agriculture

Review

Agricultural Greenhouses: Resource Management Technologies and Perspectives for Zero Greenhouse Gas Emissions

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Abstract: Resource management in agriculture is considered a pivotal issue because greenhouse farming and agriculture-related activities generate about 10–29% of all global greenhouse gas emissions. The problem of high greenhouse gas emissions is still unresolved due to the rapid expansion of arable land to meet global food demand. The purpose of this systematic literature review was to generate new perspectives and insights regarding the development of resource management and optimized environments in greenhouses, thereby lowering energy requirements and CO_2 emissions. This review sought to answer what technologies and inventions could be used to achieve zero greenhouse gas emissions through efficient energy-saving mechanisms while considering their technical and economic viability. The synthesis of the findings led to several themes which included energy-saving techniques for greenhouses, systems that reduced unfavorable external conditions and renewable energy systems. Other themes identified regarded energy storage systems, systems for managing conditions in greenhouses, carbon capture and storage, and factors influencing the performance of different technologies to enhance resource management and ensure zero carbon emissions. The findings also revealed various technologies used in the design of energy-saving techniques in greenhouses including proportional–integral–derivatives (PID), fuzzy, artificial neural networks, and other intelligent algorithms. Additionally, technologies that were a combination of these algorithms were also examined. The systems that reduced unfavorable external conditions included the use of insulation panels and intelligent shading systems. Greenhouse covers were also optimized by smart glass systems, sensors, Internet of Things (IoT), and Artificial Intelligence (AI) systems. Renewable energy systems included PV (solar) panels, wind turbines, and geothermal electricity. Some of the thermal energy storage systems widely studied in recent research included underground thermal energy storage (UTES) (for seasonal storage), phase-change materials (PCMs), and water tanks, which are used to address short-term shortages and peak loads. The adoption of the various technologies to achieve the above purposes was constrained by the fact that there was no isolated technology that could enable agricultural producers to achieve zero energy, zero emissions, and optimal resource utilization in the short term. Future research studies should establish whether it is economical for large agricultural companies to install smart glass systems and infrastructure for slow fertilizer release and carbon capture in greenhouse structures to offset the carbon footprint.

Keywords: greenhouses; zero-carbon; zero-emission; renewable energy; IoT

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1. Introduction

Recent population forecasts show that the global population is estimated to reach 9.8 billion by 2050, and subsequently, is expected to exert enormous strain on global food security and freshwater resources [1,2]. The strain is further compounded by the uneven distribution of the global population in urban areas. Beyond population growth and suppression of freshwater sources, agricultural production will also be impacted by global warming and climate change [3,4]. These multidimensional challenges underscore the need for investment in the agricultural sector in order to provide food security and to ensure better resource management strategies to mitigate the impact of climate change on agricultural production.

Greenhouses are an essential tool in modern agriculture, as they allow the cultivation of crops in controlled environments, regardless of the external weather conditions. However, the operation of greenhouses consumes a significant amount of energy, mainly in heating, cooling, and artificial lighting. Specifically, modern greenhouse structures have a low thermal mass and are poorly insulated; this often translates to higher energy demand in heated greenhouses and more emission of greenhouse gases [5]. Countries such as the US, the Netherlands, China, and Saudi Arabia have intensified greenhouse agriculture [6–9]. As of 2017, China was the world's leader in climate-smart farming, with 41,090 km^2 under greenhouses [8].

Greenhouse production also elevates energy demand. However, this energy demand can be reduced through the use of renewable energy sources, such as solar, biomass, and geothermal heat. By transitioning towards renewables, greenhouse operators can mitigate the CO_2 emissions associated with conventional fossil fuel-based energy sources.

In addition to using renewable energy sources, Thermal Energy Storage (TES) systems can also improve the energy efficiency and sustainability of greenhouse cultivation. TES systems can reduce the heat demand of the greenhouse and stabilize the indoor microclimate for plants. The reduction of heat demand in greenhouses is important when renewable energy sources are used to power the greenhouse, as these energy sources can be intermittent in nature. TES systems store excess energy when it is highly available and release it during low-availability phases. As a result, they ensure a stable indoor climate for plant growth while minimizing energy consumption.

Overall, reducing the energy consumption of greenhouse cultivation through the use of renewable energy sources and TES systems can enhance the sustainability and economic viability of the sources. The recent literature on net-zero emission buildings (NZEBs) and zero-energy requirements has focused on commercial and residential structures in the place of greenhouses [10–12]. As a result, minimal research has addressed greenhouse structures as a limiting factor considering that global warming and climate change had increased the acreage under greenhouse structures [3]. In particular, the 2017 agricultural census estimated that the total area under greenhouses for vegetables and cut herbs was 112,564,105 square feet [13]. The exponential increase in the area under greenhouses was not unique to the US, as a similar phenomenon has been reported in Turkey [14]. Out of the 59,961 ha of protected cultivated areas, 53% (31,673 ha) were under greenhouses. The findings also showed that farmers preferred to cultivate seedlings, and ornamental plants in greenhouses.

The growth of greenhouses further led to mixed benefits on food security and the environment. On the one hand, greenhouse production translated to better efficiency and yields, given that the regulation of the microclimate mitigated the risk of excess insect and pest infestation. This improved efficiency and yield has been demonstrated in the production of capsicum, tomatoes, and other vegetables [15–17]. On the contrary, intensive greenhouse agriculture has contributed to global warming [18]. Considering these challenges, there is an urgent need for innovative strategies to achieve net-zero emissions and zero energy requirements in greenhouses.

This review article provides new perspectives and insights relating to the development of resource management and optimization of environments in greenhouses, thereby emphasizing zero energy requirements and zero CO_2 emissions. The scope of this review was informed by the need to plan for a net-zero carbon and zero emissions future in line with the Paris Agreement [5,19,20]. There is a paucity of research on resource management technologies for achieving zero carbon emissions and energy autonomy in greenhouses, except for isolated case studies on resource optimization using sensors [21], precision agriculture for agricultural efficiency [22], and optimization-mediated water supplement strategies for

IoT in greenhouses [1]. The case for optimal resource management was validated by the link between agricultural production and food security.

This review more heavily emphasizes the thermal insulation of greenhouse covers, closed-loop systems, and photovoltaic (PV) systems. Likewise, the focus is directed on shading systems, geothermal energy, wind turbines, batteries, smart glass systems, sensors, IoT, and AI systems for the optimization of greenhouse covers. This review also examines the generation of CO_2 by greenhouse plants, the optimized environment in greenhouses and achievement of zero CO_2 emissions, regulation of thermal/humidity conditions in greenhouse structures, and mechanisms and strategies for achieving zero energy requirements and zero CO_2 emissions. Further aspects evaluated include the balance between external energy/electricity versus external networks, the role of thermal insulation systems on sustainability in greenhouse structures, and the environmental benefits and climate change effects of achieving zero energy requirements and zero CO_2 emissions on commercial agriculture.

This review aims to discuss the technologies and inventions that have so far been identified to effectively achieve zero greenhouse emissions. It addresses the following objectives:

i. To provide a background on the current levels of energy consumption in agricultural production with a particular focus on greenhouses.
ii. To provide an overview of the literature on the energy-saving techniques used in greenhouse agricultural production.
iii. To map the literature on the efficient energy storage systems that can be used in greenhouse agricultural production.
iv. To provide an overview of promising sustainable and environmentally friendly prospects for the development of agriculture greenhouses to reduce their energy consumption and associated greenhouse gas emissions.

This article is outlined as follows. In Section 2, the review methodology is introduced. An overview of greenhouses, their energy consumption and interaction with the environment is presented in Section 3. Energy saving techniques for greenhouses and the implementation of renewable energy sources and energy storage systems in greenhouses are presented in Sections 4 and 5, respectively. In Sections 6 and 7, an overview of new developments and prospects such as IoT and smart technologies to reduce CO_2 emissions is presented. Conclusions with key findings and future works are drawn in Section 8. Finally, Section 9 concludes the exploration paper.

2. Methods

2.1. Eligibility Criteria

Studies published in English journals were preferred in thia review paper to avoid translation errors and associated costs. Although studies published within the past ten years were preferred in this review, the actual date range used was between 1981 and 2022. In this way, it became possible to provide historical insights into the subjects, especially considering no review has so far mapped the literature on the use of smart technologies to improve energy efficiency and minimize greenhouse gas emissions. Only peer-reviewed articles were used to ensure credibility of the reported information. Both primary and secondary studies published in credible academic journals were used. Although conference reports were considered for review, unpublished manuscripts were eliminated.

2.2. Information Sources

The following primary databases were identified to provide relevant articles: ScienceDirect, MDPI, Springer, Taylor and Francis, Scopus, and Google Scholar. In addition, relevant sources of information were obtained from websites, important institutions, and organizations, in addition to the primary databases mentioned above, including but not limited to FAO and others. These additional sources contribute significantly to the breadth and depth of information available. They were the primary sources of information because they publish studies from a wide range of disciplines, including smart technologies in various sectors of the economy, including agriculture. Using multiple databases is an effective approach to ensure a broad and diverse range of sources are included in the literature review or research project. Multiple databases also help avoid any bias that may be present in a single database.

2.3. Search Strategy

The following keywords were combined using Boolean operators (AND and OR) in each database: agriculture, agricultural activities, climate change, Paris Agreement, greenhouse emissions, mitigation actions, renewable energy, efficient energy management, energy storage, smart technologies, zero emissions, and zero energy use. Additionally, apart from combining the above keywords with Boolean operators, their synonyms as frequently used in academia were identified and combined. Also, standalone keywords were used without combining them with others using Boolean operators. For example, "actions to mitigate AND emissions in agriculture", "renewable energy AND agriculture", and "energy management AND greenhouse agriculture" were searched separately on each database, where a handful of relevant articles were identified. Language (English language) and date of publication (1981–2022) limiters were used in the search process.

2.4. Selection Process

Thousands of search hits were displayed on each database each time a key-phrase or a combination of keywords was used. The selection of studies from the search hits was undertaken by two independent reviewers. An article was relevant to this subject if it focused on the energy-saving techniques for greenhouses, renewable energy systems for greenhouses, and efficient energy storage systems for greenhouse agricultural production. In case of any disagreement between the independent reviewers, a third independent reviewer was invited to provide an opinion that settled the disagreement. No automation tools or crowdsourcing techniques were used during the study selection process.

2.5. Data Collection Process

The data collection process was undertaken by two independent reviewers. In case of disagreement between the two reviewers, a third reviewer was invited to settle it by giving an opinion on the matter at hand. No automation tools were used in extracting data from the selected articles. The data collection process entailed extracting information from an article that answered the research question or addressed any or all the objectives of this review.

2.6. Data Items

Considering that this review aimed to map the literature on smart technologies to minimize greenhouse gas emissions, especially through efficient energy utilization, the primary data points that were sought after in the articles included the name of the technology and how it worked in achieving the strategy. Any relevant information about the technology, including historical information, its effectiveness, costs, etc., was also extracted from the articles. Additionally, it is worth noting that although PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines were used in drafting this review, risk of bias assessment and certainty assessment were not undertaken because the review was not focusing on the effectiveness of interventions, as is the case in healthcare sciences. As such, effect measures were also not reported because the general aim of the review was to provide a summary of smart technologies used in greenhouse agricultural production" with a particular focus on greenhouse gas emission prevention and efficient energy utilization.

2.7. Synthesis Methods

A thematic approach was undertaken in synthesizing the data obtained from the articles. First, a table was created to summarize information about a technology identified from an article. This approach helped in grouping articles into their relevant technology categories. Due to the open nature of the eligibility criteria, articles with a wide range of information were retrieved. Hence, it was not easy to find two or more articles addressing the same issue. However, articles with closely related ideas were mapped in a tabular format before the writing process started.

2.8. Study Selection

The screening process for the articles involved multiple stages. Initially, all articles were screened based on their titles and abstracts. This was followed by a full-text and abstract screening process. The selection procedure, illustrated in Figure 1, outlines the steps taken to identify relevant articles. Starting with a total of 630 articles identified from various databases, 90 duplicate articles and another 40 articles were excluded due to reasons such as being unpublished manuscripts or published in non-peer-reviewed academic journals, leaving 500 unique articles. Therefore, at this stage, 500 articles remained. Out of the 500 articles, 450 underwent screening based on their titles and abstracts. As a result, 80 articles were eliminated as they did not meet the eligibility criteria. This left 370 articles that proceeded to a thorough screening for eligibility criteria, resulting in the exclusion of 88 more articles. Ultimately, 282 articles satisfied the eligibility criteria and were considered for review. Figure 2 shows the annual distribution of these articles. The year 2020 presents the highest number of published articles (42 articles).

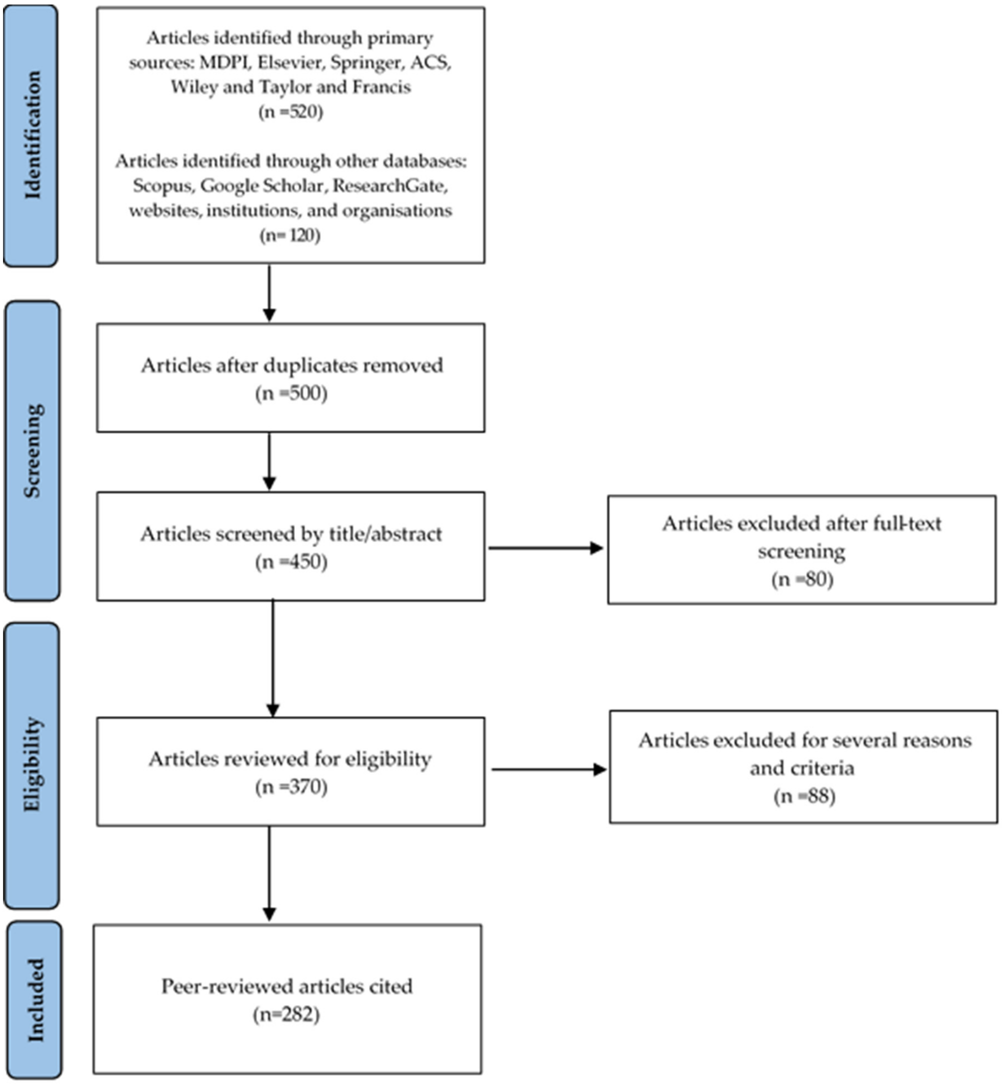

Figure 1. Flowchart of the selection procedure.

