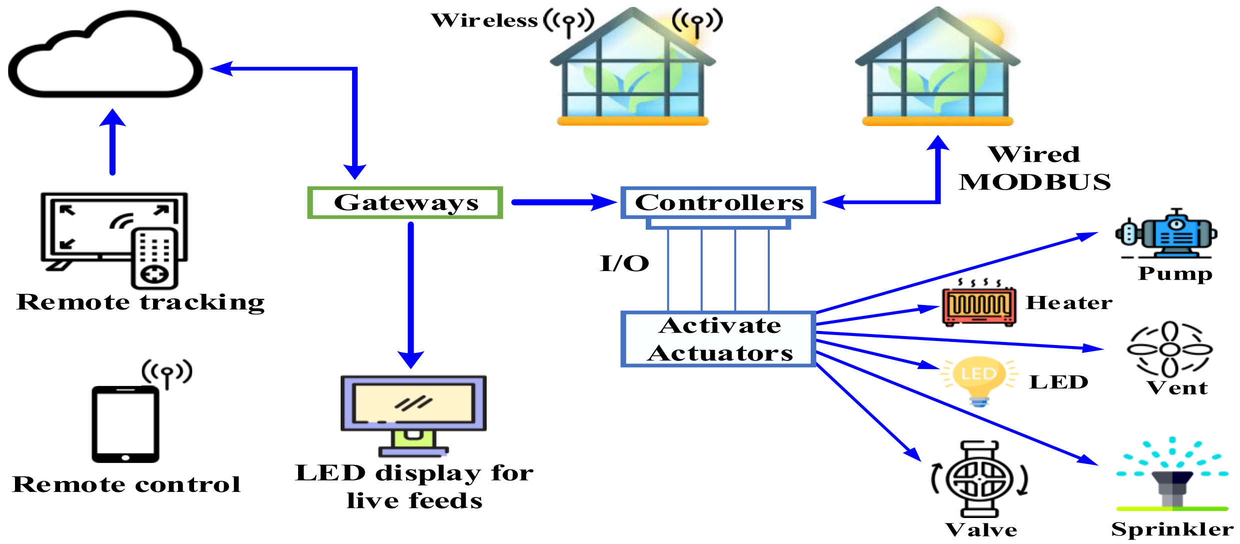

FIGURE 7. A typical schematic of a smart GH based on the IoTs [15].

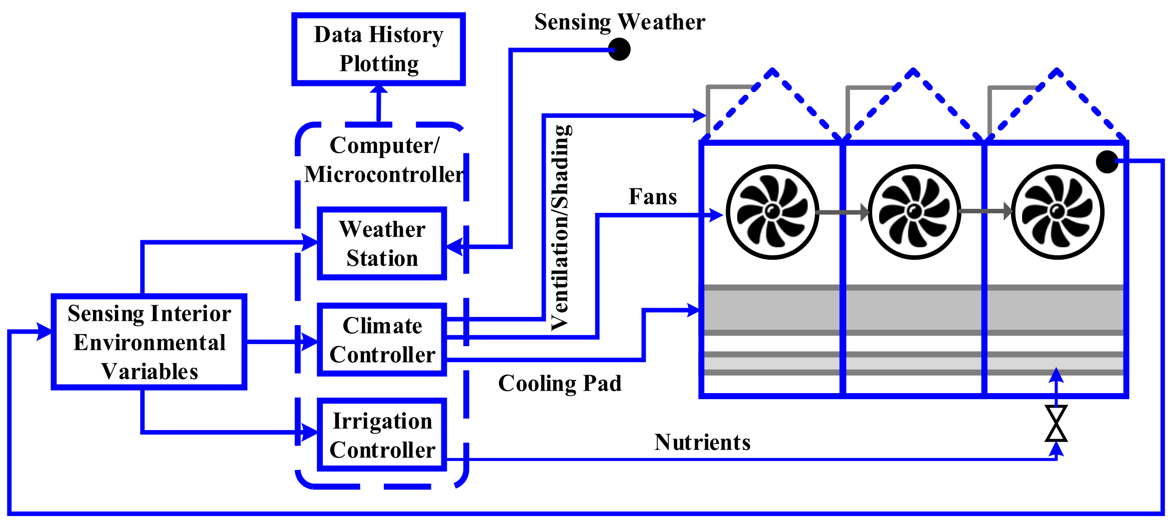

FIGURE 8. A control system schematic for GH [71].

is one of the most important systems in GH intelligentization can be expensive. Governments in many countries provide financial incentives for the construction of this type of GH. Nevertheless, the return on capital in the short and medium term can be one of the factors of investment in this field [72].

IV. INTELLIGENT LIGHTING SYSTEM IN GH

A smart lighting system is one of the simple and effective ways to make GHs smart, which enables operators to manage and control GH lights remotely. Next, smart lighting technology, smart GH lighting system [16], and smart lighting system equipment are introduced.

A. ENERGY CONSUMPTION IN THE LIGHTING SYSTEM

One of the most important advantages of the smart lighting system is energy savings [73]. For example, smart lamps that are connected to an application will warn you to turn off the lamp if a light is left on and motion is not detected. Almost all smart lighting system products are designed and built to work with efficient LED lighting fixtures, which are 75% more efficient and 25% longer lasting than traditional incandescent bulbs. Installing these systems, in addition to creating safety in GHs and open areas, which is the main function of the smart system, also creates comfort and convenience for personnel and plants [16].

The lamp is one of the greatest inventions of the 19th century in the world, which generally changed the way of human life and provided the convenience of using lighting in all places. Although low-consumption and ordinary lamps have many fans, with the passage of the 21st century, there has been a transformation in design and technologies that these ordinary lamps no longer meet the needs of modern life. In just a few decades, new lighting options have arrived on the scene, and those simple, energy-efficient incandescent bulbs have been replaced by a diverse array of energy-efficient smart devices [74]. The smart lighting system has gained great popularity as one of the main pillars of smart GHs all over the world. Smart home technology is finding innovative ways to integrate GH lighting systems, and in this way, new possibilities for customizing lighting and smart lamps are presented every day [75].

1) SMART LIGHTING SYSTEM IN GH

Smart technology helps to increase the scope and performance of the smart GH lighting system. Using smart lighting technology or smart light is an advanced method for lighting GHs. Smart LED bulbs contain software that connects to an app, or other smart accessories, to automate or control the lights remotely, eliminating the need for traditional wall switches. At the most basic level, you can remotely control smart lighting systems. This is often done through an app on a smartphone or computer. To accomplish this goal, smart lighting usually relies on a variety of wireless transmissions to send and receive its signals [76]. The smart light system can be connected to the smart hub through the built-in Wi-Fi waves to connect directly to the router or Bluetooth connection.

