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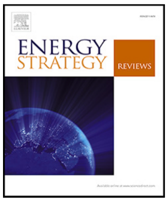

Reviews

Climate-adaptive energy strategies for sustainable greenhouse systems: A Köppen-based systematic review

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ABSTRACT

Greenhouses are essential for enhancing crop yields and enabling year-round production, but their high energy intensity and climate-sensitive demand challenge sustainability. To address the lack of climate-stratified evidence, we conduct a systematic review of climate-adaptive energy approaches for greenhouse systems structured by the Köppen climate classification (KCC). We searched the Web of Science (2019–2024) using Topic “greenhouse”, limiting to articles and refining by the “Citation Topic Micro: Greenhouse” filter; 276 records were identified and 268 articles were retained after title and abstract screening. The evidence is organized into four domains: (1) microclimate modeling and decision-support tools, (2) passive design and device-assisted enhancements, (3) active operational optimization, and (4) renewable energy integration. Results reveal climate-specific patterns: cold and arid regions most consistently benefit from insulation, thermal screens, phase-change storage, and solar–thermal-assisted heating; temperate and tropical climates increasingly adopt advanced control, including model predictive control and data-driven/learning-based controllers, to coordinate multi-variable microclimate-energy trade-offs. Renewable integration is expanding across zones, yet harmonized techno-economic and life-cycle assessments remain limited. This KCC-based synthesis supports region-specific design and operation decisions and highlights priorities for future research and deployment.

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1. Introduction

Greenhouses play a vital role in modern agriculture by providing controlled environments that enable stable and continuous crop production [1,2]. They facilitate year-round cultivation, protect crops from external climate fluctuations, and significantly improve both yield and quality [3,4]. However, these advantages are accompanied by substantial resource demands, particularly in terms of energy consumption. The operation of greenhouse systems requires considerable energy inputs for climate regulation, lighting, and ventilation, which often depend on fossil fuels [5]. This reliance not only results in high operational costs but also contributes to significant greenhouse gas emissions, undermining the environmental sustainability of greenhouse production [6]. As global climate change accelerates and energy prices fluctuate, the need for energy strategies to enhance the resilience and sustainability of greenhouse operations has become increasingly urgent.

To develop such strategies, it is essential to understand which processes dominate energy use in greenhouse systems. Heating accounts for approximately 65%–85% of the total energy consumption [7]. These energy demands are strongly influenced by external climatic conditions, which vary substantially across regions and further complicate energy management strategies [8]. For instance, annual energy consumption in greenhouses can reach as high as 3600 MJ/m^2 in northern Europe due to harsh winters, whereas it ranges from only 220 to 320 MJ/m^2 in southern Europe where milder conditions prevail [9]. These regional differences highlight the importance of climate-adaptive energy solutions tailored to local environmental conditions.

Over the past decades, greenhouse energy strategies have evolved through several stages. Early efforts (1970s–1990s) focused mainly on passive and structural innovations such as improved insulation, double glazing, thermal mass and basic ventilation control. From 2000 to 2010, computational tools and CFD models were increasingly adopted to analyze greenhouse microclimate and optimize envelope and ventilation design. Between 2010 and 2020, hybrid renewable energy systems integrating solar thermal/PV, biomass and geothermal sources emerged, accompanied by more detailed dynamic simulations. Since around 2015, the field has been moving toward smart, IoT-enabled and AI-assisted control, enabling predictive and adaptive management of greenhouse energy demand under varying climatic conditions [10,11].

In response to the growing challenges of high energy use and climate variability, considerable research has focused on improving greenhouse energy efficiency [12,13]. As illustrated in Fig. 1, greenhouse energy systems incorporate multiple components and strategies to meet these challenges, ranging from passive measures and advanced control to renewable energy integration. Despite this steady progress, most studies still focus on individual technologies or single subsystems, with limited attention to their integration and adaptation to different climate conditions.