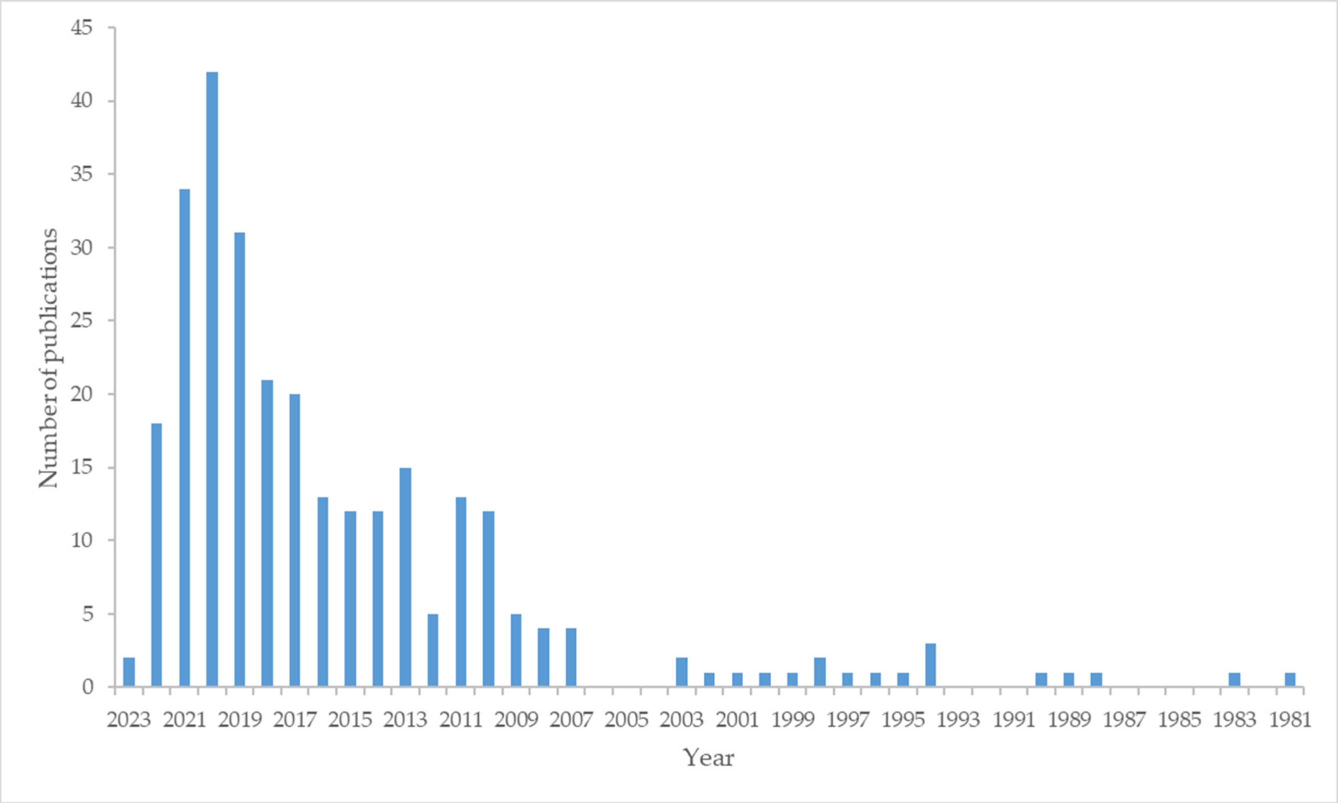

Figure 2. Selection procedure per year.

3. Greenhouses

3.1. Conventional Greenhouses

Greenhouses are an effective solution to create a controlled environment for growing plants and crops. The transparent or translucent materials used for the covering allow sunlight to pass through, while also trapping the heat inside, thereby creating a warm, humid and stable environment that can help plants grow faster and more efficiently. They can be used to grow a wide range of crops, including vegetables, fruits, flowers, and herbs. In addition to extending the growing season, greenhouses also allow farmers to control the temperature, humidity, and ventilation inside the structure, which can improve crop yields and quality. Additionally, the enclosure can protect plants from harsh outdoor conditions, pests, and diseases, providing an ideal environment for their growth. Agricultural greenhouses can be classified in several ways based on their characteristics, including their shape, construction, and materials used for their covering and structure. Specifically, greenhouses are developed into different shapes, such as even-span, gothic, Quonset, A-frame, Lean-to, and sawtooth. The shape selected depends on factors such as the size of the greenhouse, the crops being grown, and the location. The even-span greenhouse features a classic rectangular design with a symmetrical roof sloping on both sides, providing a balanced distribution of light and optimizing space utilization. It is a preferred choice for commercial production due to its efficient layout. The gothic arch greenhouse showcases a distinctive curved roof reminiscent of a gothic arch. This unique design allows for enhanced natural light penetration and efficient shedding of snow. Renowned for their durability, gothic arch greenhouses are particularly suitable for regions experiencing heavy snowfall. Quonset greenhouses exhibit a semi-circular shape with rounded contours. Typically constructed using metal frames and covered with plastic or polyethylene film, this design promotes excellent airflow and maximizes material efficiency, resulting in a cost-effective and straightforward construction process. The A-Frame greenhouse features a roof resembling the shape of the letter “A” or an inverted “V”.

The simple and compact design makes it ideal for home gardens or small-scale operations. With ample headroom and ease of construction, A-frame greenhouses offer a practical and straightforward solution for plant cultivation. The Lean-to greenhouse is constructed adjacent to an existing structure, like a house or a wall. It shares one wall with the existing building, leading to cost savings in construction and providing extra insulation benefits. Lean-to greenhouses are particularly space-efficient and frequently employed in urban or limited-space environments. The Sawtooth greenhouse boasts a distinctive design with interconnected roofs resembling a saw blade. This clever layout ensures optimal light exposure, as each roof section faces south for maximum sunlight. Sawtooth greenhouses are widely favored for the commercial cultivation of light-loving crops.

In addition, greenhouses can be constructed using various materials such as wood, steel, or aluminum. Wood is a favored option for greenhouse frames, prized for its natural charm and aesthetic appeal. It proves relatively easy to work with, cost-effective, and offers good insulation properties. Nevertheless, regular maintenance is essential to ward off rotting and decay. Steel stands as a robust and long-lasting material, providing outstanding structural support for greenhouses. Its resilience allows it to endure heavy snow loads and high winds, rendering it ideal for regions with harsh weather conditions. To prevent corrosion, steel frames are frequently galvanized or coated. Aluminum, known for its lightweight and corrosion-resistant properties, demands minimal maintenance, making it a favored option for greenhouse frames. Its excellent structural strength and ease of assembly further add to its appeal. As a result, aluminum frames are frequently employed in both commercial and hobbyist greenhouses. The selection of framing materials is influenced by factors such as cost, durability, and the load-bearing capacity of the structure. The covering material for a greenhouse can be made from materials such as glass, polycarbonate, or polyethylene film. The covering material is determined by factors such as the desired light transmission, insulation value, and durability. Glass, a traditional material for greenhouses, boasts exceptional light transmission and commendable insulation properties; however, it may be comparatively costlier and more fragile than alternative materials. Polycarbonate, an impact-resistant, lightweight, and transparent material, finds extensive use in greenhouse glazing. It delivers remarkable insulation and safeguards plants from harmful UV radiation while facilitating the transmission of light. Polycarbonate panels are available in various thicknesses to accommodate different insulation requirements. Polyethylene film is a versatile and budget-friendly material, and it is commonly employed in the construction of greenhouse frames. Its lightweight nature, ease of handling, and resistance to rust and corrosion make it highly practical. The frames are particularly well-suited for smaller and temporary greenhouse structures. In addition, greenhouses can be designed to allow natural ventilation or can be equipped with mechanical ventilation systems to regulate temperature, humidity, and carbon dioxide levels. Some greenhouses are also equipped with heating systems to maintain optimal temperatures during colder months or in colder climates.

3.2. Energy Consumption of Conventional Greenhouses

Conventional agricultural greenhouses require significant energy to maintain the optimal growing conditions for crops, which can result in high energy costs and contribute to increased greenhouse gas emissions. The costs of energy consumption in agricultural greenhouses often account for up to 50% of the production costs [23]. This is because greenhouses require a considerable amount of energy to maintain optimal growing conditions, such as temperature, humidity, and light. Some of the commonly used energy-consuming facilities in greenhouses include heating and cooling systems, ventilation and fogging systems, shading and lighting mechanisms, and CO_2 enrichment systems. These facilities account for a significant percentage of the primary energy demand, with heating and cooling applications alone accounting for 65–85% of the primary energy demand [24]. In addition, the materials used for the greenhouse envelope are often poor thermal insulators, resulting in significant heat loss, specifically about 20–40% [25]. Fossil fuels are primarily used to meet the energy demands of greenhouses, which contributes to greenhouse gas emissions. It has been estimated that around 5–6 kg/yr.m^2 are required to maintain the internal air temperature of greenhouses at around 15–20 °C. The use of fossil fuels in greenhouses contributes to greenhouse gas emissions, with the burning 4 Mtoe of fossil fuels releasing 11.3 Mt of CO_2 [26]. The high energy consumption and greenhouse gas emissions of conventional greenhouses make it one of the most intensive sectors in agriculture in terms of yield, energy consumption, investments, and costs.

To measure the energy consumption efficiency in greenhouses, the energy ratio (ER) is calculated which is given as the ratio of the energy output to the direct and indirect energy inputs. This provides a measure of the energy consumption efficiency and can help greenhouse operators identify areas where energy-saving strategies can be implemented to improve efficiency and reduce costs. The energy ratio can be calculated using Equation (1) [27,28] and the energy productivity (EP) which is used to compare the commercial greenhouses' productivity under various energy management scenarios using Equation (2) [29,30].

$$\text{Energy ratio} = \frac{\text{Energy output}\left(\frac{\text{MJ}}{\text{m}^2}\right)}{\text{Total greenhouse inputs}\left(\frac{\text{MJ}}{\text{m}^2}\right)} \tag{1}$$

$$\text{Energy ratio} = \frac{\text{Greenhouse productivity yield}\left(\frac{\text{kg}}{\text{m}^2}\right)}{\text{Total greenhouse inputs}\left(\frac{\text{kg}}{\text{m}^2}\right)} \tag{2}$$

On average, greenhouse structures in the Mediterranean region of Turkey required at least 3593–10,460 GJ/ha for the regulation of their internal microclimate [14]. These energy requirements were unsustainable, considering that it would cost about USD 150,000 per ha per year in Turkey [14]. Research on the energy requirements of greenhouse structures and ecological sustainability of greenhouse covering materials and intelligent systems have shown that energy consumption and solar energy savings vary across regions, depending on technology access, the number of days with optimal solar radiation, and incentives for technology adoption [31,32].

The cost of greenhouse heating was slightly higher in Italy, where farmers spent an average of EUR 15.7/m^2. In contrast, Moroccan farmers spend an average of EUR 450/ha on greenhouses [33]. From a theoretical point of view, the cost of greenhouse heating could be regulated by the replacement of electrical heating systems with solar heating systems [33]. However, the transition was only appropriate for regions with sufficient sunlight [34]. Poor light intensity has a detrimental effect on the efficiency of greenhouses and photosynthesis structures [35–37]; this is particularly the case for shape-morphing solar shadings [35], hydrogel-based smart window systems [38], and thin-film transparent photovoltaics [39].

The cost estimates provided by the authors of [14,33] were comparable to estimates provided by the authors of [40,41]. On the other hand, however, the observations of [14,33] contradict the observations of the authors of [42], who argued that the efficiency of solar greenhouses could be improved through the integration of electricity and thermal energy production. The only major drawback was the insufficient electrical conversion efficiency <10%, limited measurement range, and variable accuracy [33]. According to [33,43], it can be noted that the accuracy of greenhouse sensors was not determined.

Various solutions were proposed, including the use of double polyethylene covers, which have been proven to reduce heating requirements by 50%; retrofitting and winterizing openings to address the variable energy requirements [40]. However, the proposed solutions were context-specific. For example, the double polyethylene covers might be unsuitable for certain crops considering that polyethylene has a transmittance of about 80% [44]. The drawbacks of polyethylene and other traditional polymers informed the transition to carbon-based hydrogels [45].

Beyond the cost-intensive measures to reduce greenhouse heating, conservative measures can be explored, including insulation of the end walls, foundations, and the side walls with polymer materials and the incorporation of thermal blankets [40]. The utility of the interventions can be challenged due to limited utility and cost. For example, poor insulation often contributes to heat losses. Data collected by the University of Massachusetts Extension Greenhouse Crops and Floriculture Program showed that a double-wall glazed greenhouse wall loses twenty times more energy compared to a residential building structure. Despite such constraints, it could be argued that the short payback period for insulated greenhouses was a sufficient incentive.

3.3. Interaction between Greenhouses and the Environment

The interaction between commercial agricultural greenhouses and the environment was dynamic and cyclical (see Figure 3). Recent studies yielded irrefutable evidence linking greenhouse agriculture to the release of carbon emissions and the subsequent incidence of global warming [46]. Diverse contributing factors identified to increase global warming included greenhouse heating and cooling, fertilizer application, integration of energy-intensive IoT systems, intensive irrigation, mechanized farming, and deforestation to increase arable land [47–49]. According to the World Bank, global warming and climate change were directly responsible for low agricultural productivity, reduced quality of cereals, and overall crop yields [50]. At present, global economies are faced with a dilemma given the need for intensive and mechanized agriculture to address food security for the modern civilization. However, mechanized agriculture contributed to carbon emissions and climate change, as smart farming technologies were cost intensive.

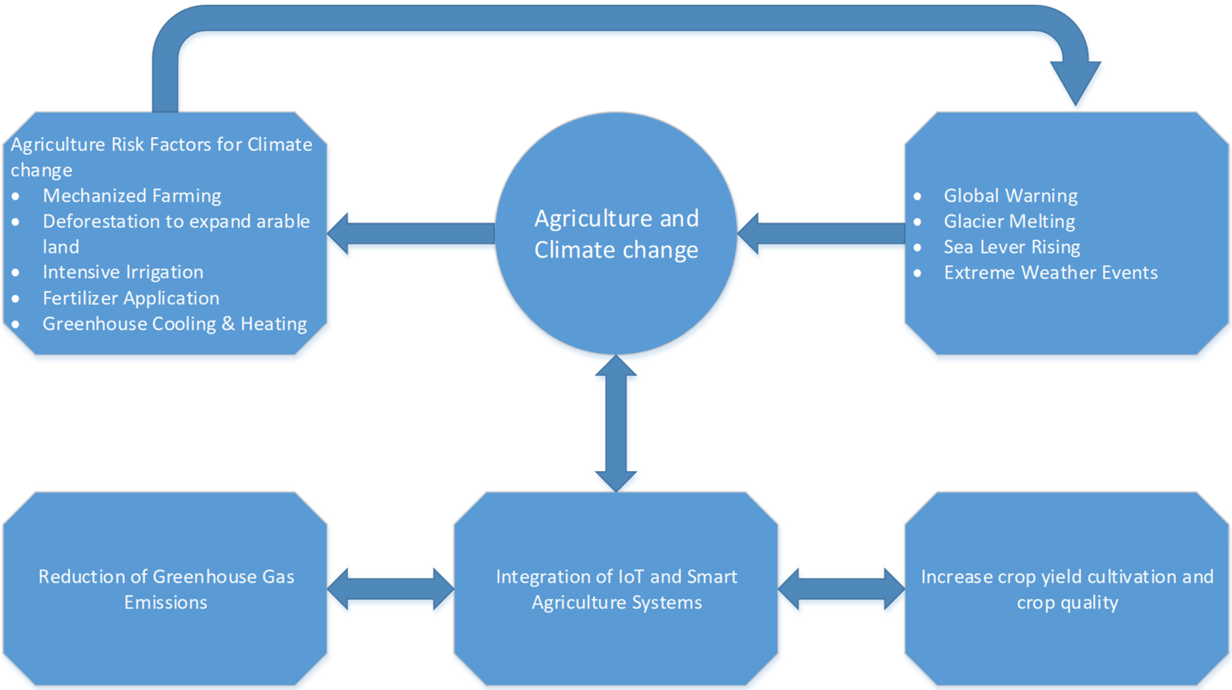

Figure 3. Climate change, global warming, and agricultural productivity.