2) LIGHTING SYSTEM CONTROL

Other smart light options have motion and brightness sensors that automatically turn on and off depending on the amount of light or the presence of people and their movement in a certain place. These simple features can reduce energy waste. In GHs, depending on the type of plant, different amounts of radiation will be needed. During the year, the brightness of the sun and the hours of sunshine change. Since GHs need adequate lighting throughout the year, the lighting of lamps compensates for this [77]. Intelligent and optimal control of this lighting according to the amount and hours of radiation as well as the type of plant can be effective in reducing the consumption of electrical energy. Smart lighting systems also use more advanced technologies, including certain types of machine learning techniques. There are various options for controlling smart lighting systems, including smart switches and dimmers, smart lamps, and smart GH system lamps [78]. In a general summary, lighting or smart lighting options include the following:

- Smart Light Bulbs
- Hub-Controlled Smart Lights
- Smart switches and dimmers

3) HOW THE SMART LIGHTING SYSTEM WORKS

A smart light usually consists of an LED module, constant current (CC) LED driver, microprocessor, transmitters, and receivers (for example Wi-Fi, ZigBee, Z-Wave, and Bluetooth waves), and sensor devices that are integrated into a lamp or installed completely. The driver usually regulates the current to LEDs, also providing power to the transceiver, the microprocessor, or other devices. Additionally, the driver can receive pulse width modulation (PWM) or other digital signals from the microprocessor to adjust the dimming or turning on/off the LEDs. Digital signals work based on the events and instructions that are communicated over a wireless network (for instance via a smartphone, hub, or through a wireless cloud network). Microprocessors control the light of the LED according to the input signals received from the connected sensors [79].

4) ROLE OF THE HUB IN INTELLIGENT LIGHTING

Most smart lighting systems require a gateway, bridge, or central station, often known as a hub, to communicate. Bluetooth and Wi-Fi devices are not required to connect to the hub. A central hub can be configured to support multiple smart lighting systems. Hence, it acts as a data coordinator to communicate between a lighting controller such as a microprocessor and a web server, or even a smartphone or tablet. Another essential item is the lighting management software that collects and analyzes the running algorithm on the information technology network or cloud network, so it can provide advanced analysis and reporting while providing easy management of the intelligent lighting system [80].

The widespread use of smartphones, tablets, and computers as well as high-speed Internet enables the management of smart lighting systems or smart lights through Android or iOS devices, which are the communication interface between users and lighting systems [81].

5) NETWORK COMMUNICATION IN GH LIGHTING SYSTEM

Smart lighting relies on a data carrier including the Internet or a similar network to make the information of each lamp node individually and digitally addressable and controllable. A network connection is vital in communicating from lighting nodes to information carriers. Smart lighting systems are often considered to consist of wireless devices, but it does not mean that wired solutions are not suitable. The advantages of using a wired network include highly dependable connectivity and fast data transmission rates across greater distances. So, this might be the IP infrastructure's database for commercial buildings [82]. The great degree of flexibility, simplicity of installation, and cheaper deployment costs of the wireless network make it popular as well.

The smart lighting system helps, in addition to saving energy, easily and remotely control the lights and their brightness. The smart lighting system is connected to the wireless network of the GH and the brightness can be increased or decreased based on the activity [83].

B. ADVANTAGES OF USING A SMART LIGHTING SYSTEM IN GH

1) THE ABILITY TO INCREASE AND DECREASE THE LIGHT

In traditional lamps, lights are controlled only through a switch. To reduce the brightness of the environment, a dimmer switch should be wired and installed on the wall. However, in the smart lighting system or smart light, the brightness and dimming of the environment are controlled only through a software program on the computer system, mobile phone, or other smart control accessories.

2) LONG LIFE AND DURABILITY OF SMART LAMPS

One of the important topics is the type of lamps used in the GH. Smart LED lamps last much longer than conventional lamps and produce less heat than conventional lamps. In this way, the energy consumption of these smart lamps will be much less. Smart lighting system products are almost universally designed to work with LED lighting technology. This fact means that the average smart bulb will last anywhere from 15 to 25 years, or 15,000 to 25,000 hours. In some cases, the lifespan of smart LED lights is shorter than that of non-smart LED bulbs. However, the longevity and durability of these lamps are much higher than the old incandescent lamps [84].

3) CONNECTING TO OTHER SMART GH DEVICES

By connecting a smart lighting system or smart light with other connected devices such as cameras, wireless sensors, appliances, thermostats, or home assistants, internet-based devices can be used to build a smart GH.

4) AUTOMATIC OPERATION

Smart LED bulbs can be configured individually or in groups. For this purpose, a timer can be set for these lights to turn off and on automatically at a specific time, even when the personnel are not present in the GH. In addition, it is possible to program the smart lights to provide different levels of light output at different times, for example, to turn off completely during certain hours of the day or automatically dim in the evening [85].

5) INSTANT ADJUSTMENT OF BRIGHTNESS BASED ON NEED AND APPLICATION

By using smart lighting technology or smart light, you can create and assign predetermined and customized lighting for each zone. For example, if different plants are planted in different zones of GH, a different light spectrum can be created for them.

V. ENERGY MANAGEMENT IN GHS

A. THE IMPORTANCE OF CONTROLLING ENERGY AND CONSUMPTION IN THE GH

For the optimal growth of plants grown in the GH environment, it is necessary to control environmental factors such as light, heat, humidity, and ventilation. The GH should be designed in terms of structure and ancillary facilities in such a way that environmental factors do not create an obstacle to the growth and production of the product in terms of these factors. Therefore, energy is used in the GH to provide heat, humidity, ventilation, and light. The most important energy used in the GH is heating energy and electrical energy is second in importance [86]. On the other hand, due to the increase in the price of fossil fuels such as diesel, gas, and oil, the need to pay attention to energy consumption, especially heating energy, is more evident than in the past.

B. HEAT EXCHANGE IN THE GH

Most of the plants grown in the GH should grow in the temperature range of 18-28 degrees Celsius. On the other hand, the intensity of sunlight is another influential factor in the production of GH products. If the GH cover is made of glass, we see the maximum penetration of sunlight into the GH, but with a glass cover, not only does the heat loss to the outside environment increase a lot, but it also requires a strong structure, which leads to an increase in the initial investment [87].