This lack of integration highlights a critical gap in current research. While numerous studies have reported energy-saving technologies for greenhouse systems, and several reviews have summarized individual approaches, a climate-explicit synthesis remains limited. In particular, few studies systematically connect these technologies with globally comparable climate zones, making it difficult to assess which strategies are most effective under specific climatic constraints. A climate-responsive systematic review is therefore needed to consolidate fragmented evidence and to support context-specific technology selection and research prioritization for sustainable greenhouse development.

To address this gap, this paper proposes a climate-based framework for analyzing and organizing greenhouse energy strategies using the Köppen climate classification (KCC), which categorizes global climates according to long-term temperature and precipitation patterns [14]. Unlike existing reviews that focus on individual technologies or single subsystems, this review provides a cross-climate synthesis across four interrelated domains: microclimate modeling (as an enabling tool), passive design strategies, active operational optimization, and renewable energy integration. By mapping evidence from these domains to specific climate zones, the study clarifies climate-dependent performance patterns, highlights the strength of evidence across study types, and identifies zone-specific opportunities and research gaps for targeted, effective and scalable energy solutions.

The remainder of this paper is organized as follows. Section 2 introduces the methodology and explains the application of the Köppen climate classification to greenhouse energy systems. Section 3 synthesizes the literature across the four domains in different climate zones. Section 4 discusses cross-cutting trends and implications for future research, while Section 5 concludes with key findings and recommendations.

Nomenclature	
ANN	Artificial neural network
APV	Agri-photovoltaics
ASHP	Air-source heat pump
CCHP	Combined cooling, heating, and power
CFD	Computational fluid dynamics
CHP	Combined heat and power
CSAU	Container-sized agricultural unit
CSG	Chinese solar greenhouse
FEM	Finite element method
GCHP	Ground-coupled heat pump
GPR	Gaussian process regressor
HVAC	Heating, ventilation, and air conditioning
IoT	Internet of Things
KCC	Köppen climate classification
LDAC	Liquid desiccant air conditioning
MOGA	Multi-objective genetic algorithm
MPC	Model predictive control
NARX	Nonlinear autoregressive exogenous
NF	Nanofiltration
OPV	Organic photovoltaic
PAR	Photosynthetically active radiation
PCM	Phase change materials
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
RBF	Radial basis function
RMPC	Robust model predictive control
RMSE	Root mean square error
STPV	Semi-transparent photovoltaic
SVM	Support vector machines
TES	Thermal energy storage

2. Methodology

2.1. Köppen climate classification

To analyze the impact of climate on greenhouse performance, this study uses the KCC, a widely recognized framework that classifies global climates by temperature, precipitation, and their seasonal variations [15]. The KCC offers a consistent and globally recognized framework that supports the analysis of regional differences in greenhouse energy use and environmental control [16]. Its broad applicability also enables comparisons across climate zones, which is essential for developing location-specific strategies. The KCC divides climates into five main groups: tropical (A), arid (B), temperate (C), continental (D), and polar (E) [17]. Each group is further divided into subtypes according to annual and seasonal variations in temperature and rainfall. Table 1 presents the coding structure used in this classification, while Fig. 2 shows the global distribution of climate zones to provide a spatial basis for further analysis.

Understanding the KCC provides a structured perspective on how climate differences influence greenhouse energy strategies across regions. In tropical climates (A), high temperatures and humidity require the use of cooling and dehumidification systems to maintain optimal growing conditions [18]. In arid zones (B), greenhouses often depend on water-saving technologies and evaporative cooling to cope with low humidity and intense heat [19,20]. In temperate (C) and continental (D) climates, heating is usually necessary during colder months, which increases energy consumption and shapes decisions about insulation and heating systems [21,22]. By linking climatic characteristics with greenhouse design and operation, the KCC helps inform targeted strategies for improving energy efficiency in diverse environments.