Carbon emissions from agriculture were not ubiquitous since regional variations were identified over time. Higher CO_2 emissions were linked to poor crop cover management practices, inadequate crop rotation, excessive fertilizer use, and intensive irrigation practices [51–54]. Greenhouse cooling and heating elevated energy use and, by extension, led to global warming. However, on a positive note, greenhouse crops contribute to carbon sequestration [55,56]. Recent LCA suggests that the carbon captured via carbon sequestration in greenhouses is lower compared to the carbon footprint of the entire agricultural life cycle. The worldview was supported by the US Environmental Protection Agency (EPA), which claimed that agricultural emissions accounted for 10% of all carbon emissions, and the entire value chain (including nonpoint emission sources) accounts for up to 60% of the carbon emissions [57]. The dynamic relationship between agriculture and the environment justifies the need for better resource utilization.

Reducing carbon emissions in agriculture is resource-intensive, making it impractical for most smallholder farmers as shown by the marginal adoption of precision agriculture in developing countries [47]. In the absence of policy incentives, smallholder farmers have minimal motivation to invest in climate-smart agriculture [58,59]. Currently, commercial farms lead in the adoption of smart technologies in agriculture [60]. The current status quo is unsustainable, given that small-scale farmers make an enormous contribution to global food security. Therefore, there is a need to map the literature on the innovations that can be used to achieve optimal greenhouse agricultural production using energy-efficient systems with a view to minimize the production of greenhouse gas emissions. The review findings can be used to facilitate future research on how smallholder farmers can be encouraged to adopt smart technologies in greenhouse agricultural production.

3.4. Zero-Energy Greenhouses and Energy Conservation

The need for zero-emission greenhouse structures is reinforced by the growing risk of climate change, energy demand, CO_2 emissions from plants in greenhouse environments [61], and violation of the Kyoto Protocol and acquiescence towards the Paris Agreement [62]. The average demand for greenhouses is expected to increase by 40% [8]. However, the Energy Information Administration (EIA) hypothesized that the demand would surpass 50% due to strong demand from Asia (see Figure 4) [63]. On the contrary, inconsistent investments in climate-smart agriculture across Asia have been identified compared to Europe; this means it is challenging to attain zero greenhouse gas emissions through sustainable resource management technologies. For example, even though China has the largest land under farming, the lack of water has led to reduced crop yields [64]. The agricultural resource constraints could be offset by greenhouse farming, but care should be taken to minimize carbon dioxide emissions from plants. For example, through natural fertilization with sludge and cow manure to catalyze CO_2 production in greenhouse crops [61].

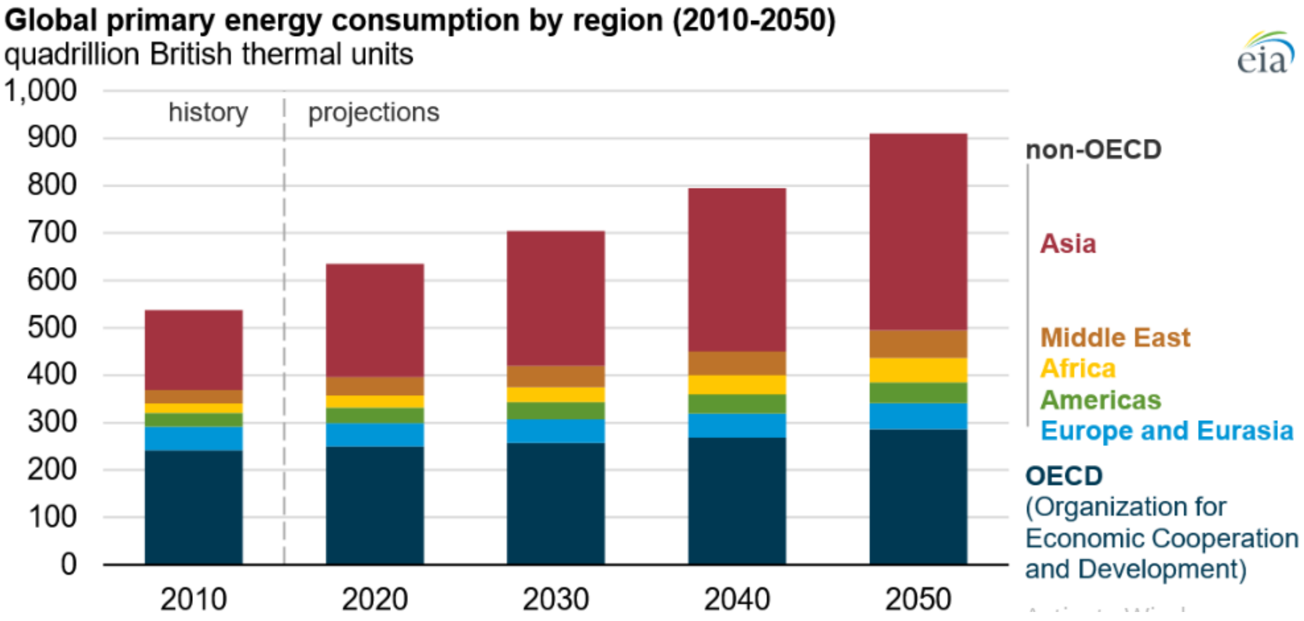

Figure 4. Global energy outlook in the OECD, America, Europe, MENA, and Asian regions [65].

The growing power demand has partly contributed to greater investments in complementary sources of energy ranging from photovoltaic systems to agricultural power structures and commercial buildings [62,66]. On the downside, the rate of renewable energy adoption is inconsistent with the demand as corroborated by data drawn from Eurostat, which showed that the ratio of renewable energy contribution to the national grid was below 40% for most EU members except for Finland, Latvia, and Sweden [67]. From a theoretical point of view, the inconsistent investments in renewable energy were paradoxical considering that countries are projected to experience significant climate change-related events, which would make open-field agriculture less sustainable [68,69]. Even though climate-smart agriculture is considered a practical alternative, various challenges remained unresolved. For example, how would the largest emitters of greenhouse gases compensate for the environmental effects linked to global warming in other countries? The piloted carbon emission trading schemes have yielded mixed outcomes. Some of the preliminary evidence drawn from the EU showed that the trading schemes reduced carbon emissions by 3.8% between 2008 and 2016 [70]. On the contrary, the level of commitment by the different countries was inconsistent.

The US and China, and other large emitters of greenhouse gas pollutants were also less committed to the carbon emission trading schemes [71]. The phenomena generated negative implications on global climate [71]. For example, the International Panel on Climate Change (IPCC) estimated that the UK would receive 10% more rainfall by 2100 compared to the aggregate rainfall recorded in 1986 [72]. The estimates provided by IPCC were in line with recent hydrological assessments, which mapped areas prone to flooding across the UK [73]. A similar scenario was observed in Germany [74]. The climate projections underscore the need for concerted sustainability measures to safeguard global food supplies through climate-smart agriculture. A fundamental question is whether the availability of affordable smart IoT solutions for smallholder farmers would catalyze climate-smart agriculture.

The climate-related effects on rainfall and weather that were documented in the UK, had an impact on agriculture in the country. The UK's case was not unique as both developed and developing nations were contending with climate change and global warming [75]. The UK Parliament declared climate change a national emergency in 2019 which led to the redirection of national resources towards sustainability initiatives. The sustainability interventions were augmented by the Scottish Government and the NHS sustainability strategy for 2022 to 2026 [76], and the subsequent construction of submerged barriers and dams [46]. However, public sentiments generated on the interventions were mixed. Some proponents argued that government policy measures were needed to mitigate climate change. However, critics believed that reducing carbon emissions through de-industrialization would help address the problem [77]. As a result, this explains the growing demand for sustainable manufacturing and production that was aligned with UN sustainable development goals [12]. The mixed insights had practical consequences on climate change mitigation, for example, drawing from the timelines of climate change interventions led to uptake of sustainable operations in industries.

4. Energy-Saving Techniques for Greenhouses

4.1. Conventional Saving Techniques

Several energy-efficient techniques have been applied to reduce greenhouse energy requirements. The main strategies applied in greenhouses to increase the energy-saving potential also aim to achieve the optimum environmental climate growing conditions (temperatures, relative humidity, light) for the plants. Such strategies include: (i) energy-efficient structural design, (ii) installation of energy-efficient screens, (iii) installation of energy-efficient heating, ventilation, and lighting systems, and (iv) installation of energy-efficient environmental control systems [78]. An energy-efficient design of a greenhouse can reduce the heating requirements of the greenhouse by increasing the solar energy gain and energy conservation inside. The main design parameters that affect the energy consumption are the type, shape and orientation, and cover materials [79]. Regarding the type of greenhouses, there are two types: detached or freestanding, and gutter-connected.

The freestanding greenhouses are suitable for the production of most crops. These greenhouses can provide stand-alone growing environmental conditions for plants, which can help control diseases and pests. The detached greenhouses are usually narrower than those connected by gutters, and this facilitates their natural ventilation. On the other hand, gutter-connected greenhouses cover less growth area than detached greenhouses and, therefore, need less heat, and the space can be used more effectively [79]. Another important design parameter to increase the solar gain and decrease the heat loss in the greenhouses is their shape [24,80]. The usual shapes for the greenhouse roof are (i) single-span gable roof, (ii) uneven-span gable roof, (iii) gothic arch shape, (iv) vinery shape, and (v) the Quonset shape. In the literature, several research papers have studied the selection of the optimal choice of greenhouse roof from the heating point of view for different locations [81,82]. In [83], the thermal performance of the five different greenhouse shapes under three different climate conditions in India was studied and the results showed that the uneven-span gable roof was the optimum choice. In [84], the results showed that the gothic arch shape could receive the highest solar radiation than the other four shapes for a greenhouse in Turkey. Therefore, the studies show that the shape of the greenhouse depends on the weather conditions of the area where the greenhouse will be installed.

The orientation of a greenhouse can also maximize the solar radiation inside the greenhouse and therefore, decrease its heat energy requirements especially during winter. Usually, the east–west orientation is preferable for even-span greenhouses since the average solar energy gain is higher than the north–south orientation and subsequently, the greenhouses require less thermal energy [85–87]. On the contrary, gutter-connected greenhouses should be oriented in the north–south direction so that the shadows will move from the west side in the morning to the east side in the afternoon and hence the shadows will not affect plant growth [88,89]. The cover materials for greenhouses significantly affect the greenhouses' energy consumption [90]. The common materials for greenhouses are glass (low emissivity and diffusive), acrylic panel, poly-carbonate panel, polyethylene film, and fiberglass [79]. These materials can be used as a single-layer cover or multiple-layer cover. The method that further reduces the heating energy required in greenhouses (up to 40% energy savings) without affecting the plants' growth and increase the sunlight in greenhouses (up to 20%) is the use of a double-layer cover [91–93].

The use of thermal screens provides dual benefits: (i) reduction of needed thermal energy during night, especially in winter and reduction of the cooling requirement during summer due to the shading of the crops. Thermal screens are usually aluminized woven fabrics that are frequently placed across the roof in order to be act as thermal barrier between the crop and the roof. As a result, the thermal screens retain heat and assist maintenance of the optimal temperatures inside the greenhouse [94]. The thermal screens can save up to 60% in energy costs depending on the location [95,96]. However, the use of thermal screens reduces the vertical space of a greenhouse which cannot be used for crop production, although in contrast the greenhouse requires less thermal energy due to the smaller available space.

Energy-efficient heating, ventilation, and lighting systems are required in a greenhouse in order to provide the necessary environmental conditions for the growth of plants and to maintain their quality. The main unit heaters for greenhouse heating are the vented and the unvented heaters. The vented heaters are classified as gravity-vented, power-vented, and separated combustion and high-efficiency heaters. The efficiencies of gravity-vented, power-vented, and separated combustion heaters range from 60 to 80% and the high-efficiency heaters are typically rated at 90% thermal efficiency (some high-efficiency hot water boilers for hydronic systems have efficiencies up to 98%) [97]. The unvented heaters have been mainly utilized for CO_2 enrichment in greenhouses. The main factors that affect the thermal efficiency of the unit heaters are: (i) ensuring fresh-air duct to the heater for complete combustion, (ii) the appropriate choice of heat exchanger material because it affects the life span and warranty of the unit heater due to the high-humidity environment and the pesticide chemicals used in greenhouses, and (iii) the optimum heat distribution location which can reduce overall energy consumption while increasing plant growth and crop yields. Most of the unit heaters are reliable and have low capital and installation costs. The use of multiple heaters is usually necessary to ensure heating of the greenhouse even in a scenario where one heater stops operating. In these greenhouses, vented heaters are used to provide the required heat during the night and the unvented heaters are used for CO_2 enrichment during the day [98]. Moreover, ventilation systems can also control the temperature and humidity in the greenhouses. The use of speed controllers for ventilation fans is preferable, as they can provide variable load operation of the fans. In this way, a reduction of the fan energy consumption is achieved as the speed (hence the energy consumption) increases when the temperature grows and respectively decreases when the temperature reduces. In addition, taking into consideration that each crop has different responses to light, supplementary lighting systems for greenhouses can be used to control and/or increase the photosynthesis rate of the plants. These systems can also contribute to the heating of the greenhouses, depending on the types of lamps used [99]. In [100], the supplementary lighting system contributed about 40%, while in [101] about 25–41% of the greenhouse heating requirements were covered by the supplementary lighting system.

A summary of the conventional energy-saving techniques for greenhouses and each technique's advantages and disadvantages are presented in Table 1. The insulation technique in greenhouses involves the addition of insulating materials to walls, floors, and roofs. Its main purpose is to minimize heat loss during cold weather. By reducing heat loss, insulation helps lower heating costs and maintain a consistent temperature, which in turn improves crop growth and quality. However, implementing insulation may require additional structural support and can potentially limit ventilation, leading to increased humidity levels and the risk of disease [102–104]. The double-layer glazing technique is characterized by the installation of two layers of glazing with an intermediate layer of air or gas. This setup provides enhanced insulation for greenhouses. It effectively reduces heat loss, resulting in lower heating costs. Additionally, it contributes to maintaining a stable temperature, which is beneficial for optimal crop growth and quality. Double-layer glazing can also be combined with shading methods to control light levels. It is important to note that implementing this technique may necessitate additional structural support, and regular cleaning is essential to maintain its effectiveness [105,106]. Shading is a technique that involves the use of shade cloth, paint, or screens to reduce solar radiation and heat gain in greenhouses during hot weather. It significantly decreases cooling costs by minimizing solar radiation and heat absorption. By maintaining a consistent temperature, shading contributes to improved crop growth and quality. However, it is important to be aware that shading can reduce light levels, potentially negatively impacting plant growth. Regular maintenance is required to prevent degradation of shading materials [107–109]. The ventilation technique focuses on regulating airflow within the greenhouse to control temperature and humidity levels. This can be achieved through natural ventilation, such as vents or louvers, or mechanical ventilation, including fans or evaporative cooling systems. Ventilation reduces the need for heating and cooling, resulting in lower energy costs. It also helps maintain a consistent temperature and humidity level, which is favorable for optimal crop growth and quality. However, it is worth noting that ventilation may require additional structural support and should be properly managed to avoid increased energy consumption [110–112].