Besides, if using a plastic cover, the heat exchange with the outside environment is reduced, but the penetration of light is less compared to the glass cover. In general, heat exchange, and as a result, heat loss in a GH or any other building takes place in 4 ways: conduction, convection, leakage, and radiation depending on its type and size [88].

1) CONDUCTION

Heat transfer or flow through a material such as plastic covers of GHs is called heat conduction. The speed of this transfer varies depending on the material [42].

2) CONVECTION

Heat is exchanged between the moving air inside the GH and the surface of the objects in that environment. This type of heat exchange is convection. As the air inside the GH heats up, it rises and loses some of its heat through the GH roof covering. After that, it becomes colder and the heavier air settles towards the floor of the GH to be heated by a heater or warmer floors and platforms [89].

3) LEAKAGE

Heat exchange or air penetration through openings and gaps in the GH cover is called leakage. It happens when cold air enters and warm GH air leaves through small cracks and openings on the cover, doors, and fittings.

4) RADIATION

Heat transfer between two bodies, without contact or the presence of a heat transfer material, is called radiation. In the phenomenon of radiation, energy exchange takes place without the need for a carrier called air. Sunlight with the phenomenon of radiation heats the air, plants, soil, and the structure of the GH. After absorbing the energy from the solar radiation of the plant, the soil and the structure of the GH become warmer than the surrounding environment, and in turn, these objects emit heat in the form of thermal radiation. Heat losses due to radiation on cold winter nights are significant and have an important effect on GH heat exchange [90]. Familiarity with the methods of moving and transferring energy (conduction, convection, leakage, and radiation) enables a significant impact on energy consumption management. For this purpose, the effect of structure, coating, type, and heating systems is discussed. Due to the large size of industrial GHs and their exposure to air, as well as the nature of their surfaces and the sensitivity of plants to temperature changes, keeping the temperature constant is the main priority in GHs. Therefore, the issue of energy management in GHs is one of the most vital things that investors, builders, and operators of GHs pay attention to [89].

Tables 2 and 3 compare the energy consumption of heating and cooling in different GH scenarios, taking into account GH size, insulation, climate conditions, and specific heating and cooling technologies employed [91], [92]. Typically, a large GH would have an area ranging from 5,000 square meters to 10,000 square meters or more.

These GHs are often used for commercial-scale agricultural production. A medium-sized GH would typically have an area ranging from 1,000 square meters to 5,000 square meters. These GHs can accommodate a moderate level of production and are commonly found in both commercial and small-scale operations [93], [94].

Small GHs generally have an area ranging from a few hundred square meters up to 1,000 square meters. They are commonly used for hobby gardening, research purposes, or small-scale commercial production. It is important to note that these size ranges are approximate and can vary based on regional or industry-specific standards. The actual categorization of GH sizes may differ depending on specific criteria, such as production capacity, intended use, or local regulations.

Also, a high insulation level refers to GH structures that are designed and constructed with advanced insulation materials and techniques to minimize heat loss and optimize energy efficiency. These GHs typically have insulation values that exceed the standard requirements. High-quality insulation materials such as double or triple glazing, insulated panels, or specialized insulation films are commonly used to achieve superior thermal performance. A medium insulation level signifies GHs that have insulation measures in place to provide moderate thermal resistance and energy efficiency. These GHs may use standard insulation materials, such as single-pane glass or polycarbonate panels, with insulation values that meet the minimum requirements for thermal efficiency [91]. A low insulation level implies that the GH has limited or minimal insulation measures in place, resulting in higher heat loss and lower energy efficiency. These GHs often use basic materials with lower insulation values, such as single-layered plastic film or non-insulated glass, which offer less resistance to heat transfer.

Different methods have been presented for this purpose, which usually include a combination of construction equipment to methods of reducing electricity or gas consumption, as well as the use of geothermal or renewable energy production systems [95]. Other items also can play important roles in the energy management of GHs. A schematic of energy transfer mechanisms in a typical GH is presented in Figure 9.

One of the effective ways to use solar energy is to implement solar collector systems in GHs. In this type of system, the sun's heat is collected by the thermal collector and causes the fluid to heat up. In brief, this hot fluid moves in a closed cycle in the GH and heats the environment.

Figure 10 shows a schematic of solar collector and communication lines with equipment along with storage tanks for heating a GH.

One of the effective ways to use solar energy is to implement solar collector systems in GHs. In this type of system, the sun's heat is collected by the thermal collector and causes the fluid to heat up. In brief, this hot fluid moves in a closed cycle in the GH and heats the environment.

C. MANAGEMENT OF FOSSIL FUEL COSTS IN THE HEATING SYSTEM OF GHS

In the reference [98], it was observed that the cost of fossil fuel for the heating system of thermal blowers was 5.3 times higher than the central heating system, and it was also observed that the cost of diesel fuel was 3 times higher than city gas fuel. Loss of energy in the structures, covers, and facilities of GH production units or the lack of use of new technologies imposes many costs on the operators. Therefore, one of the important topics is to provide cheap, reliable, available, and environmentally friendly fuel for GH heating. Using natural gas to generate heat in the engine house and transfer this heat into the GH in a closed cycle is one of the GH heating methods [99]. In addition, using electricity for heating can be another option for heating the GH in cold seasons.

Several studies have been done to use geothermal energy to heat GHs [55], [100]. The main problem is that the location of the GH and the geothermal energy should be close to each other. The use of other renewable energies such as the use of photovoltaic cells to generate electricity and supply energy to the GH is another method that has been studied [101]. Using an energy storage system such as a battery at the same time as a photovoltaic system to store electricity can increase the efficiency of the entire system [102].

D. USING THERMOSTAT CONTROL HEAT IN GH

Before the invention of thermostats and temperature sensors, the temperature of heating systems was adjusted manually. After the introduction of thermostats, more flexibility was created in temperature regulation in buildings. But even programmable thermostats have their limitations; now, technology has brought another option to control the temperature with which you can easily adjust the cooling and heating systems. This new technology, which is called the smart thermostat, does not have the limitations of the previous equipment and brings many advantages to the smart GH [103].

This new technology is an ideal option for making GHs smarter. Smart thermostats minimize the need to constantly adjust the temperature through the device's buttons, and

TABLE 2. Energy consumption for heating (kWh).

Heating System	GH Size	Insulation Level	Climate Condition	Energy Consumption (kWh)
Natural Gas Boiler	Large	High	Cold	12,000
	Medium	Medium	Moderate	7,500
	Small	Low	Warm	3,000
Heat Pump	Large	High	Cold	10,000
	Medium	Medium	Moderate	5,500
	Small	Low	Warm	2,500
Biomass Boiler	Large	High	Cold	14,000
	Medium	Medium	Moderate	8,500
	Small	Low	Warm	3,500

TABLE 3. Energy consumption for cooling (kWh).