2.2. Information sources and search strategy

A systematic literature search was conducted in the Web of Science Core Collection to identify peer-reviewed research on greenhouse energy strategies. The search parameters were set as follows: “Topic” = greenhouse, “Document Type” = Article, and “Citation Topic Micro” = 3.4.1651 Greenhouse. The publication years were restricted to 2019–2024. The search was last updated on October 7, 2024, yielding 276 records in total. This “Citation Topic Micro” filter is a Web of Science classification metric that organizes articles into specific thematic areas based on citation patterns and topic relevance; selecting “3.4.1651 Greenhouse” helped refine the corpus to studies closely aligned with the specialized scope of this review.

To enhance transparency and reproducibility, the search strategy was supplemented by a structured keyword combination within the Topic field to capture energy-related and climate-adaptive dimensions of greenhouse systems. The search terms covered four domains corresponding to the analytical framework of this review, including microclimate modeling, passive design and envelope enhancement, active operational control, and renewable energy integration. Representative keywords included combinations of “greenhouse” with “energy”, “heating”, “cooling”, “insulation”, “phase change material”, “microclimate model”, “HVAC”, “control”, “model predictive control”, “artificial intelligence”, “photovoltaic”, “biomass”, and “geothermal”. The reference lists of highly relevant articles were also screened to identify additional eligible studies.

2.3. Eligibility criteria

Studies were included if they: (i) focused on greenhouse systems or comparable controlled-environment cultivation structures; (ii) investigated at least one energy-related strategy aligned with the four-domain framework of this review (microclimate modeling, passive design, active operational optimization, or renewable energy integration); (iii) reported quantitative outcomes relevant to energy use, thermal performance, renewable contribution, emissions reduction, or closely related indicators; and (iv) were original, peer-reviewed journal articles published between 2019 and 2024. Studies were excluded if they were review papers, conference papers, editorials or reports without original data, if they did not address greenhouse energy strategies, or if they lacked quantitative performance outcomes pertinent to the objectives of this systematic review.

2.4. Study selection

The study selection process followed PRISMA principles and is summarized in Fig. 3. After removal of clearly unrelated records through title and abstract screening, 268 articles were retained for full-text assessment and synthesis. Specifically, 8 records were removed as unrelated to greenhouse energy strategies, and 6 review papers were excluded to maintain a focus on original research evidence. The final set of included studies was then classified into the four thematic domains: microclimate modeling (n = 54), passive design and device-assisted enhancements (n = 107), active operational optimization (n = 41), and renewable energy integration (n = 60).

2.5. Quality assessment

Given the heterogeneity of included studies (simulation, laboratory and field-based research), a brief quality assessment was conducted to support interpretation of the strength of evidence. Each study was appraised according to: (i) study type and level of validation (simulation vs. laboratory vs. field experiment); (ii) clarity and completeness of system description; and (iii) whether uncertainty or variability was reported where applicable. Based on these criteria, studies were qualitatively categorized into high, medium or low evidential strength. This