Table 1. Summary of conventional energy savings saving techniques for greenhouses.

Technique	**Description**	**Advantages**	**Disadvantages**	**Refs.**
Insulation	Adding insulating materials to reduce heat loss during cold weather.	Reduces heat loss, lowers heating costs.	- May require additional structural support. - Can limit ventilation, leading to increased humidity levels and the risk of disease.	[102–104]

Table 1. *Cont.*

Technique	**Description**	**Advantages**	**Disadvantages**	**Refs.**
Double-layer glazing	Installing two layers of glazing with air or gas between them for improved insulation.	- Reduces heat loss, lowers heating costs. - Can be combined with shading to control light levels.	- May require additional structural support. - Requires regular cleaning.	[105,106]
Shading	Adding shading materials to reduce solar radiation and heat gain during hot weather.	- Reduces solar radiation and heat gain, lowers cooling costs. - Can improve temperature consistency.	- Can reduce light levels, negatively impacting plant growth. - Requires regular maintenance to prevent shading materials from degrading.	[107–109]
Ventilation	Controlling airflow to regulate temperature and humidity.	- Reduces need for heating and cooling, lowers energy costs. - Improves temperature and humidity consistency.	- May require additional structural support. - Can increase energy consumption if not properly controlled.	[110–112]

4.2. Control Systems in Greenhouses

In the last decade, various control systems have been applied in greenhouses to maintain optimal growing environmental conditions while improving greenhouse energy efficiency and decreasing greenhouse energy needs [91]. The main energy management systems used for greenhouses consider temperature, humidity, CO_2, and nutrients as control parameters when adjusting the indoor greenhouse temperature [92–94], the indoor greenhouse humidity [95], the supplemental lighting intensity [96], the optimal CO_2 levels inside the greenhouse [113], and the control of the amount and type of nutrients that plants receive [114].

In Table 2, a summary of the control systems with their advantages and disadvantages is presented. Specifically, the temperature control system in greenhouses utilizes heaters, fans, and vents to monitor and regulate the internal temperature. Its purpose is to maintain optimal growing conditions for plants and protect them from temperature extremes. However, achieving a proper balance between temperature and humidity control can pose difficulties [115,116]. Greenhouse humidity control involves the use of humidifiers, dehumidifiers, and ventilation systems to monitor and adjust the humidity levels. Its main objectives are to prevent damage caused by excessive humidity and to ensure plants do not suffer from water stress due to low humidity. Nonetheless, this system can lead to increased energy costs and requires continuous monitoring to avoid over-humidification or under-humidification [109,117]. The lighting control system manages the amount and duration of light received by plants through artificial lighting, shade cloths, and curtains. Its benefits include providing consistent light levels for optimal plant growth and extending the growing season to enhance crop yield. However, operating this system requires electricity, which can result in higher energy costs. Additionally, the production of heat from the lighting system can raise greenhouse temperatures [118,119]. CO_2 control systems in greenhouses maintain optimal CO_2 levels using generators and sensors. They aim to promote plant growth and increase crop yield while improving water use efficiency. However, operating such a system requires electricity, potentially leading to increased energy costs. It can also contribute to elevated temperatures inside the greenhouse. Proper monitoring is crucial to ensure safety, as incorrect operation may pose risks and generate toxic byproducts [120,121]. Nutrient control systems regulate the quantity and type of nutrients provided to plants through fertilizers and monitoring systems. Their goals are to enhance plant growth and increase crop yield while minimizing waste by delivering only the necessary nutrients. However, maintaining nutrient balance requires consistent monitoring, and additional equipment is necessary to monitor and adjust nutrient levels [122,123].

Table 2. Control systems in greenhouses.

Control System	**Description**	**Advantages**	**Disadvantages**	**Refs.**
Temperature Control	Monitors and controls the temperature using heaters, fans, and vents.	- Maintains optimal growing conditions for plants. - Prevents damage from temperature extremes.	- Difficult to balance temperature and humidity control.	[115,116]
Humidity Control	Monitors and controls the humidity level using humidifiers, dehumidifiers, and ventilation systems.	- Prevents damage from excessive humidity levels. - Prevents water stress in plants due to low humidity.	- Increases energy costs. - Requires constant monitoring for proper humidity control.	[109,117]
Lighting Control	Controls the amount and duration of light that plants receive using artificial lighting, shade cloths, and curtains.	- Provides consistent light levels. - Increases crop yield by extending the growing season.	- Increases energy costs due to the electricity usage. - Can produce heat, raising greenhouse temperatures.	[118,119]
CO_2 Control	Maintains optimal CO_2 levels inside the greenhouse using CO_2 generators and sensors.	- Increases plant growth and crop yield. - Reduces water use by improving plant water use efficiency.	- Increases energy costs due to the electricity usage. - Can produce heat, raising greenhouse temperatures. - Requires careful monitoring to ensure safety. - Improper operation may produce toxic byproducts.	[120,121]
Nutrient Control	Controls the amount and type of nutrients that plants receive using fertilizers and nutrient monitoring systems.	- Increases plant growth and crop yield. - Reduces waste by providing only the necessary nutrients.	- Requires constant monitoring to prevent nutrient imbalances. - Requires additional equipment to monitor and adjust nutrient levels.	[122,123]

According to the literature, most of the studies on control strategies for greenhouses are based on PIDs, fuzzy, artificial neural networks, and other intelligent algorithms or a combination of these. The development of IoT-based algorithms will generate significant upgrades to greenhouse energy management [124]. Intelligent algorithms have the potential to revolutionize greenhouse farming by enabling more efficient and sustainable practices, as it enables precise control and monitoring of the environment, leading to increased productivity and improved resource utilization [125]. Sensors can be utilized to observe the levels of temperature, humidity, and CO_2 in greenhouses, and send the data to an intelligent system which can then adjust heating, cooling, and ventilation systems to uphold the desired conditions and guarantee that plants are exposed to optimal growing conditions [126]. Additionally, these advanced programs can support farmers in making the most of their water resources by scrutinizing data on soil moisture levels, weather conditions, and plant development trends. The system can then modify irrigation schedules and amounts appropriately, lowering waste and guaranteeing that plants obtain proper amounts of water [127]. Moreover, intelligent algorithms have been used to examine images of plants to pinpoint diseases, pests, and other issues before they generate losses for the farmers [128]. Such intelligent insights allow farmers to take proactive measures to shield their crops, for example, applying pesticides or discarding infected plants. Furthermore, through analysis of data pertaining to elements such as weather trends, soil conditions, and plant growth rates, AI can assist farmers in predicting crop yields with great accuracy [129]. This information can be utilized to optimize planting schedules, adjust resource allocation, and prepare for harvests [130]. In recent times, mixed control systems have been investigated in the literature, such as neuro-PID, which combines artificial intelligence/machine learning with PID. Findings show that neuro-PID design systems can robustly provide control for complex and nonlinear time-varying environments, which is a significant challenge in traditional PID control systems [124]. In such a case, the combination of artificial intelligence with IoT can facilitate development of robust predictive models for nonlinear environmental variabilities, which can then be used to feed the PID controller in real-time, leading to better adaptability. The technologies for reducing unfavorable external conditions are reviewed in the next section.

5. Renewable Energy Systems and Energy Storage Systems in Agricultural Greenhouses

5.1. Renewable Energy Systems in Agricultural Greenhouses

Recent scholarly studies have advocated for the adoption of renewable energy technologies to meet cooling and heating needs in greenhouses [131]. Critical emphasis was placed on solar thermal collectors, micro-turbines, geothermal heat pumps, and rooftop photovoltaic systems as enablers for the net-zero-energy buildings and the mitigation of climate change [34]. Despite the growing clean energy advocacy, current greenhouse structures are mainly powered by PV systems in place of wind turbines and geothermal energy [132,133]. The growing preference for solar energy systems has direct implications for the achievement of zero-carbon emissions.

Solar energy technologies for greenhouses can be categorized into two: first are greenhouses integrated with PV modules for electricity generation in order to supply both heat and electricity; and second are greenhouses integrated with solar thermal collectors in order to convert the solar energy into heat, which can then be consumed in greenhouses. The typical systems of PV-greenhouses for electricity generation are grid-connected and off-grid systems. In grid-connected systems, the greenhouse directly consumes the produced power from the PV modules while the excess power is injected into the grid [134]. In off-grid systems, the greenhouse's electrical energy requirements are fully covered by the system and since the energy is produced during the day, these systems include a fossil-fueled generator and/or a battery bank [135,136]. Few studies have investigated different types of PV units installed on a greenhouse roof by examining energy production and the effect of shading on plant growth [137–140]. The obtained results indicate that: (i) the placement method (e.g., straight-line or chessboard) [141] is important to avoid undesirable shading impacts to the growth of crops and provide sufficient light transmittance for their photosynthesis; and (ii) the choice of PV type is crucial since there are units such as the semi-transparent modules [142,143] that can mitigate the negative effect of shading, and other units such as bifacial modules [144] that can increase electricity generation due to the absorption of the ground-reflected radiations. In addition, the use of solar thermal collectors is a promising alternative and sustainable solution to meet the heating requirements of greenhouses [145], able to cover up to 60% of the annual heating demand [146]. Today, the ubiquity of solar-harvesting systems in greenhouses is due to the availability of low-cost PVs (solar collectors) made of mono- and polycrystalline silicon, organic solar cells, and thin-film solar cell technology [2].

On the contrary, the generation of renewable energy from wind turbines and geothermal sources is untenable, especially for regions without geothermal resources, such as Greece and Turkey [147]. The preliminary studies conducted in these countries revealed that small geothermal wells with an installed heating capacity of 2.3 MWh could sustain large greenhouses (up to 10,000 m^2) [147]. On the downside, the power-generating capacity of geothermal wells was variable and widely dependent on the geography of specific areas; this explained why the "use of geothermal energy is negligible in many parts of the globe" [34]. In addition, the geothermal energy resources were concentrated in volcanic areas [148].

Beyond the limited availability of geothermal resources, the cost of geothermal extraction was prohibitive; nearly EUR 6 million was required to drill one geothermal well with a depth of 1700 m [148]. The initial investment costs for geothermal energy [8] were considerably higher relative to those who estimated the cost to be about EUR 200/m^2 (threefold higher compared to solar energy) [9]. From an economic perspective, the geothermal costs were prohibitive, given that farmers spend about EUR 450/ha on greenhouse heating [33].

Additionally, the comparable cost of greenhouse structures with a capacity of 20 MW was USD 30 million [8]. Since the cost was a critical barrier to the exploitation of geothermal energy, it was practical for large greenhouse projects covering at least 20 hectares for better economies of scale. Such requirements diminish the suitability of geothermal in smallholder farms, except for farming cooperatives. Even in cases when geothermal resources are close to the surface, the practicality of relying on geothermal energy resources remains limited owing to the high concentrations of boron. Excessive levels of boron are harmful to plant life [148]. The distinct advantages of PV systems over geothermal resources indicate that the attainment of zero-energy emissions and near-zero energy requirements would be difficult to achieve in the short term. In turn, this would translate to higher carbon emissions from greenhouses and conventional agriculture.

The geothermal energy phenomenon raises fundamental questions on the practicality of achieving zero energy requirements and zero energy emissions through better renewable resource management. The narratives advanced by [147] concerning the merits and shortcomings of geothermal energy vis-à-vis photovoltaic systems, show that the former was suitable for largescale farming in volcanic areas. Even though the cost was cited as a critical barrier, geothermal resource accessibility was the primary constraint. The drawbacks should motivate stakeholders to develop affordable and scalable strategies for geothermal energy recovery and harness geothermal environments for renewable.

On the downside, geothermal energy was considered practical in the long term rather than the short term. The generation of geothermal energy to power greenhouse structures in Greece was a case in point [147]. The researcher's criticism of the suitability of geothermal energy in greenhouse structures was corroborated by [34], in which the authors noted that geothermal energy resources in most countries were negligible. Despite the concerns made concerning the availability of geothermal resources, an integrated approach that encompassed small wind turbines, biomass boilers, geothermal heat pumps, and solar thermal collectors was advocated in [149]. The integrated approach advocated by [134] was also corroborated by [147], based on a successful case study of greenhouses heated with low-enthalpy geothermal water and solar-mediated vertical ground source heat pumps in Argentina and Turkey.

Similar to geothermal energy, the installation of micro-wind turbines in greenhouses is viewed as a challenge. Significant research on micro-wind turbines focused on their utility in decentralized smart grids and direct air capture rather than smart greenhouse structures [150,151]. Despite limited real-world data, researchers have advocated for the installation of wind turbines to address cooling and heating needs in greenhouses [60,152]. In theory, wind energy might be a more practical alternative compared to geothermal energy because of the low investment costs, even distribution across the nation, and ideal weather [9,19,34]. However, the contribution of wind energy systems towards zero energy requirements in greenhouses remains marginal. Further research was important to determine the suitability of wind energy compared to solar and geothermal energy. In summary, findings showed that PV energy resources were best suited for greenhouses compared to geothermal and wind energy, except for areas with active volcanic phenomena such as Argentina, Turkey, and Greece.

PV panels can be used in greenhouses alongside solar thermal collectors, geothermal heat pumps, biomass boilers, and/or small wind turbines, depending on the local conditions and the potential of the local renewable energies. Similarly, hybrid photovoltaic/thermal systems can be used for an effective contribution to electricity and heat demand. However, transparent/thin-film PV systems have a lower thermal conversion efficiency compared to opaque PV systems [153].

Main findings from various studies on agricultural greenhouses integrated with different types of renewable energy technologies are presented in Table 3. Specifically, the study in Arizona, USA, focused on solar-powered greenhouses equipped with semitransparent organic solar cells. The system successfully generated sufficient thermal energy to sustain year-round operation, with the potential to contribute excess energy to the grid network [154]. In Agadir, Morocco, researchers investigated a solar-powered greenhouse system utilizing flexible photovoltaic modules. The arrangement of PV modules in a checkboard pattern did not have a noticeable shading effect, ensuring that the yield of products inside the greenhouse was not negatively impacted [155]. Researchers in Kunming, China, studied solar-powered greenhouses equipped with semitransparent mono-Si cells. The combination of semi-transparent PV modules and a polyethylene cover reduced solar radiation by 35–40% on clear days, without creating significant shading [140]. In Viterbo, Italy, solar-powered greenhouses with flexible and semitransparent modules, along with mono Si cells, were examined. The greenhouse's curvilinear shape resulted in uniform shading below 40% throughout the year [138]. A study in Matsue, Japan, focused on solar-powered greenhouses using semi-transparent, Poly-Si spherical microcells. These PV modules were suitable for installation on both the sidewalls and roof, capturing ground-reflected radiation and maintaining a low module conversion efficiency variation [139]. Researchers in Bari, Italy, explored a solar photovoltaic (PV) hydrogen system integrated with a low enthalpy geothermal heat pump for greenhouse heating. The system, incorporating PV panels, hydrogen storage, fuel cells, and geothermal heat pump, demonstrated efficient and sustainable operation [156]. In Souss-Massa, Morocco, a study investigated a greenhouse heating system utilizing passive solar energy and rock-bed thermal energy storage. The combined system effectively improved winter temperatures, reduced air relative humidity, and significantly increased tomato yield [157]. Researchers in the Sanbei area of China examined a wind-powered underground heating system for greenhouses. The technology demonstrated significant potential in reducing coal consumption and CO_2 emissions, providing a substantial amount of thermal energy for greenhouse operations [158]. The study in Izmir, Turkey, focused on a hybrid heating system for greenhouses, combining solar and biomass energy sources. The hybrid configuration showed potential in enhancing greenhouse performance, sustainability, and crop production, meeting a significant portion of nocturnal heating demands [159]. In Chalkidiki, Greece, researchers investigated the application of biomass combustion units in greenhouses. The study revealed that implementing biomass combustion units, with capacities ranging from 900 kW to 2 MW, could be a profitable investment, with a relatively short payback period for the larger unit [160].