Cooling System	GH Size	Insulation Level	Climate Condition	Energy Consumption (kWh)
Evaporative	Large	High	Hot	9,000
	Medium	Medium	Mild	5,000
	Small	Low	Cool	2,500
Air Conditioning	Large	High	Hot	12,000
	Medium	Medium	Mild	7,000
	Small	Low	Cool	3,500
Geothermal	Large	High	Hot	7,000
	Medium	Medium	Mild	4,500
	Small	Low	Cool	2,000

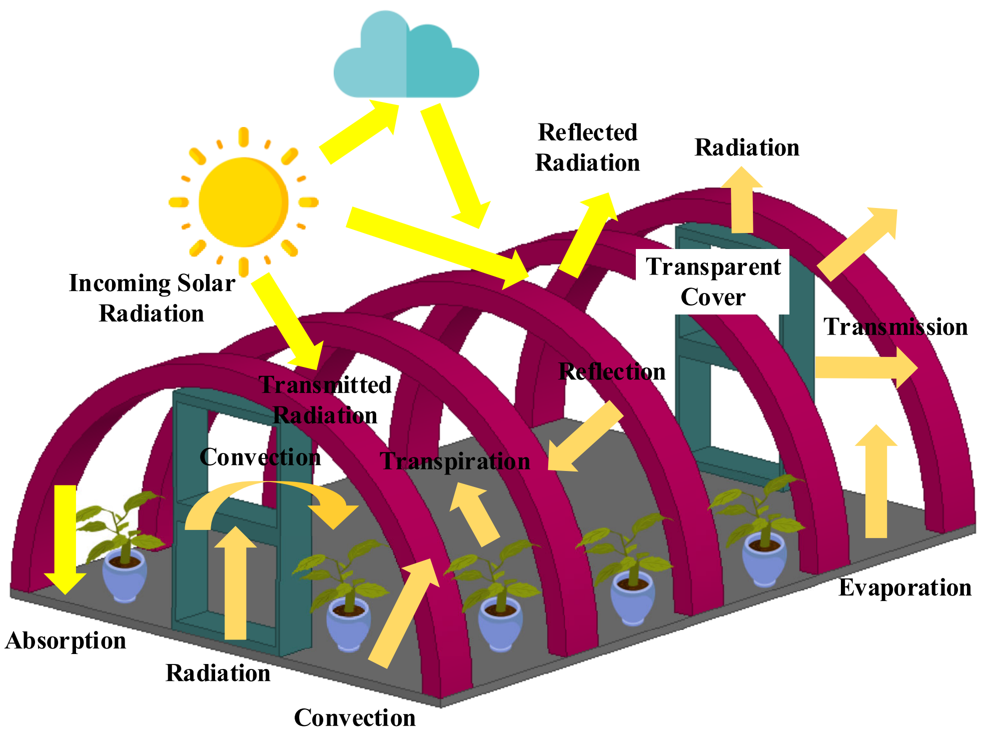

FIGURE 9. A schematic of energy transfer mechanisms in a typical GH [96].

whenever the need to change the temperature is felt, it can be adjusted remotely and through the application. In addition, the smart thermostat learns patterns and adjusts the temperature accordingly. Smartening the cooling and heating system in this way, in addition to creating comfort and convenience, is also effective in saving energy consumption and reducing its costs. Using the user guide and energy-saving tips that smart thermostats provide, a time for each section to save

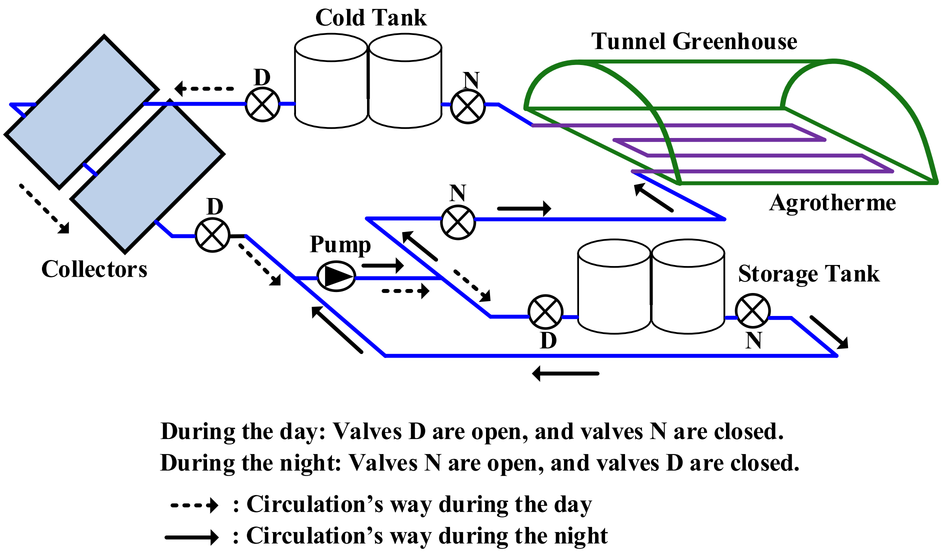

FIGURE 10. A schematic of solar collector and communication lines with equipment along with storage tanks for heating a GH [97].

money and energy can be scheduled. Therefore, this system provides more comfort and saves energy [104].

E. SMART AIR-CONDITIONING SYSTEM

The air conditioning system is one of the important components in a smart GH, which is responsible for air conditioning and temperature regulation. Using a smart ventilation system brings obvious benefits to plants and people working in smart GHs. Intelligent ventilation systems respond to scheduled changes in temperature as well as air quality inside the GH. In addition to creating a comfortable indoor environment, they are also effective in supporting the health of people and plants [105]. The quality of indoor air affects a lot of health problems that are brought about by tiny particles like CO_2, humidity, dust, aerosols, bacteria, allergies, or airborne viruses. It is possible to ensure cleaner conditions inside the GH by using a technology that automatically checks and responds to the levels of these invisible contaminants [106].