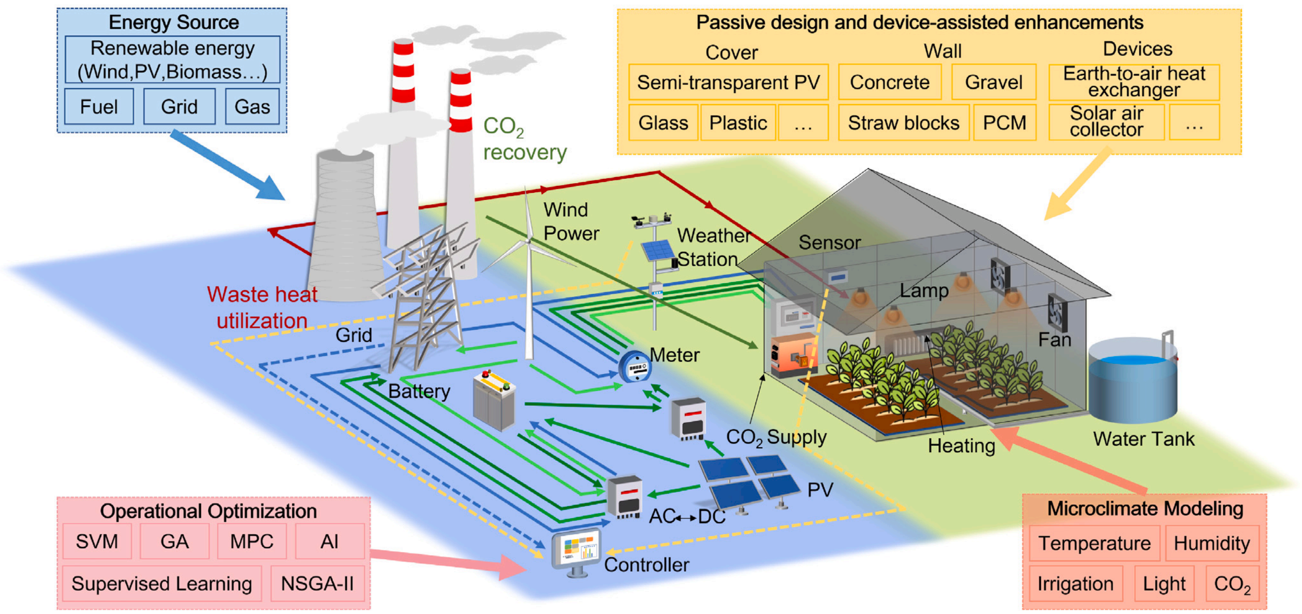

Fig. 1. Conceptual framework of greenhouse energy strategies and system integration.