Table 3. Agricultural greenhouses with different types of renewable energy technologies.

Study Area	**Type of Facility**	**Main Findings**	**Refs.**
Arizona North Carolina, US	Solar-powered Semitransparent organic solar cells	- Generates enough thermal energy for year-round operation; - Excess energy can be contributed to the grid network;	[154]
Agadir, Morocco	Solar-powered Flexible PV modules	- Checkboard pattern of PV modules does not affect product yield inside the greenhouse.	[155]
Kunming, China	Solar-powered Semitransparent mono-Si cells	- Combination of semi-transparent PV modules and polyethylene cover reduces solar radiation by 35–40% on clear days, but no significant shading effect.	[140]
Viterbo, Italy	Solar-powered Flexible and semitransparent modules, mono Si cells	- Curvilinear greenhouse shape maintains shading percentage below 40% throughout the year.	[138]
Matsue, Japan	Solar-powered Semi-transparent, Poly-Si spherical microcells	- These PV modules are suitable for installation on sidewalls and roofs, since they have a low module conversion efficiency variation of only 0.2% over a wide range of incident radiation angles.; - Higher yield ratio due to capturing ground-reflected radiation; - Low module conversion efficiency variation over a wide range of radiation angles;	[139]

Table 3. *Cont.*

Study Area	Type of Facility	Main Findings	Refs.
Bari, Italy	Solar photovoltaic hydrogen system powering a low enthalpy geothermal heat pump	- Alkaline barometric water electrolyzer shows promise in greenhouse-integrated heating system; - Efficiency depends on location, climate, and energy demand; - Includes photovoltaic panels, hydrogen storage, fuel cells, and geothermal heat pump;	[156]
Souss-Massa, Morocco	Passive solar and rock-bed thermal energy storage	- Combined heating system improves winter temperatures in the greenhouse (3–5 °C on sunny days and 2–3 °C on cloudy/rainy days); - Reduces air relative humidity and benefits plant growth and health; - Significant increase in tomato yield (49% increase in tomato yield); - Cost-effective and efficient solution for covering heating requirements.	[157]
Sanbei area, China	Wind powered underground heating system	- Reduces coal consumption and CO_2 emissions significantly; - Provides a substantial amount of thermal energy for the greenhouse (130.27 GJ/quarter); - Effective reduction coal consumption of 8.10 ton/quarter; - Effective at reducing greenhouse gas emissions of 21,222 kg/quarter;	[158]
Izmir, Turkey	Solar and biomass energy system	- Hybrid heating system improves greenhouse performance and sustainability; - Contributes to high-quality crop production; - The hybrid configuration provided 88.87% of the total nocturnal heating demands; - The solar and biomass fractions of 30.32% and 58.55%, respectively, indicate that both renewable energy sources are contributing to the system's performance;	[159]
Chalkidiki, Greece	Biomass-powered	- Biomass combustion units applied to greenhouses are a profitable investment; - A subsidy can make the investment even more attractive; - The payback period of 4 years for the 2 MW biomass combustion unit is particularly noteworthy, as it suggests that the initial investment can be recouped relatively quickly;	[160]

5.2. Energy Storage Systems in Agricultural Greenhouses

Energy storage systems fulfil multiple functions in agricultural greenhouses and structures, including providing voltage support for weak grids, renewable energy storage during periods of intermittent supply and demand-side flexibility/stabilization [161–163]. The Building Integrated Photovoltaics (BIPV) systems for general grids, solar batteries, and Trombe walls are a case in point [164]. Recent studies have also documented commendable progress in the development of affordable energy storage systems for greenhouses [33]. However, there is minimal research specific to smallholder farms which are integral to global food security.

The commercially available energy storage systems in greenhouses are primarily for thermal/solar energy and heat storage [165,166]. However, widespread adoption has been constrained by technical limitations and the link between thermal energy storage capacity and the reliability of sustainable solar heating systems [33]. Subsequently, advanced renewable energy systems are required to address the variability of solar energy and non-programmable energy production profiles [167].

Various thermal energy storage technologies have been developed for greenhouse heating and cooling applications, including (i) underground thermal energy storage (UTES), which is most used for seasonal storage, (ii) phase change materials (PCM), and (iii) the water tank which are both utilized for short term storage to address daily demands and peak loads [82].

UTES systems use underground soil and/or rocks or underground water as the heat storage material to store the thermal energy. UTES systems that use natural groundwater basins are referred to as aquifer thermal energy storage (ATES). ATES operates with extraction and injection wells to circulate groundwater [168]. UTES systems that use the subsoil for thermal energy storage are referred to as Borehole thermal energy storage (BTES). In BTES systems, vertical or horizontal tubes are inserted to the ground and are used as heat exchangers within the ground [169]. An alternative cost-effective heat storage material is the rock bed (pebble, gravel, and bricks) which is placed underground or outside the greenhouse. In these systems, the excess thermal energy from the greenhouse is stored in the large rock bed, and, thereafter, it is circulated with a heat transfer fluid (water or air) to exchange heat [137]. In [170], a novel method for thermal energy storage that relies on the thermal inertia of a rock bed, in comparison to the traditional evacuated tube collector. The study demonstrated that a greenhouse equipped with this thermal energy storage system was able to store and retain 6.2% to 10.6% of the solar energy. These findings highlight the effectiveness of the rock bed-based storage system in capturing and utilizing solar energy.

Several UTES systems have been installed for the heating and cooling of greenhouses in the world [171]. In [169], the ATES systems installed in the Netherlands demonstrated an increase in the yield per m^2 of about 10% for tomatoes and cucumbers and energy savings by 30%. ATES systems for greenhouses compared to conventional heating systems in the Mediterranean climate have demonstrated major benefits such as an increased yield of approximately 20–40% for tomatoes and about 30% energy savings [171]. Such systems were also utilized not only for heating, as the conventional heating systems, but also for cooling the greenhouse [172]. The concept of BTES systems has also been used and studied for several greenhouses [173–175]. A BTES system was installed for cooling a closed greenhouse in Norway and operations were studied for one year. The results showed that BTES can maintain the greenhouse temperature below the maximum limits, providing about 90% savings in fossil fuels [169]. Another BTES system was installed for heating and cooling a greenhouse in China, providing optimal conditions for the plants while reducing greenhouse energy costs [168]. In addition, several greenhouses using rock-bed as thermal storage to satisfy the greenhouses' heating needs, have been developed and studied [82]. According to the literature, most rock bed heat storage systems can meet about 20–70% of the annual heating needs of a greenhouse while maintaining the temperature inside the greenhouse from 4 °C to 10 °C higher than the minimum ambient air temperature [176–182].

Plastic water tanks and/or ground tubes can be used and placed as water-heat-storage systems for greenhouses. These systems serve as solar collectors where they store heat during the day by absorbing the solar radiation and return the heat to the greenhouse during the night when the air temperature is lower than the temperature of the stored water. In these systems, the water tanks can be placed inside the greenhouse, usually on the north side of the greenhouse, or outside the greenhouse where they are buried underground. Several water storage systems have been installed for greenhouses, achieving efficient thermal performance [82]. Specifically, these systems maintain the air temperature inside the greenhouse at from about 2 °C to 11 °C higher than outdoor conditions during winter nights [82,86].

The use of PCM applications in greenhouses is an efficient way of storing thermal energy since latent heat storage can offer higher energy densities than sensible thermal energy storage systems [162]. PCMs store heat as they change their phases from solid to liquid by absorbing large amounts of heat in the form of latent heat of fusion at a constant temperature. Thereafter, the heat is released by the circulating fluid (air or water) which causes the phase change of the storage unit to solidify. PCMs can be classified into three categories: organic, inorganic, and eutectic compounds. There are several variants of PCMs in each category where their freezing and melting temperature range between 0 °C and 120 °C [183]. The most used PCMs for thermal energy storage in greenhouses are $CaCl_2 \cdot 6H_2O$, $Na_2SO4 \cdot 10H_2O$, polyethylene glycol, and paraffin [24]. According to the literature, the most commonly used PCM as a latent heat storage material for short-term heat storage in greenhouses is $CaCl_2 \cdot 6H_2O$ which can satisfy 30–75% of the annual heating needs [81]. In [184], a thermal storage system based on PCM was studied to heat a 500 m^2 greenhouse for roses, situated in Nice, France. The energy savings of the system was 51%. In a similar system, 2970 kg of stored $CaCl_2 \cdot 6H_2O$ material was used in a 200 m^2 greenhouse for tomatoes, situated in Avignon, France. The system provided 30% energy savings [185]. In [186], the PCM application in a 180 m^2 greenhouse for strawberries at Adana, Turkey, revealed 40% energy savings. In addition, several studies showed that the use of PCM for greenhouses maintained the air temperature of greenhouses in a range of 2–12 °C higher than the outdoor conditions [187]. In [188], the PCM could maintain the temperature of a 14.8 m^2 greenhouse in Tunisia by about 5 °C higher during the night as compared to the controlled greenhouse. In [185], the system maintained the indoor air temperature of a greenhouse (176 m^2) for lettuce and tomatoes in Montfavet, France by about 7–8 °C higher as compared to outside air at night. Some representative PCM applications in agriculture greenhouses are presented in Table 4.

Table 4. PCM applications.

Location	Type of Facility	PCM	Area (m^2)	Findings	Refs.
Isfahan, Iran	PCM integrated with heater	Hydrated salt of sodium acetate	1320	- PCM increased greenhouse temperature by 3 °C - Exhaust gas temperature reduced by 24 °C - Gas consumption reduced by 48% - Payback period of 4 months	[189]
Borj Cedria, Tunisia	PCM with solar thermal collector	Capsule AC27	14.8	- PCM stored 56% of the diurnal excess heat inside the greenhouse - The stored heat represents 30% of the total nocturnal heating requirement	[190]
Beijing, China	PCM wallboard	Paraffin wax	400	- Wall surface temperature increased by 2.2–3.4 °C - Indoor temperature increased by 0.8–1.4 °C	[166]
Marrakesh, Morocco	PCM wallboard	Calcium chloride hexahydrate	24	- Indoor temperature increased by 6–12 °C	[187]
Adana, Turkey	PCM storage container	Oleic Acid (OA) and Capric Acid (CA)	500	2.4 °C higher temperature	[191]
Cabrils, Barcelona, Spain	PCM storage container	Rubitherm RT18HC, RT15HC, RT12HC	230	Optimum melting temperature 15 °C	[192]

In the past few years, several other energy storage systems have also been developed for greenhouses, including ternary transition metal chalcogenides [193], graphene [194], and lignin–sodium ion batteries [195]. In other cases, heat and energy storage has been attained with active–passive ventilation walls (APVWs) [166]. The disadvantage is that the choice of a heat/energy storage material involves a trade-off between cost and material performance.

According to [166], the APVWs could optimize energy use in greenhouses during off-seasons. However, achieving the optimal balance and significant energy saving was problematic due to the influence of confounding factors including local meteorological conditions, material performance, and type of greenhouse structure. In real-world settings, optimizing the operational parameters is challenging because phase change materials, ternary transition metal chalcogenides, and batteries, among other energy storage/heat storage materials, have unique bond thermal conductivity, electrical resistance, capacitance, emissivity, thermal efficiency radiation, and output temperature [165]. Additionally, there is a trade-off between material performance and cost.

In theory, PCMs were ideal compared to other energy storage systems given that the materials store large amounts of energy as latent heat [164]. However, the storage capacity is contingent on the material characteristics. PCMs are made of polymeric compounds such as poly(2-(2-(octadecyloxy) ethoxy) ethyl methacrylate) and poly (Octadecyl methacrylate) (PSMA) [196]; these polymers have distinct thermal and optical properties. For example, a noticeable decrease in optical transmittance and a concomitant surge in latent heat storage was observed with the modification of the polymer and the inclusion of non-crystallizable spaces [196]. In addition, the super-cooling, low thermal conductivity, phase segregation, cost, and sensitivity towards the moisture of PCMs were significant barriers to their use. Furthermore, there is a lack of information in the literature regarding the cost maintenance of PCMs in large-scale greenhouse production [24].

5.3. Economic and Environmental Impact

Energy for greenhouse structures is often derived from non-renewable sources with a high carbon footprint [14]. Coal is a widely preferred source of greenhouse energy owing to its high energy density relative to liquid petroleum gas and liquid natural gas. The shift towards coal generated mixed benefits. Some of the advantages of coal include its affordable and readily available nature [14]. Cost is a critical consideration in smart/intelligent agriculture, given that USD 6180 is required to construct a greenhouse structure covering two hectares [7]. On the contrary, coal is a leading atmospheric pollutant and has a high carbon footprint relative to hydropower or liquid natural gas. Complete coal combustion emits 204 pounds of CO_2/million Btu [197]. In contrast, LNG emits about 116 pounds of CO_2/million Btu [197]. From an ecological perspective, the use of natural gas was a sustainable option since low carbon emissions are critical to the realization of net-zero emissions.

The low carbon footprint of natural gas incentivized Dutch greenhouse growers to invest in the source of energy instead of other forms of renewable energy [9]. The only drawback to natural gas was the volatility in the international markets; a factor that impacts the profitability of greenhouse agriculture. The higher carbon footprint for coal used in greenhouse heating underscores the need for renewable energy such as geothermal energy, biofuel, and solar to power sustainable greenhouse structures [197]. A comparative analysis of the investment costs, natural gas savings, electricity requirements, and emission savings for solar thermal and certain biofuels shows that geothermal renewable energy offers higher benefits relative to solar thermal energy in terms of emission savings. However, these benefits are offset by the higher initial investment costs (Table 5). Industry data suggest that higher investment cost-related barriers have a marginal effect in light of the high return on investment (ROI) and net present value (NPV) for solar renewable energy; this was demonstrated in Chinese greenhouses with large energy production capacities (8–20 MWs) [8]. The solar power energy output demonstrates the practicality of net-zero energy requirements and energy-sufficient PV-powered greenhouses.

Table 5. Investment costs, natural gas savings, electricity requirements, and emission savings for solar thermal, biofuel, and geothermal energy [9].