In addition, by using the most effective air conditioning techniques at the chosen time and location, these systems can dramatically decrease energy consumption. The smart GH ventilation system is activated using the Internet and Wi-Fi technology so that it can be easily integrated and controlled with other smart devices. Smart tools can control the air conditioning system of the smart GH. This system is connected to one of the walls or windows and can be adjusted and controlled through the relevant applications. The remote-control feature allows the system to be turned on and off remotely. The smart GH air conditioning system can be controlled by smart mobile phones, tablets, and other equipment and by sending voice commands [107]. Some types of these systems do not need control to be activated and are activated with preset settings or voice commands. Despite this, for ease of work, these devices are usually equipped with a remote control. To better understand the work procedure of a smart heating and cooling system, we need to know how traditional thermostats work. The thermostat utilizes temperature to decide when to switch on and off the heat or air conditioning. Normally, this system functions like a light switch, but it also uses temperature and equations to determine when to turn on and off the fan, heating, and cooling [13].

A standard thermostat contains four wires: a hot wire, a normal wire, one for the fan blower, and one for the HVAC system, which controls the temperature. Auxiliary heat, emergency heat, two-stage cooling, and heating, or wiring for a system that separates heating from air conditioning are examples of additional wires that could be included. Similar to conventional thermostats, smart thermostats connect to the GH's Wi-Fi network as well. Also, the thermostat settings can be changed remotely with the accompanying application. When the temperature settings are entered into the application, the desired settings are transferred to the smart cooling and heating system through the Wi-Fi network, and the thermostats send signals to the blower or HVAC system [108].

Many GHs with a smart HVAC system can be upgraded to a smart heating and cooling system, where there is a Wi-Fi connection. Whereas, when investing in a smart thermostat, make sure it will work with the heating and cooling system because there are various sorts of settings available. The heating and cooling thermostat wiring configuration can also need a C-wire (or ordinary wire) [109].

Nevertheless, what should be the basic use of smart thermostats in the mechanism of smart cooling and heating systems? A smart heating and cooling system is installed just like a conventional model and requires manual adjustments for the first few weeks. As soon as the thermostat is set to the desired level, the thermostat learns these preferences and makes the adjustments automatically. When the schedule is different, the smart thermostat automatically adapts to it, and the times when the personnel are not in the GH can save on heating and cooling. Ventilation strategies with intelligent control, either naturally or mechanically, automatically adjust the ventilation system and its performance in response to several items that can adversely affect the air conditions inside the GH [110]. Typically, this is done through a three-step process that includes sensing (sensors), behavior, and action.

1) SENSE

The GH has a network of sensors carefully positioned throughout it to track important aspects of indoor air quality. These factors include the following:

The internal and external temperatures of the building

- CO2 level
- Amount of humidity
- External conditions of weather

The control panel, which is typically a component of the building management system (BMS), receives this information. Moreover, crowd detection sensors can stop the needless ventilation of empty spaces. Certain intelligent control systems can give operators details on the air quality inside the hospital, how much energy it uses to run, and even whether there are any problems in the system or whether filters need to be changed [111].

One important thing to pay attention to in the GH is the amount of carbon dioxide. Also, due to global warming, the emission of polluting gases should be minimized. One of the main reasons for this problem in GHs is excessive energy consumption in old buildings. Their old air conditioning systems did not have precise controls to automatically turn the air conditioning on and off based on heating, carbon dioxide levels, weather forecasts, or other factors. By installing a smart ventilation system and benefiting from benefits such as adjustments based on population, weather conditions, etc., you can have more control over energy consumption [16], [112].

2) BEHAVIOR

The control panel analyzes the information received through the sensors. If the detected levels are greater than the preset parameters, the system should decide what to do. Frequently, the system must concurrently respond to several different factors and decide how best to integrate their overall feedback. In hybrid or mixed systems, these controls are extremely crucial since they activate various systems based on the environment [113]. Control systems can be set up and modified to employ various air conditioning techniques at various times (such as nighttime ventilation strategies or cooling strategies during summer). Some systems can even be controlled remotely [114].

3) ACTION

The system's action depends on the invoice or invoices it needs to perform. For instance, the system may open windows or turn on ceiling lights using motors or fans if the temperature or humidity level is too high. Certain intelligent ventilation systems can be configured to employ air direction to improve or limit ventilation. For instance, if the wind is blowing from one side of the building to the other, the system can open the best vents to ensure that the air is moving through the environment effectively. To prevent the air from becoming excessively dry, only wind-shielded vents should be chosen if the weather is bad outside or the room is too cold [115]. Sometimes, pure automation can result in poor design, even though a smart, automated air conditioning system can be quite useful by offering total control over energy usage and indoor conditions without requiring any input.

It is a fundamental point that designers give building users tools to control the systems according to their needs. Operators should have the ability to activate an automatic system with the options of manual window opening, skylights, or simple access with a control interface. Nevertheless, they must be aware of the best practices for using the system, including closing vents when using a mechanical system, to avoid problems with the ventilation system or energy loss [116].

F. ADVANTAGES OF USING SMART VENTILATION SYSTEM IN GH

A smart ventilation system is self-sufficient, intelligent, and efficient in energy consumption. Installing this system in a smart GH can significantly reduce energy consumption costs, keep the airflow and the environment fresh, and eliminate the need to manually control the system. The smart ventilation system brings with it various advantages, some of which are mentioned below [117].

1) CONTROL OF AIR CONDITIONING VALVES BASED ON THE AMOUNT OF HEAT AND CARBON DIOXIDE

The amount of heat and carbon dioxide in the GH can change a lot during the day, week, month, and year. In the past, operators had to identify and adjust these changes manually. However, today, smart air conditioning systems provide automatic control based on the amount of heat and carbon dioxide. As soon as the sensors detect abnormal values in a zone of the GH, they send the data to the controller to change the ventilation status if necessary [118], [119].

2) ADJUSTING THE WEATHER BASED ON THE FORECAST

The intelligent ventilation system can optimize the ventilation and air conditions based on the weather forecast for the next day. Therefore, if tomorrow is predicted to be the hottest day of the summer, the smart ventilation system will know this the night before and start cooling the building before the start of the next day. This intelligent system detects rainy, stormy, cloudy, dry, wet, windy, snowy, etc. days, and adjusts according to any weather conditions [120].

3) ENERGY SAVING WITH A SMART VENTILATION SYSTEM

An intelligent ventilation system reduces the overall energy consumption of the GH largely. This system will always have the lowest energy consumption and since its sensors detect changes in the moment, it can change the ventilation settings as many times as needed in a day. Controlling the amount of energy by optimization algorithms can provide suitable solutions for significant savings in energy consumption [121].