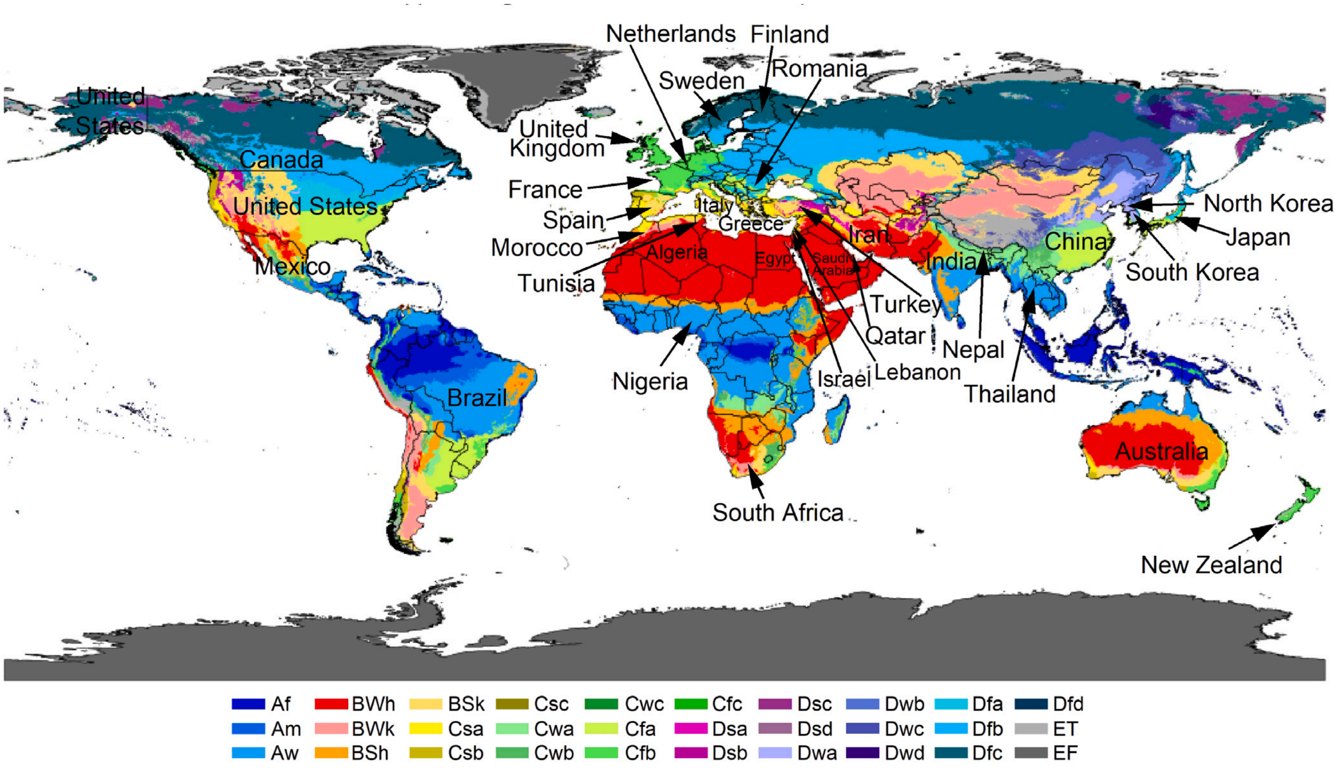

Fig. 2. Köppen climate classification of countries included in this review.

assessment was used in the Discussion to distinguish strategies supported by field-validated evidence from those primarily demonstrated under modeling assumptions, and to highlight priorities for future validation and integrated assessments.

2.6. Limitations of the KCC approach

The KCC approach provides a coarse, long-term characterization of climate based on temperature and precipitation patterns. It does not explicitly capture short-term variability, wind speed, humidity extremes or rare events such as heat waves or cold snaps, which are also important for greenhouse energy demand. In this review, KCC is therefore used as a first-order grouping framework, while detailed study-level discussions consider local weather parameters where available. Site-specific design must still rely on high-resolution climatic data beyond Köppen classes.

3. Climate-zone-oriented classification of energy strategies

Fig. 4 presents the regional distribution of the 268 reviewed articles according to their geographical origin. Asia contributes the largest number of studies (157 articles), with China accounting for 93 of them. This is followed by Europe (51 articles), Africa (26), North America (24), Oceania (3), and South America (1). These figures reflect clear

Table 1

Subtypes, climatic zones and key characteristics of the Köppen climate classification.

Main group	Subtype	Climatic zones	Characteristics
A: Tropical	Aw	Tropical Savanna	Distinct wet and dry seasons, hot temperatures throughout the year, grassy landscapes
B: Arid	BWh	Desert	Very low precipitation, high temperatures, arid landscapes, sparse vegetation
	BSh, BSk	Steppe	Limited precipitation, hot summers, cooler winters, grasslands
C: Temperate	Csa, Csb	Mediterranean (hot and warm summer types)	Mild, wet winters, hot, dry summers, vegetation adapted to drought conditions
	Cfa, Cwa	Humid Subtropical	Hot, humid summers, mild to cool winters, ample precipitation
	Cfb	Marine West Coast	Mild, wet winters, cool summers, high precipitation
D: Continental	Dwa	Humid Continental	Hot summers, very cold winters, low winter precipitation, large seasonal temperature variations
	Dfb	Humid Continental (Warm summer)	Warm to hot summers, cold winters, moderate precipitation, evenly distributed
	Dsa	Mediterranean (dry-summer, cold-winter type)	Hot, dry summers; cold, wet winters; large annual temperature range
E: Polar	ET, EF	Tundra	Very cold climates, short summers, low precipitation, frozen ground, sparse vegetation