Alternatives Attributes	Solar Thermal Energy	Bio-Fuel Energy	Geothermal Energy
Beginning investment (EUR/m^2)	65–80	20–25	80–200
Amount of natural gas saved [m^3 a.e./(m^2jr)]	10–11	8–13	21–120
Additional electricity required (kWh/m^2)	25–27	2–3	7–11
Emission savings (gr/m^2)	6–7	22–31	32–66

The benefits of renewable energy, such as emission savings [9], outweigh the investment costs; this view is reinforced by long-term economic analyses of solar-powered greenhouse structures in China [8]. On average, the net present value for greenhouses with 20 MW-capacity PV systems was USD 30 million. Despite the tangible economic benefits, the pace of renewable energy adoption in greenhouses is low. For example, farmers in Crete, Greece had explored the use of olive kernel wood (renewable biomass) to heat greenhouse structures [147]. Such practices are only practical in regions with adequate olive kernel wood. Even for greenhouses with a high PV energy capacity, the variability of solar energy and non-programmable energy production profiles remain a critical disadvantage [167]. The unique costs–benefits of different geothermal systems show that customized solutions for greenhouses are necessary.

The intermittent energy production by renewable energy technologies, makes the integration of TES necessary in order to ensure the shifting of energy from periods of low demand when energy is stored, to periods of high demand where energy from the storage is supplied to the greenhouse. The disadvantage is that the large-scale integration of energy storage/heat storage systems in greenhouses powered with renewable energy remains a challenge considering the high initial investment costs. Therefore, several researchers have conducted economic and environmental analyses to understand the effects of TES systems on renewable greenhouses. Economic analysis of TES systems in greenhouses involves calculating the cost savings achieved by using these systems compared to traditional heating and cooling methods. This analysis also considers the initial investment required for installing TES systems, the operational costs, and the payback period. Environmental analysis of TES systems in greenhouses involves evaluating the reduction in greenhouse gas emissions achieved by using these systems. This analysis also studies the energy efficiency of TES systems, the environmental impact of producing the necessary materials, and the end-of-life disposal of such systems.

In [198], the authors evaluated the economic performance of a pilot greenhouse that was coupled with a Latent Thermal Energy Storage (LTES) unit and powered by PV panels. The study compared the economic outcomes of this system with a diesel system. The Levelized Cost of Energy (LCOE) is a measure of the total cost of producing electricity from a particular energy source over its lifetime, including the initial capital costs, operating costs, and maintenance costs. The LCOE is expressed in units of dollars per kilowatt-hour (USD/kWh) or per gigajoule (USD/GJ) and is utilized to compare the costs of different energy sources. According to the study, the LCOE value of the PV system was calculated as 0.068 USD/kWh, while the LCOE value of the diesel system was 0.230 USD/kWh. The implication is that the proposed system was significantly cheaper than the diesel system, with a cost reduction of over 70%. These results suggest that coupling a greenhouse with an LTES unit and powering it with PV panels can lead to significant economic benefits compared to using a diesel system which is the most traditional solution for greenhouse agriculture. An explanation for the observation is that the use of RES such as PV panels can lead to lower operational and maintenance costs, as well as a reduced dependence on fossil fuels. Furthermore, the use of an LTES unit can facilitate the storage of excess energy produced during periods of high solar irradiance, which can be utilized later when the energy demand is high, leading to further cost savings.

An economic and environmental performance evaluation of a greenhouse powered by solar collectors and assisted with a Borehole Thermal Energy Storage (BTES), was conducted in [146]. The study compared the LCOE and CO_2 emissions of this system with natural gas boilers. According to the study the LCOE of the proposed system was found to be 34 and 31.3 USD/GJ for high- and low-temperature systems, respectively. The installation cost of solar collectors was estimated as USD 500/m^2, and the drilling and installation cost of the BTES was estimated as USD 125/m^2. These results suggest that the proposed system can be competitive with natural gas boilers in terms of energy cost. Moreover, the proposed system was identified to generate environmental benefits such as mitigating CO_2 emissions by 220 tons/0.4 ha per year compared to natural gas boilers.

The study estimated a payback period of 7 years if a 70% subsidy and carbon tax of USD 200/ton CO_2 were utilized. Overall, the study suggests that coupling a greenhouse with solar collectors and BTES can result in significant economic and environmental benefits compared to using natural gas boilers.

In addition, the authors in [199], compared the use of Polypropylene Heat Exchanger (PHE) with Liquid Thermal Energy Storage (LTES) and Sensible Thermal Energy Storage (STES) for heating a tunnel greenhouse. The study established that the cost of the PHE was cheaper when used with LTES than STES. The use of LTES led to significant cost savings compared to STES, as it allowed more efficient heat transfer and storage, leading to reduced operational and maintenance costs. The study concluded that the use of LTES with PHE was an economically viable option for heating tunnel greenhouses, especially in regions with high solar irradiation. The use of LTES can lead to significant cost savings and environmental benefits compared to conventional heating methods that use fossil fuels. Therefore, the use of LTES with PHE can be a cost-effective and sustainable mechanism for heating tunnel greenhouses.

The evaluation of the economic feasibility of integrating PCM for heating in greenhouses has also been conducted. In [192], the results showed that integrating PCM for root area heating was not economically feasible, especially when biomass heating was considered. The cost of PCM accounted for 47% of the total annual investment which made the system economically unviable. Although the use of PCM resulted in a saving of 20–30 kg of CO_2 emissions per hectare and night, the cost of PCM was still too high. The study concluded that for PCM integration to become economically feasible, there is need for a significant reduction in the cost of PCM. However, it is noteworthy that this study focused only on the economic feasibility of using PCM for root area heating in greenhouses, and did not consider other potential benefits such as improved plant growth or energy savings.

In [200], the economic feasibility of using solar air collectors with paraffin wax as PCM for heating a 180 m^2 greenhouse was evaluated. The study established that the proposed system was economically viable, achieving a net present value of USD 102,462.21 after 15 years of operation, with a payback period of around 8 years. The use of solar air collectors with paraffin wax as PCM led to significant cost savings relative to conventional heating methods. The study concluded that the proposed system was a cost-effective solution for heating greenhouses, especially in regions with high solar irradiation. The use of solar energy can reduce operational and maintenance costs, as well as lower the dependence on fossil fuels, resulting in reduced CO_2 emissions. Overall, the study suggests that the use of solar air collectors with paraffin wax as PCM can be an economically viable option for heating greenhouses. However, further research is needed to explore the potential benefits and limitations of the proposed system in different regions and under different environmental conditions.

It is noteworthy that the environmental impact of TES systems is highly dependent on the materials used, the design, and operational practices. The choice of materials should be determined cautiously in order to minimize risks to public health and the environment. While STES may have the lowest carbon footprint due to the use of fewer chemical materials, PCMs can pose potential problems due to their toxicity, health hazards, and fire risks. For instance, paraffin wax, which is a non-renewable and non-biodegradable PCM, contains volatile compounds such as formaldehyde and vinyl chloride. Additionally, it includes toxic materials such as benzene, toluene, naphthalene, and methyl ethyl ketone, posing environmental concerns for their disposal. However, vegetable oil-based waxes are deemed more sustainable and safer. While most inorganic PCMs such as salt hydrates are safe and non-toxic, they may however cause corrosion to metal containers. As such, encapsulation of PCM can be a promising technique to reduce the risk of leakage and prevent direct contact between the active PCM substance and the environment [201]. Overall, the economic and environmental analyses of TES systems in greenhouses suggest that these systems can lead to significant cost savings and environmental benefits. However, the actual impact of

TES systems on renewable greenhouses depends on various factors such as the size of the greenhouses, the type of crops grown, the local climate, and the energy demanded.

6. Developments and Prospects

6.1. Intelligent Shading Systems

Recent research and development (R&D) projects have led to the development of novel materials for the thermal insulation of greenhouse structures, including thin-film solar concentrators/luminescent solar concentrators (LSCs). The mechanism of action of the solar concentrators is demonstrated in Figure 5. In [132], the utility of thin-film-based solar concentrators (comprising of fluorescent polymethylmethacrylate) was demonstrated for greenhouse applications. The analyses confirmed that the transparent PMMA films could be optimized to align with the spectra sensitivity of specific plants. In [202], the benefits of solar radiation manipulation on greenhouse crops were underscored and the results revealed that the PMMA-based thin-films had an electrically measured gain of 1.9.

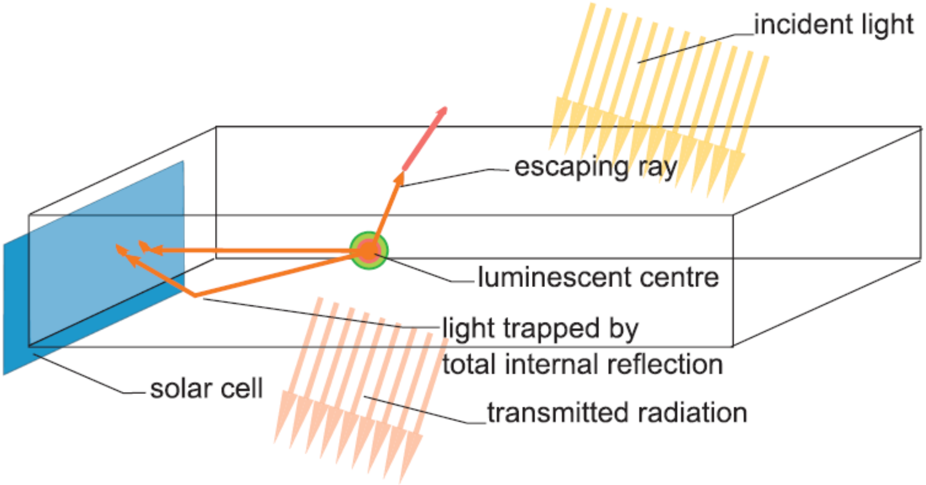

Figure 5. Mechanism of action of solar concentrators [203].

According to the study, the thin-film-based solar concentrators reduced solar energy costs. In contrast, the exploration of new materials enhanced the photon transport mechanisms of solar concentrators; the deployment of solar concentrators made of polydimethylsiloxane and lumogen F red 305 with light gains of 1.86–1.89 were a case in point [204]. The light gains reported in different materials are expected to increase over time. However, there are certain drawbacks that must be addressed moving forward. First, the average visible transmittance and power conversion efficiency (PCE) of the transparent photovoltaics (TPVs) depends on the material characteristics—crystalline silicon (c-Si) PVs have a PCE of 26%, which is two-fold higher compared to dye-sensitized solar cells [39]. In addition, a PCE of 27% was achievable using 165 µm thick Si wafers despite poor absorption of long wavelengths [205]; this was commendable considering the theoretical limit was 30%. The widely acclaimed amorphous (a-Si) PVs have a photo-conversion efficiency of about 14% [39]. The lower PCE in the latter case was associated with the impeded flow of electrons and holes and rapid degradation.

Another fundamental constraint is that luminescent species suffer from high self-absorption and low stability; this is further compounded by the limited knowledge of the variables that impact the stability of the molecules [203,206]. Even though the progress in tackling the self-absorption of LSCs with quantum dots (QDs) has been reported [203], commercial applications are limited to imaging, optoelectronics, and bio-sensing [45]. On a positive note, the growing scholarly interest in quantum dots [207–209], would catalyze the development of efficient and affordable QDs for LSCs.

Apart from quantum dots, the disadvantages associated with the existing TPVs could be resolved following the development of new materials such as hydrogenated microcrystalline silicon (μc-Si: H) [210]. In contrast to other materials, μc-Si: H-based TPVs exhibit limited IR light absorption and light-induced meta-stability; this was addressed through the deposition of a-Si: H. The deposition process translated to better conversion efficiencies and better light-trapping.

6.2. IoT Systems for the Optimization of Greenhouse Structures

The focus on the impact of IoT in precision farming technologies was informed by the ongoing transition from agriculture 3.0 to 4.0 [211], characterized by unmanned aerial vehicles for aerial monitoring and spraying next-generation wireless communication (5G and WLAN), crop surveying [212–215], sensors for assessing plant water levels, nutritional content, soil pH, humidity, and temperature among other innovations [216].

At present, the adoption of precision farming technologies has been concentrated in developed nations. As of 2019, at least eight in every ten Canadian farmers had invested in precision agriculture technologies [217]. Similarly, Japanese farmers deployed UAVs in rice farms to mitigate the costs associated with manual spraying. The patterns observed in Japan and Canada were but a microcosm of the changes in developed countries, including the US, where the deployment of IoT protocols and advanced 5G connectivity had improved precision farming. The chapter builds upon previous research on “closed-loop process control for precision farming” from the perspective of agriculture 4.0 [218] and research on the optimization of agricultural greenhouses using IoT systems [32,219].

Beyond the presentation of the state-of-the-art information, the focus on closed-loop precision farming technologies would translate to tangible cost savings and reduce the costs associated with climate change in agriculture. For example, climate-induced disruptive events would cost farmers about USD 11 billion in pesticide application [220]. Smart agriculture might facilitate offsetting greenhouse gas emissions through tailored interventions. The disadvantage is that the higher investments costs associated with agricultural infrastructure have not been addressed [21]. In the absence of economies of scale and government incentives, the adoption of IoT systems would be confined to agricultural corporations.

6.3. Sensors and AI Systems for the Optimization of Greenhouse Covers

There is growing agreement among scholars that smart greenhouses featuring IoT systems, artificial intelligence, sensors, and smart greenhouses are integral to the realization of near-zero-emissions and near-zero energy requirements [2]. The outlook is further augmented by the variable efficiency of existing materials (see Table 6), the relationship between the greenhouse heat loss and the type of covering material [33], thermal screens, the number of layers, and wind speeds. Based on this evidence, the choice of the greenhouse covering materials impacts the performance of the smart glass systems.

Table 6. Efficiency of different materials [36].

Fabrication Method	Material	Size of Individual Micro Solar Cells (μm)	Efficiency under One Sun (%)	Efficiency under Concentrated Illumination	Comments
Area-selective electrodeposition	$CuInSe_2$	200	0.26	No	Patterned SiO_2 layer on top of Mo back contact, concentration.
					By power variation of red laser.
$Cu(In, Ga)Se_2$		10–500	2	4.6% (35×)	Patterned SiO_2 layer on top of Mo back contact, concentration.
					By power variation of red laser.

Table 6. *Cont.*

Fabrication Method	Material	Size of Individual Micro Solar Cells (μm)	Efficiency under One Sun (%)	Efficiency under Concentrated Illumination	Comments
	Cu(In, Ga)Se_2	1000	7.64	No	Patterned Mo back contact, line-shaped cells.
	$CuInSe_2$	105	5.38	No	Patterned Mo back contact, line-shaped cells.
	Cu(In, Ga)Se_2	200	4.8	No	Patterned SiO_2 layer on top of Mo back contact.
LIFT	Cu(In, Ga)Se_2	50–100	0.15	0.237% (20×)	No re-patterning of the substrate. Transfer of the donor film in a spatially structured manner
Area-selective PVD	$CuInSe_2$	50–100	1.4	3.36% (20×)	Glass patterned by fs-laser, PVD Mo layer.
	$CuInSe_2$	50–100	2.9	3.06% (3×)	Glass patterned by fs-laser, PVD Mo layer.
PVD	close	60	2.9	3.1% (3×)	No re-patterning of the substrate, growth of indium islands.

Notable progress has been made in the development of smart materials for autonomous regulation of temperature, humidity, irrigation, and pesticide applications in greenhouses [133,221,222]. The development of new materials has also led to the widespread use of smart glass systems [223,224]. Beyond greenhouse micro-environments, IoT systems are critical to autonomous electrochromic control of glazed surfaces. In [66], the authors demonstrated that AI models could change the transmittance of glazed surfaces from 4 to 62% (high transmittance to low transmittance); this, in turn, helped to reduce the electric lighting load during the day.

Despite the superior performance of IoT systems, their performance was influenced by the reliability and responsiveness of temperature, light, humidity, and radiation sensors [225,226]. Despite the intricate role played by IoT systems and sensors in smart greenhouse structures, their contribution towards the realization of near-zero energy requirements has been under-emphasized; these gaps are reviewed in the subsequent sections.