4) REMOTE CONTROL OF THE INTELLIGENT VENTILATION SYSTEM

One of the interesting features of smart air conditioning systems is the possibility of remote control. Therefore, it is possible to enter the ventilation management system using the Internet and change the ventilation system from there. Therefore, the remote control also allows you to control the settings of the ventilation system from anywhere and at any time [122].

5) CHECKING AND REAL-TIME MONITORING WITH AN INTELLIGENT VENTILATION SYSTEM

The ability to predict and observe smart ventilation systems and energy consumption in GHs is another advantage of this network. Not only can you view the history of energy consumption and current energy consumption status, but you can also predict future energy consumption. This issue also helps in budgeting and identifying better ways to save energy [123]. Some other examples of the best climate control equipment for making GHs smart can include the following:

- Smart air purifier
- Smart fumigator
- Intelligent dehumidifier
- Smart fan
- Smart weather station
- Smart thermostat

Using such suitable climate control equipment in the smart GH air control system allows the ventilation system to adapt to the environmental changes of the GH, optimize the use and consumption of energy, and, at the same time, create a healthy and comfortable environment for people and plants.

Considering receiving energy from renewable sources or the power grid, a smart GH can include various subsystems that aim to regulate the microclimate and ideal conditions for plant growth. Therefore, the most important of these different subsystems can be listed as follows [124]:

- Energy source
- Heating subsystem
- Subsystems for controlling temperature, humidity, and soil
- Lighting subsystem
- Irrigation subsystem

Figure 11 displays a simple schematic of a smart GH. Investigating and introducing energy consumption optimization solutions in the agricultural sector in such a way that energy losses are reduced without reducing welfare and enjoying energy services. Implementation strategies to improve the efficiency of fossil energy can be divided into two parts including policy-making strategies, and implementation strategies. Since policymaking solutions are very difficult due to the specific complications that exist in this field, it is often accompanied by trial and error and has many economic consequences for society. Therefore, identifying the implementation solutions to modify the energy consumption pattern can be a more appropriate and accessible option that will bring less negative economic consequences.

G. OPTIMAL ENERGY CALCULATION OF GHs

After analyzing all the structural issues of smart GHs, to calculate the optimal energy usage inside a GH, considering various factors such as the building structure, energy conversion, heating, and cooling systems, the following equations are reviewed. References [125] provided some strategies for optimal energy management in GHs. Some of the calculations related to this issue are given in the reference [126]. To calculate the heating issues of the greenhouse, the first equation that should be considered is the heat transfer equation of the building envelope, which is shown in equation (1).

$$Q_{env} = U_{env} \times A_{env} \times \Delta T \tag{1}$$

where Q_{env} represents the heat transfer rate, U_{env} is the overall heat transfer coefficient, A_{env} gives the envelope surface area, and ΔT provides the temperature difference across the envelope.

The next step is a calculation of heating and cooling energies that can be obtained using equations (2) and (3), respectively.

$$E_{heat} = Q_{heat} \times t_{eheat} \tag{2}$$

$$E_{cool} = Q_{cool} \times t_{cool} \tag{3}$$

Equation (2) represents the heating energy required in the GH, where E_{heat} is the heating energy, Q_{heat} gives the required heat transfer rate, and t_{hat} represents the heating duration. Equation (3) also represents the cooling energy required in the GH, where E_{cool} is the cooling energy, Q_{cool} gives the required heat transfer rate for cooling, and t_{cool} provides the cooling duration.

To calculate energy conversion efficiency, equation (4) can be used.

$$\eta_{conv} = \left(E_{output}/E_{input}\right) \times 100 \tag{4}$$

where η_{conv} represents the efficiency, E_{output} gives the output energy, and E_{input} is the input energy.

One important item in GH is the heat-pump coefficient of performance (COP) which can be calculated using formula (5).

$$COP_{hp} = Q_{heat}/E_{input\_hp} \tag{5}$$

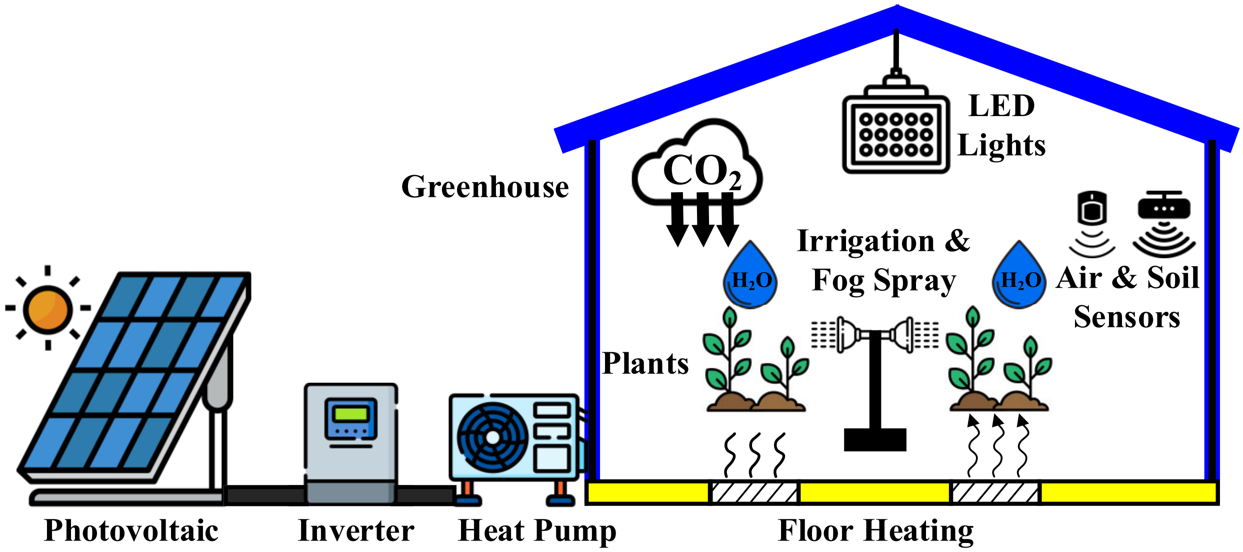

FIGURE 11. A simple schematic of a smart GH [124].

where COP_{hp} represents the heat pump coefficient of performance, Q_{heat} gives the heat transfer rate for heating, and E_{input_hp} represents the input energy to the heat pump. Another important factor in solar GHs is calculating solar radiation which can be obtained using equation (6).

$$Q_{solar} = A_{solar} \times GHI \times \tau \tag{6}$$

This equation calculates the solar radiation absorbed by the GH, where Q_{solar} is the solar radiation, A_{solar} gives the solar panel surface area, GHI provides the global horizontal irradiance, and τ represents the transmittance factor. To obtain the lighting energy of GH, equation (7) can be used.

$$E_{lighting} = P_{lighting} \times t_{lighting} \tag{7}$$

where $E_{lighting}$ is the lighting energy, $P_{lighting}$ gives the power consumption of lighting fixtures, and $t_{lighting}$ provides the lighting duration. In addition, to calculate the ventilation energy of GHs, equation (8) can be given.

$$E_{vent} = Q_{vent} \times t_{vent} \tag{8}$$

where E_{vent} represents the ventilation energy, Q_{vent} gives the ventilation rate, and t_{vent} provides the ventilation duration.

Another important factor in condoling temperature is evaporative cooling energy calculation which can be obtained with formula (9).

$$E_{evap} = O_{evap} \times t_{evap} \tag{9}$$

Equation (9) determines the energy used for evaporative cooling, where E_{evap} represents the evaporative cooling energy, Q_{evap} gives the cooling capacity of the evaporative cooling system, and t_{evap} is the cooling duration.

Also, many GHs use geothermal for heating buildings. In this regard, to calculate geothermal heat-pump energy, equation (10) can be used.

$$E_{geothermal} = Q_{heat} \times COP_{geothermal} \tag{10}$$

This equation calculates the energy used by a geothermal heat pump for heating, where $E_{geothermal}$ represents the geothermal heat pump energy, Q_{heat} is the heat transfer rate for heating, and $COP_{geothermal}$ gives the coefficient of performance of the geothermal heat pump.

Considering these equations, we can calculate the most important factors of energy design in a GH. Based on these equations and the size of the GH (large, medium, and small), a comparison of average energy consumption for heating and cooling systems in GHs is given in Figure 12.

H. EFFECTIVE STRATEGIES FOR REDUCING ENERGY CONSUMPTION IN SMART GH

A comparison and evaluation of effective strategies for reducing energy consumption within smart GH are given as follows:

1) ENERGY-EFFICIENT CLIMATE CONTROL SYSTEMS

Smart GHs employ advanced climate control systems that optimize heating, cooling, and ventilation to minimize energy consumption. Strategies such as the use of thermal screens, insulated glazing materials, and natural ventilation techniques can help maintain optimal temperature and humidity levels while reducing the need for artificial heating or cooling. Additionally, employing intelligent control algorithms that integrate real-time weather data and crop-specific requirements can further enhance energy efficiency [38], [121].

2) LED LIGHTING SYSTEMS

Traditional GH lighting consumes significant energy. However, the adoption of LED technology in smart GHs has

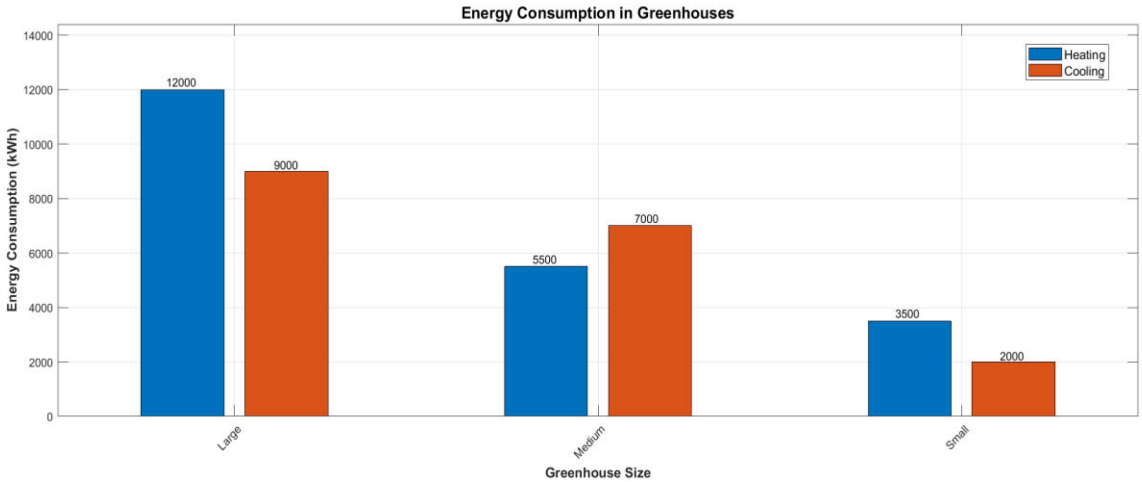

FIGURE 12. A comparison of average energy consumption for heating and cooling systems in GHs.

revolutionized energy-efficient lighting. LED lights provide tailored spectra for specific plant growth stages, optimizing energy usage by minimizing unnecessary light wavelengths. Furthermore, smart lighting systems can be programmed to deliver light only when needed, minimizing energy waste. Incorporating sensors that monitor plant growth and adjust lighting levels accordingly can further optimize energy consumption [127].

3) WATER AND NUTRIENT MANAGEMENT

Efficient water and nutrient management strategies play a crucial role in reducing energy consumption. Implementing precision irrigation systems, such as drip irrigation or hydroponics, ensures that plants receive the required amount of water and nutrients while minimizing wastage. Sensor-based technologies can monitor soil moisture levels, enabling precise irrigation scheduling based on real-time data. By avoiding overwatering and nutrient leaching, energy-intensive processes like water pumping and fertilizer production can be minimized.

In this regard, the paper [128] emphasized the importance of mass balance principles in optimizing fertilizer use for closed hydroponic and soilless substrate systems. The authors advocated for maintaining a closed system by replenishing water removed through transpiration with a nutrient-rich solution, ensuring efficient plant nutrition without wasteful discarding or leaching. The concentration of nutrients in the replenishment solution is calculated based on optimal leaf nutrient concentrations and water-use efficiency (WUE). The study highlights the varying WUE in controlled environments, influenced by factors like elevated CO_2 levels, which can dramatically affect nutrient demands. To accommodate these variations, the refill/irrigation solution concentration must be adjusted throughout plant growth stages. Also, it proposed using measurements such as electrical conductivity and emphasizes the critical role of the ammonium-to-nitrate ratio in PH management. The authors successfully applied these principles across diverse species and environments, achieving long-term, steady-state nutrient concentrations without discharge or leaching of the solution.