6.4. Smart Glass Systems

Smart glass systems have been adopted as thin-film solar concentrators and as complementary tools that minimize the energy needs of greenhouses by altering the transmission of light to facilitate the conversion of sunlight into electricity [17]. The utility of the technology has been examined by researchers across Europe, Oceania, Asia, and North America where variable levels of success have been observed [227]. For example, researchers at the Horticulture Innovation Australia and Western Sydney University deployed smart glasses to regulate the performance of glasshouses using a Luminescent Light-Emitting Agricultural Film (LLEAF) red film. The smart glass transmits light that is optimal for vegetative growth [228]. Similar progress has been documented in the EU, where smart glass systems in greenhouses have optimized crop yields. The chemical mechanisms that govern thermochromic, electrochromic and humidity-chromic hydrogels are demonstrated in Figure 6.

Based on the considerable benefits associated with smart glass systems, the various materials have been developed to enhance commercial application, including polyampholyte hydrogel (PAH), ethylene glycol-modified pillar arene [22], hydroxyl propyl cellulose, poly (N-isopropyl acrylamide) (PNIPAM) hydrogel [223]. The application of the hydrogels is widely augmented by tunable transmission, low critical solution temperature, temperature sensitivity, optical modulation associated with energy conversion, electromechanic-chromic behavior, and electrothermal-based active control [17,38,223,229]. The data in Table 7 highlights the variations in the mechanical properties of the hydrogel-based smart glass materials, including solar energy modulation ability (ΔT_{sol}) and luminous transmittance (T_{ulum}).

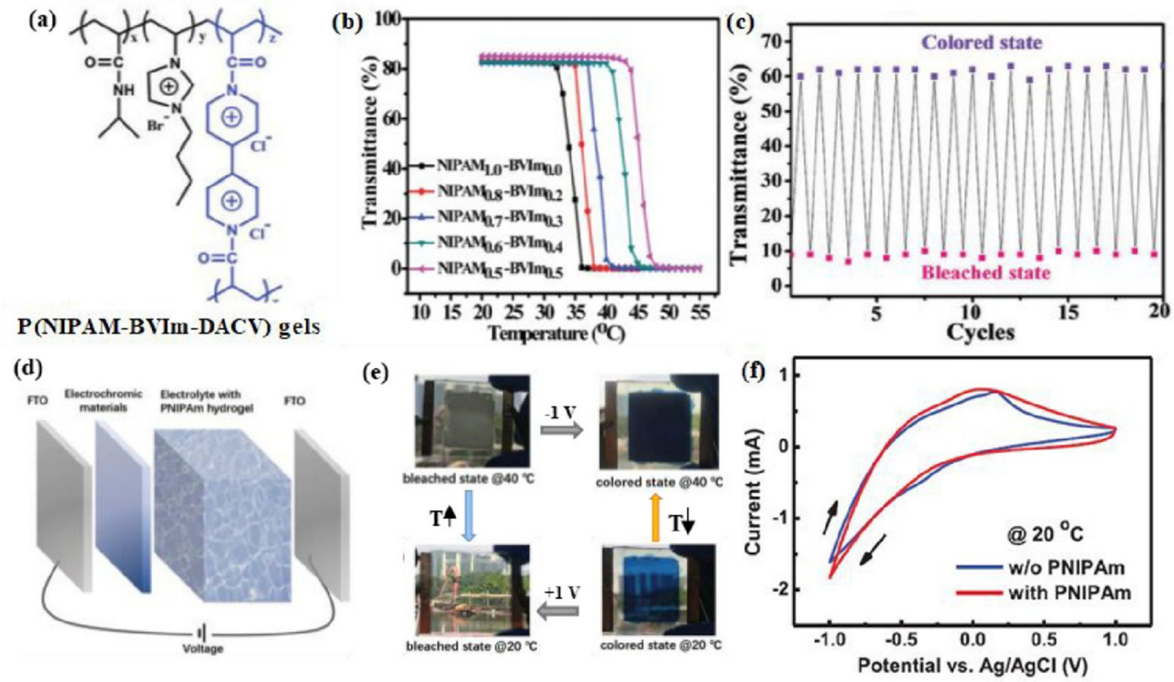

Figure 6. (**a**) Chemical structure; (**b**) temperature-dependent transmittance behavior; (**c**) Dynamic transmittance curves; (**d**) structure of electrochromic device with electrolyte containing hydrogel; (**e**) the four distinct states achieved in the electrochromic device of a poly (N-isopropyl acrylamide) (PNIPAM)-based hydrogel and (**f**) CV traces of WO_3 films [223].

Table 7. Characteristics of thermochromic, electrochromic, and humidity-chromic hydrogels for smart glass structures [38].

Classification	Material	Luminous Transmittance (T_{ulum})	Solar Energy Modulation Ability (ΔT_{sol})		Characteristics
Single function hydrogel	PNIPAm	70.7	25.5	32	Conventional thermochromic hydrogel with excellent Tulum, Dtsol, and suitable sc
		87.2	81.3	32	
	HPC	90	—	40	Hydrogel in liquid state with easy to control sc, which is applicable to a wide range of environmental conditions
		67.4	25.7	38	
		80	—	30	
	PNVCL	88	—	34	
Regular the solar	PNIPAm-	62.6	34.7	—	By enhancing the IR regulating ability, the Dtsol was increased
modulation ability	VO_2 PNIPAm/	38.4	62.7	40	
	$VO_2@SiO_2$ HPC-VO_2	67.4	25.7	38	
	CS × WO_3/	45.3	32.9	—	
	PAM-				
	PNIPAm				

Table 7. *Cont.*

Classification	Material	Luminous Transmittance (T_{ulum})	Solar Energy Modulation Ability (ΔT_{sol})		Characteristics
Mechanical	EGP5	77.2	56.1	32.1	Fabricated host–guest interaction-based hybrid hydrogels to avoid shrinkage
properties	Si-Al-	73.5	80.1	32.5	and increase the durability
	PNIPAm				
	PNIPAm/	—	—	32	
	BOMA-16				
Photo-	ATO/	62.7	35.7	—	High absorbance materials were added to increase the response speed of
thermochromic	PNIPAm HPMC/	50.5	25.5	35	thermochromic hydrogels
	AuNCs GO/	—	58.2	—	
	PNIPAm				
Adjusting colors	EGP6	64.0	66.9	—	Materials with both thermochromism and cool/warm tone switchability
					functions
Devices	PNIPAm/Ag	74.6	58.2	32	Thermochromic hydrogels were attached to a transparent electrothermal
	grid Si-Al-	73.5	80.1	32.5	heater to fabricated devices, which are able to change color by adding electricity
	PNIPAm/Ag				
	grid PGVCL/FTO	88	—	34	
	layer				
	HPC/Si solar cell	95.0	—	40	Material that achieves both the energy (electricity) conservation and generation functionality

The observed features of hydrogel-based smart glass materials are important to facilitate energy expenditure regulation within greenhouses. However, there is also further room for enhancement through carbon sequestration from the atmosphere.

Heating, ventilation, and air conditioning (HVAC) systems play a vital role in maintaining optimal conditions within greenhouses. In recent years, there have been advancements in greenhouse HVAC systems, including the integration of innovative technologies.

Variable refrigerant flow (VRF) systems are advanced HVAC solutions that use refrigerant as a heat transfer medium to provide both heating and cooling to different zones within a building. These systems are highly efficient and offer several benefits, including individualized temperature control, simultaneous heating and cooling in different areas, and zoning capabilities [230]. With VRF systems, each indoor unit can operate independently, allowing occupants to set their desired temperatures for their specific zones. This individualized control helps to optimize comfort levels and can lead to energy savings by avoiding the need to condition the entire building uniformly [231]. Moreover, VRF systems can provide heating and cooling simultaneously in different areas of the building. For example, while one zone requires cooling, another zone can be in heating mode, ensuring thermal comfort across the building without the need for separate HVAC systems [232].

Geothermal heat pumps utilize the stable temperature of the earth to provide heating, cooling, and hot water. During the heating mode, geothermal heat pumps extract heat from the relatively warmer earth and transfer it into the building. Conversely, during the cooling mode, they remove heat from the building and discharge it into the cooler earth. This heat exchange process takes advantage of the earth's constant temperature, which remains relatively stable throughout the year, regardless of the external weather conditions [233]. The installation of geothermal heat pumps can be tailored to suit the available space and requirements of the building. They can be installed vertically in wells, known as borehole systems, which require less horizontal space but go deeper into the ground. Alternatively, they can be installed horizontally in trenches, known as ground loop systems, which cover a larger surface area but do not require deep drilling [234,235].

Demand-controlled ventilation (DCV) systems are an essential component of modern HVAC design that adjusts the ventilation rates in buildings based on occupancy and indoor air quality measurements. These systems utilize sensors to monitor either carbon dioxide (CO_2) levels or occupancy, enabling them to modulate the amount of outside air brought into the building [236]. This dynamic adjustment ensures optimal indoor air quality while minimizing energy consumption, as the system responds to real-time conditions by increasing or decreasing the ventilation rates accordingly. By implementing DCV systems, buildings can achieve energy efficiency, maintain a healthy indoor environment, and enhance occupant comfort by providing the right amount of fresh air when needed [237].

Energy recovery ventilation (ERV) systems play a crucial role in HVAC design by capturing and transferring heat or coolness from exhaust air to incoming fresh air. This heat exchange process effectively pre-conditions the supply air, resulting in reduced energy requirements for heating or cooling [238]. Furthermore, ERV systems enhance energy efficiency while ensuring indoor air quality by effectively removing contaminants from the incoming air [239].

Smart thermostats and building automation systems have transformed HVAC control through the integration of advanced sensors, algorithms, and connectivity. These innovative systems are designed to optimize energy management and enhance user comfort in buildings [240]. Smart thermostats utilize sensors to learn user preferences and dynamically adjust temperature settings based on occupancy patterns. By analyzing data and patterns, these thermostats proactively optimize heating and cooling to provide comfort while minimizing energy waste. Additionally, smart thermostats offer remote control functionality through mobile applications, enabling users to adjust temperature settings and monitor energy consumption from anywhere [241]. This remote accessibility adds convenience and flexibility while promoting energy savings. Building automation systems take HVAC control to a higher level by integrating it with other building systems, such as lighting and security. Through a centralized platform, facility managers can efficiently manage and monitor multiple systems. This integration allows for co-ordinated scheduling and enhanced control, leading to improved energy efficiency and overall building performance. Moreover, building automation systems leverage data analytics to provide valuable insights for energy management. By analyzing data from various systems, these systems can identify patterns, anomalies, and opportunities for energy optimization. This data-driven approach empowers informed decision-making and further enhances energy efficiency, resulting in reduced operational costs [242,243].

Hybrid HVAC systems are designed to achieve maximum efficiency and comfort by integrating multiple HVAC technologies. These systems combine different components, such as a heat pump and a gas furnace, to utilize the most efficient heat source depending on outdoor temperatures and energy prices. The key advantage of hybrid HVAC systems lies in their ability to adapt to changing conditions and optimize energy usage accordingly. For instance, during moderate weather conditions, the heat pump can efficiently provide heating or cooling by transferring heat between the indoor and outdoor environments [244]. However, in extremely cold weather, when the heat pump's efficiency decreases, the gas furnace can take over to meet the heating requirements. This dynamic switching between heat sources ensures optimal energy utilization and cost savings [245]. By continuously monitoring outdoor temperatures and energy prices, hybrid HVAC systems can intelligently determine the most efficient mode of operation at any given time. Through sophisticated control algorithms, these systems automatically adjust the operation of the components, optimizing energy consumption while maintaining desired comfort levels. The versatility of hybrid HVAC systems allows them to adapt to seasonal changes and fluctuating energy prices. They offer customizable settings, enabling users to prioritize energy efficiency or cost savings based on their preferences and the prevailing utility rates [246].

7. Reduction of CO_2 Emissions through Carbon Sequestration (Carbon Capture and Storage)

7.1. The Optimized Environment in Greenhouses and Achievement of Zero CO_2 Emissions

Commercial agriculture generates large amounts of CO_2 during photosynthesis which hinders the achievement of net-zero CO_2 emissions in greenhouses. Several factors influence the levels of CO_2 emissions from crops in open fields and greenhouses including: the type of crop, water quality and rate of fertilizer application, pH, precipitation, temperature, and soil nutrients (see Figure 7). For example, high CO_2 emissions (32.75–33.86 ton/ha) were linked to the application of nitrate fertilizers [52]. In contrast, a link between deep and shallow tillage and CO_2 flux in greenhouses was demonstrated in [52].

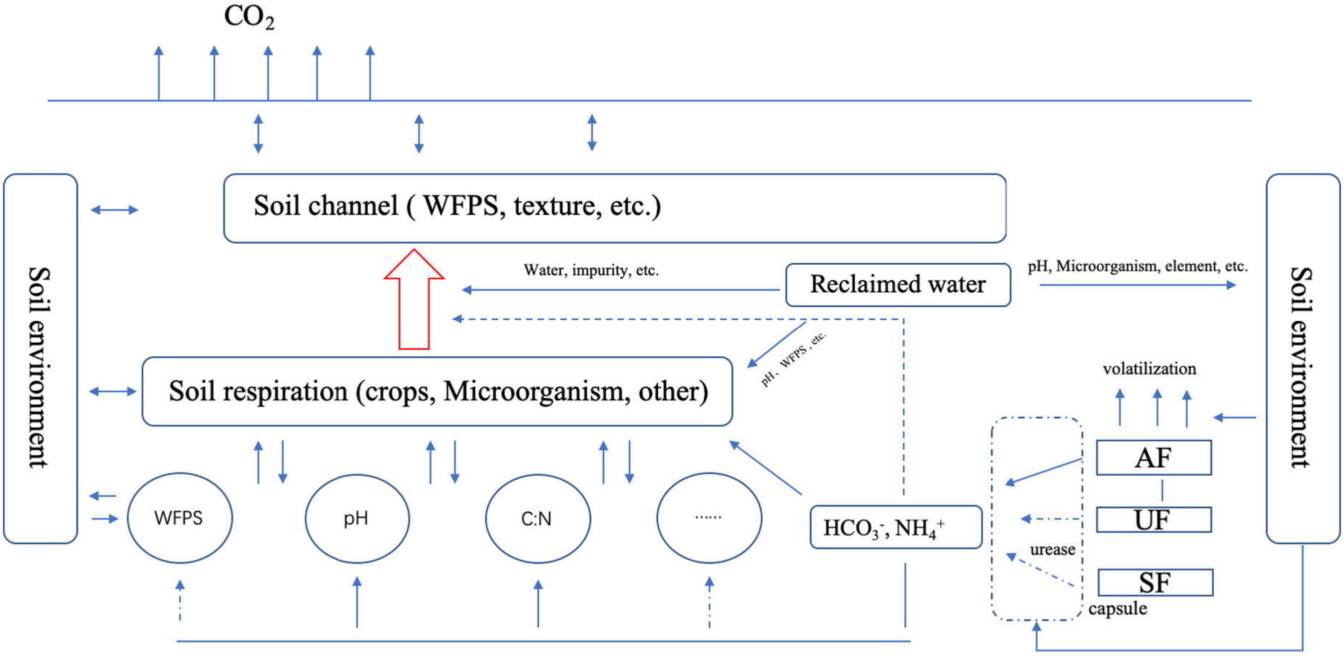

Figure 7. Variables that predict the production of CO_2 from greenhouse plants. WFPS denotes the water-filled pore space. AF, UF, SF represents the variable concentrations in soil N levels 1.10 g/kg, 1.09 g/kg, and 1.02 g/kg [52].

A higher CO_2 flux was noted in both shallow and deep tillage based on the residues left on the soil surface [53]. Drawing from the latter study [53], changes in the tillage methods could mitigate agricultural sources of CO_2 emissions. Further reductions in CO_2 emissions could be further achieved through the slow release of fertilizers [52]. On the contrary, there is no consensus among scholars on the subject, given that it is difficult to precisely determine the amount of CO_2 in greenhouses because the levels are variable depending on the rate of photosynthesis. Despite the lack of consensus on the actual CO_2 levels in greenhouses and appropriate methods for mitigating carbon dioxide fluxes, the need also arises for concerted measures to address the problem.

Diverse interventions can be adopted to reduce the CO_2 emissions linked to agriculture including: carbon capture and storage in plants and slow-release fertilizers [30]. The disadvantage of the accumulation of CO_2 in the atmosphere is its contribution to climate change and global warming [247]. As of 2020, the concentration of CO_2 in the atmosphere was about 413 ppm, and climate models predict that atmospheric carbon dioxide levels would continue to rise by 12 ppm per year on average [248,249]. Despite the global industrial slowdown associated with COVID-19, it is noteworthy that the accumulation of CO_2 remains unchanged. To address the high CO_2 problem in the atmosphere, various strategies have been explored, including: reforestation, direct air capture, Bioenergy with Carbon Capture and Storage (BECCS), photo-electrocatalysts, two-dimensional metal–organic frameworks, carbon mineralization, and ocean-based entrapment of CO_2 [250,251]. However, a key constraint is that these techniques are under development, and none has proven effective in the large-scale removal of CO_2. Additionally, the efficiency of the existing CO_2 capture techniques was highly variable (50–71%) and energy-intensive [251]. The variability of these methods poses new challenges to the attainment of net-zero CO_2 emissions.

The deployment of novel technologies for CO_2 removal is indispensable to mitigating climate change and ensuring achievement of net-zero emissions [251]. Carbon Engineering, Canada, and other CCS-centric technology companies have demonstrated the role of carbon capture in ameliorating anthropogenic contamination of the atmosphere [252]. However, worldwide upscaling of this technology is still a challenge.

Various CCS capture methods have been explored, including: direct air capture (low-temperature solid sorbent-based direct air capture and aqueous solution-based direct air capture), electrochemical CO_2 removal and bioenergy carbon capture and storage, scrubbing CO_2 gas using amines, and chemical looping combustion [253,254]. However, several factors influence the selection of the different CCS capture methods including: a tradeoff between commercial scalability, energy expenditure, financial feasibility, land use, scalability, efficiency, and sustainable impact. Such constraints inform the need to develop novel carbon capture and storage materials.

Recent research has also contributed to the development of new materials such as activated carbon honeycombs functionalized with hydrated Na_2CO_3 [255], multi-functional nanofluids developed using silica nanoparticles and poly(allylamine) [256], and cellulose nanocrystals and nanofibrils [255]. Given that the performance of cellulose nanocrystals and nanofibrils is constrained by chemical properties, the deployment of functionalized carbon-based hydrogel materials such as graphene oxide is considered a practical alternative. Criticism against direct air capture is advanced that it remains untenable, considering that vast land areas are needed in light of the technology's low area efficiency [19]. In addition, the direct air capture process might elevate the risk of energy and water stress. Based on such challenges, carbon hydrogels are identified as a potent material of choice.

The effectiveness of hydrogels for carbon sequestration stems from the fact that they hold significant quantities of water in the 3D hierarchical structures and large surface areas for CO_2 adsorption [45]. Similarly, the surfaces of hydrogels can be tuned to create large frameworks. For example, cellulose nanofibrils and nanocrystals with tunable surface properties were developed in [255]. The presence of OH groups on the hydrogel surface was critical to surface functionalization to enhance selectivity to carbon dioxide. Third, the surface area reduction had a minimal impact on the carbon capture ability/chemisorption of CO_2 (2 mmol/g) [255]. Physisorption can be enhanced by incorporating metal–organic frameworks, zeolites, and silica.

The decision to adopt carbon hydrogels was further augmented by research is revealed the development of graphene-based CO_2 filters. For optimal efficiency, direct air capture systems have been deployed in regions with optimal solar radiation to minimize the usage of fuel-based grid electricity [55,247,254].

7.2. Graphene–Oxide (GO) Hydrogels

The novel GO hydrogels have been widely applied in biomedical applications (tissue engineering and drug delivery systems) [257,258] and environmental applications, including carbon capture and storage (CCS) [215,259]. The research evidence confirmed the versatility of GO hydrogels in CCS owing to the large surface areas, super-adsorbent properties, surface functionalization, high SA, electrical conductivity, swelling ratio, and ability to form interactions with other functional groups [260,261]. Despite the application of GO hydrogels in agriculture, there is uncertainty whether they would help mitigate carbon emissions in the agricultural sector. An explanation is that there are multiple sources of emissions, including inconsistent results in real-time applications, cost, and poor market adoption. The criticism of hydrogels in CO_2 reduction is further reinforced in [262], where the stacked graphene oxide nanosheets generated a CO_2 permeance of about 500 GPU. The limited uptake of CO_2 was attributed to the extended CO_2 diffusion pathways. However, advantages show that the challenge could be offset through the surface functionalization of GO with metals.

Given that the existing barriers to the surface functionalization of GO can address the inherent drawbacks to CCS, recent R&D projects have also led to the development of low-cost hydrogels. For example, the Swiss Federal Institute of Technology Lausanne confirmed that hydrogels would reduce the cost of CCS to about USD 30/ton [263]. In contrast to the Swiss Federal Institute of Technology Lausanne, according to [19,61] the cost savings would be achieved over time (EUR 55/tCO_2 by 2050). The estimated cost savings by the Swiss Federal Institute of Technology Lausanne were significant compared to [247] where it was established that savings of USD 1000/ton of CO_2 would be obtained. Subsequently, the projected reduction in costs would facilitate the integration of GO hydrogels in agricultural structures.

GO is associated with unique advantages, including the value addition of CO_2 into graphene, a high-value material for engineering applications; this is achieved via photo-electrocatalytic and electrocatalytic techniques [264]. Based on the current reviewed literature, insights show that the lower production costs in isolation would not suffice to enhance market adoption of CCS technologies in agriculture, because "intrinsic graphene has high sensitivity at low gas concentrations; but the sensor selectivity is poor, limiting its use in many practical applications" [260]. As such, the problem was not resolved by using quantum dots (QDs) and gold nanoparticles [208,261,265]. Therefore, further research is required to address the barriers to CCS technologies in agriculture.

7.3. Integrated Interventions: Plant-Based CO_2 Reduction Using Biofuels, and IT Tools

Based on the capital-intensive nature of hydrogels, it is important to explore the use of biofuels to aid zero carbon emissions. For example, the suitability of Miscanthus grasses-based biofuel production was confirmed by [265]. However, the shortcoming with the use of biofuels was the competition for agricultural land, and secondary greenhouse emissions linked to land cultivation, harvesting, and processing. The use of crops to reduce emissions was also supported by [266,267]. In contrast to [265], the use of the MOTIF monitoring tool in dairy farm production was proposed in [268], while the regular energetics assessment was advocated in [269]. The MOTIFS system was proven effective in optimizing resource use in selected dairy farms. Likewise, other techniques considered the adoption of integrated practices for sustainable pasture management, cropping, tillage, manure management, and livestock feed management [270]. On the contrary, other disadvantages highlighted that the benefits of the beneficial management practices were only demonstrated in the Canadian prairies [270]. Therefore, additional experimental data is needed before widespread adoption.

Despite the positive arguments highlighting need for integrated practices, further criticism posited that it was impractical to achieve optimal greenhouse production without higher greenhouse emissions; a phenomenon referred to as the tragedy of the commons [271,272]. The latter findings raise pertinent issues that ought to be addressed in future scholarly work. However, the CCS technologies are advantageous as they may help reduce carbon emissions in greenhouses.

8. Discussion

8.1. Environmental Benefits and Climate Change's Effects on Agriculture

The achievement of zero energy is associated with diverse positive ecological and agricultural benefits. A surge in global temperatures above the current 1.5 °C limit leads to adverse consequences on commercial and small-scale agriculture and climate [252]. The short-term and long-term adverse effects were extensively documented in recent studies [273]. Based on the negative effects of global warming, it is argued that reversing agriculture's contribution to climate change and global warming can yield tangible economic benefits in the long term. The benefits encompass the lower cost of production given that climate protection can lead to desertification [274]. The incidence of pests and diseases can also be mitigated by leveraging the positive relationship between climate change and the proliferation of agricultural pests and diseases in commercial farms [15,37,275]. The investment in carbon footprint trading schemes can also facilitate improvement in cost savings by enhancing crop yields.

Despite the benefits, other scholars have critiqued the economic and ecological benefits that are incurred. One argument advanced is that the cost–benefit profile is expected to be context-specific [163]. For example, region-specific variables that influenced the profitability and valuation of environmental and social externalities were identified including existing structures for climate protection and technical expertise, and life cycle analysis of the green technologies [276,277]. However, shifting the focus to the broader context is deemed to be more prudent and advantageous. The United Nations estimated that investing USD 1.8 trillion in climate change mitigation would yield about USD 7 trillion in direct economic benefits [278]. The economic estimates justify the need for climate-smart agriculture, zero energy emissions, and zero energy requirements.

Agricultural greenhouses are also a significant contributor to greenhouse gas emissions. Achieving zero energy greenhouse operations can reduce greenhouse gas emissions and help mitigate the adverse consequences of climate change. Agriculture greenhouses can generate a significant impact on the environment due to their energy consumption, greenhouse gas emissions, and water usage. By achieving zero energy greenhouse operations, we can minimize these environmental impacts and promote sustainable agriculture.

Zero energy greenhouse operations can be achieved by employing four unique strategies; (i) designing energy-efficient greenhouses that are well insulated, use natural light, and have efficient heating and cooling systems in order to reduce energy consumption, (ii) incorporating and using RES and adapted thermal energy storage systems which can supply the energy loads of greenhouses and further reduce energy costs, (iii) using IoT systems in order to control environmental factors such as temperature, humidity, and light levels optimizing optimize plant growth, reducing energy consumption, and minimizing waste, and (iv) smart technology and sensors in order to monitor and control irrigation systems, reducing water usage, waste, and the use of pesticides and fertilizers.

The arguments underscore that there is no isolated technology that can enable agricultural producers to achieve zero energy and zero emissions, and optimal resource utilization in the short term. The reduction of the greenhouse energy requirements is influenced by the integration and seamless operation of different technologies, including thin-film solar concentrators/luminescent solar concentrators (LSCs) (for thermal insulation of greenhouse structures) [132]; thin-film-based solar concentrators; smart glass systems capable of altering light transmittance and converting sunlight into electricity [17]; carbon capture and storage and slow-release fertilizers [52]. The adoption of diverse technologies available for the optimization of agricultural resource optimization was dependent on local needs, and capital expenditure versus the benefits that would accrue in the short term and long-term.

However, the adoption of smart glass systems in greenhouses is constrained by the lack of a universal material with optimal light transmittance properties; a factor that explains why the technology has been poorly adopted in developed countries. Further insights from different studies advocate for materials such as polyampholyte hydrogel (PAH), ethylene glycol-modified pillar arene, hydroxyl propyl cellulose, poly (N-isopropyl acrylamide) (PNIPAM) hydrogel [38,223]. Other issues emphasize the cost of the existing technologies relative to the traditional polymer films for greenhouse covering [279,280]. Additionally, there is inconclusive evidence whether smart glass systems could be integrated with IoT and Al systems for optimal energy harvesting. Therefore, the unique cost–benefits of smart glass systems might explain the low rates of market penetration. Similarly, each of the enabling technologies for resource optimization were associated with unique challenges and benefits. For example, the thin-film solar concentrators/luminescent solar concentrators (LSCs) made from fluorescent polymethylmethacrylate had variable spectra sensitivity [132,202]. Further disadvantages encompass the fact that the PMMA materials have high self-absorption and low stability [203,206]. While emerging research studies proposed the transition from PMMA to QDs, there are limited empirical data on the potential benefits versus the risks.

On a positive note, there was extensive literature on the long-term advantages of advanced communication systems to facilitate autonomous communication between different farm equipment [212–214]. The wireless communication infrastructure was critical to facilitate the operation of sensors for plant water levels, nutritional content, soil pH, humidity, and temperature (IoT and AI systems) [216]. The disadvantages of AI and IoT regarded the high initial capital outlay, need for technical expertise, and higher energy use (at the expense of zero energy targets) [281,282]. From a sustainability perspective, the beneficial impact of IoT and AI outweighed the short-term concerns, which could be resolved using renewable energy.

8.2. Future Research Agenda

Optimal resource management in greenhouse farming is influenced by the pace at which industry stakeholders work together and collaborate in developing solutions in the next generation to limit CO_2 emissions and achieve zero emissions and zero energy. Currently, there is limited corroboration between agricultural companies and researchers to explore how carbon capture technologies can be integrated in greenhouses, and smart glass systems. The adoption of climate smart agriculture has the potential to reduce greenhouse warming, resulting in sustainable agricultural production. Future research studies should investigate the economic advantages for large agricultural companies in installing smart glass systems, infrastructure for slow fertilizer release and carbon capture in greenhouse structures to offset the carbon footprint. The proposals are grounded in the fact that agricultural stakeholders were early adopters of technologies. The adoption of emerging technologies facilitates the reduction of operational costs and increased yields using humidity and temperature sensors, remote soil pH and nutrition monitoring, wireless communication (5G and WLAN), crop surveying. The benefits associated with IoT and wireless technologies in smart agriculture can influence the adoption of zero energy and zero emission greenhouses. Subsequently, future research data will help confirm the validity of this hypothesis.

9. Conclusions

The findings from this review article have synthesized recent scholarly findings and market data on the advantages of resource management in an optimized greenhouse environment, emphasizing zero energy requirements and zero CO_2 emissions. Global agricultural statistics support the case for climate-smart resource management and zero emissions. The increase in greenhouse acreage in the Mediterranean region, Europe, and North America led to higher carbon emissions. For example, Turkish farmers burned coal to generate greenhouse energy. Despite the affordability of coal, it was associated with a higher energy density and higher ecological impact.

The combustion of coal released 204 pounds of CO_2/million Btu, nearly two-fold higher compared to LNG's 116 pounds of CO_2/million Btu. Considering the emissions that lead to global warming, climate change, and the depletion of existing water sources, the long-term economic benefits of renewable sources of energy such as geothermal, wind, and solar outweigh the short-term higher investment costs. The case for solar energy was further reinforced by the short-payback window and high NPV; this was demonstrated in China. On the downside, the optimization of renewable energy resources was impacted by technological constraints relating to the energy storage system's feasibility of energy microgeneration technologies to meet cooling and heating needs.

The existing solar thermal collectors, micro-turbines, geothermal heat pumps, and rooftop photovoltaic systems have unique benefits and challenges and further research for long-term real-world applications. Recent research and development programs have led to the development of advanced materials such as mono- and polycrystalline silicon, smart glass, phase change materials, hydrogels, organic solar cells, and thin-film solar cell technology, which offered immense potential for renewable solar energy. The resource optimization would be further reinforced by the integration of IoT systems for autonomous regulation of thermal/humidity conditions in greenhouse structures. In brief, the mechanisms and strategies for achieving zero energy requirements and zero CO_2 emissions require a balance between short-term economic losses and long-term economic gains and mitigation of climate change and global warming.

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