4) INTEGRATED RENEWABLE ENERGY SYSTEMS

Integrating renewable energy systems into smart GHs can substantially decrease the reliance on traditional energy sources. By installing PV panels on the greenhouse roof, it's possible to generate electricity to power various essential operations [129], [130]. In this regard, the paper [131] presented a mathematical model called Composite Probabilistic Energy Emissions Dispatch (CPEED), incorporating renewable energy systems. The study introduced a novel framework based on the Astute Black Widow Optimization (ABWO) algorithm to address the complex interplay between conventional thermal power plants and renewable sources like wind and solar. The research focused on optimization solutions for cost and pollutant emissions, thereby contributing to environmental sustainability and the diversification of energy sources. The proposed model not only lowers the environmental impact but also reduces reliance on imported fuels, fostering greater energy supply diversity. The findings suggested that the designed scheme effectively lowers fuel costs and pollutant emissions, while concurrently boosting the integration and utilization of renewable energy sources.

Wind turbines can also be strategically placed to capture wind energy in suitable locations, while geothermal systems can tap into the stable underground temperature for either heating or cooling purposes. To enhance the efficiency of these renewable energy solutions, smart energy management systems play a pivotal role. They enable the seamless integration and optimized utilization of renewable energy sources, leading to the most efficient use of energy and reduced dependence on the grid.

TABLE 4. Energy-saving strategies and their potential impact on GHs.

Energy-Saving Strategy	Description	Potential Impact
Energy-Efficient Climate Control Systems	Utilize thermal screens, insulated glazing, and natural ventilation	Reduced energy consumption for heating and cooling
LED Lighting Systems	Adopt energy-efficient LED lights with tailored spectra	Minimized energy waste in lighting operations
Water and Nutrient Management	Implement precision irrigation and sensor-based monitoring	Reduced energy for water pumping and nutrient production
Integrated Renewable Energy Systems	Integrate PV panels, wind turbines, and geothermal systems	Decreased reliance on conventional energy sources

To provide a clearer comparison of these diverse energy-saving strategies, Table 4 outlines the key strategies and their potential impact on GH operations.

VI. DISCUSSION

The comprehensive analysis of energy management and efficiency in greenhouse agriculture presented in the paper sheds light on crucial aspects influencing the sustainability and productivity of these controlled environments. The discussion below synthesizes key findings and explores the implications of the presented study.

A. IMPORTANCE OF RADIATION AND HEAT TRANSFER

The acknowledgment of radiation as a primary mode of heat transfer in greenhouses underscores the significance of understanding energy dynamics. The paper rightly emphasizes the substantial heat losses during cold winter nights due to radiation, highlighting the need for effective insulation and energy-efficient heating systems.

B. ENERGY CONSUMPTION VARIABILITY

The detailed comparison of energy consumption for different heating and cooling systems under varying greenhouse scenarios provides valuable insights. It underscores the importance of tailoring energy solutions to specific GH sizes, insulation levels, and climate conditions, reflecting the nuanced nature of energy management in agricultural operations.

C. ROLE OF INSULATION LEVELS

The classification of greenhouse insulation levels (high, medium, and low) underscores the pivotal role of insulation in minimizing heat loss. High insulation levels, utilizing advanced materials, exemplify a proactive approach to energy conservation, aligning with the growing emphasis on sustainable and environmentally conscious practices.

D. RENEWABLE ENERGY INTEGRATION

The integration of renewable energy sources, such as solar collector systems, photovoltaic panels, wind turbines, and geothermal systems, emerges as a key strategy. This not only aligns with global efforts towards sustainable agriculture but also addresses the imperative of reducing dependence on conventional energy sources, offering long-term benefits to both operators and the environment.

E. SMART TECHNOLOGIES AND AUTOMATION

The discussion on smart thermostats, smart air-conditioning systems, and the implementation of smart ventilation systems signifies a paradigm shift towards automation and precision in greenhouse management. These technologies not only contribute to energy efficiency but also offer real-time monitoring and control, providing growers with unprecedented flexibility and control over their operations.

F. OPTIMIZATION THROUGH MATHEMATICAL MODELS

The inclusion of mathematical models and optimization algorithms introduces a quantitative approach to energy management. This reflects a commitment to continuous improvement and the application of data-driven strategies to achieve optimal resource allocation, energy utilization, and cost-effectiveness.

G. WATER AND NUTRIENT MANAGEMENT

The emphasis on precision irrigation and sensor-based monitoring in the context of water and nutrient management aligns with broader goals of resource efficiency. By minimizing wastage and optimizing nutrient delivery, these strategies contribute not only to energy savings but also to the overall sustainability of greenhouse agriculture.

H. CHALLENGES AND FUTURE DIRECTIONS

While the paper provided a robust framework for understanding and implementing energy-efficient practices in greenhouse agriculture, it is essential to acknowledge potential challenges. These may include initial investment costs, technological integration hurdles, and the need for continuous education within the agricultural community.

VII. CONCLUSION

Smart greenhouses (GHs) represent the convergence of various cutting-edge technologies spanning electrical engineering, control systems, computer science, mechanical engineering, civil engineering, and agriculture. These innovative structures have emerged as versatile environments capable of year-round cultivation of diverse agricultural products, regardless of external weather conditions. However, their extensive reliance on energy for heating, cooling, and lighting presents sustainability challenges that can be mitigated through proper design and optimization.

This systematic review has thoroughly examined the optimal and practical methods encompassing the design, construction, control, energy management, and operation of smart GHs. We have delved into the structural aspects of smart GHs, explored various construction types and materials, dark GH concepts, scrutinized cooling and heating systems, and evaluated intelligent lighting solutions.

Additionally, we have investigated strategies to reduce energy consumption within these smart GHs.

In conclusion, the multifaceted approach presented in the paper highlights the intricate relationship between energy management and greenhouse productivity. By integrating renewable energy sources, leveraging smart technologies, and embracing optimized practices, greenhouse agriculture can evolve towards a more sustainable and resource-efficient future. The paper lays the groundwork for further research, innovation, and collaboration within the agricultural sector, aiming to address the pressing challenges of our time. This comprehensive review serves as a valuable resource for both academia and industry, offering insights and knowledge that can guide further research, construction projects, and the optimal operation of smart GHs. It paves the way for the development of efficient energy management strategies in the design of smart GHs, aligning with the broader objective of promoting sustainable and environmentally conscious practices within the agricultural sector.

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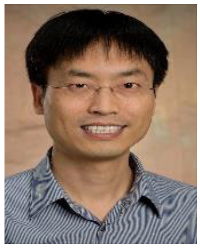

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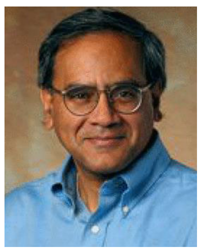

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