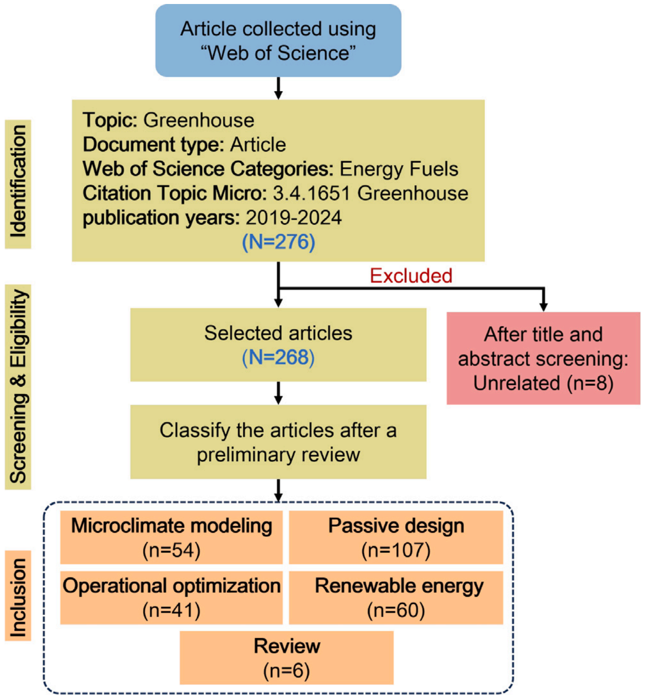

Fig. 3. PRISMA-based flow diagram.

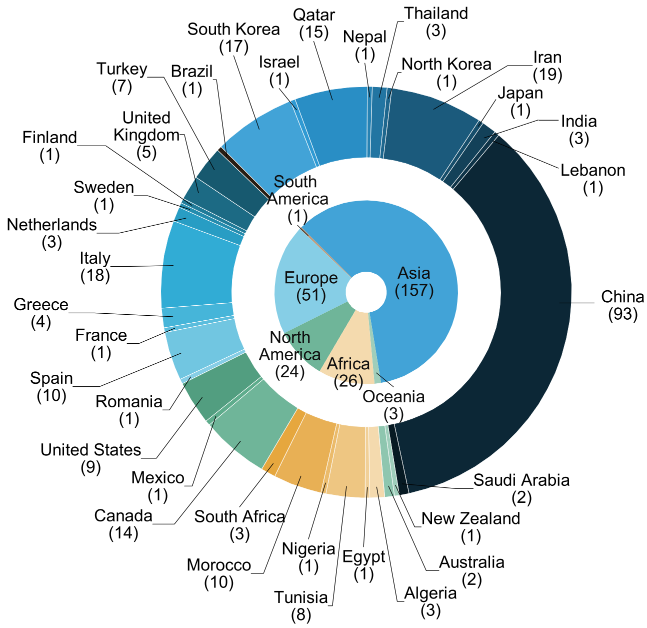

Fig. 4. Geographic distribution of the reviewed studies.

regional differences in greenhouse-related research, which are likely influenced by climatic conditions, agricultural development goals, and national investment in greenhouse technologies.

The following sections analyze the selected studies in more detail. They are organized into four main thematic areas: greenhouse microclimate modeling, passive design and device-assisted improvements, operational optimization, and renewable energy integration. Each theme is examined in the context of different Köppen climate zones to better understand the relationship between climate and energy strategies in greenhouse systems.

For clarity, the four-domain framework distinguishes microclimate modeling as a cross-cutting methodological and decision-support layer from technology- and operation-oriented strategies (passive measures, active control, and renewable integration). This clarification avoids conflating analytical tools with deployable interventions and strengthens the internal logic of the climate-based synthesis.

3.1. Zone A

Tropical regions, classified as Zone A in the KCC and shown in Fig. 5, include countries such as Thailand and southern Nigeria. These areas are characterized by consistently high temperatures, intense solar radiation, and variable rainfall patterns. The lowest monthly average temperature remains above 18 °C, while relative humidity typically ranges from 50% to 75% during the dry season and from 75% to 100% in the rainy season. Although these climates are generally favorable for open-field cultivation, greenhouse systems play a vital role in mitigating extreme weather events, reducing pest pressure, and ensuring stable production of high-value crops.

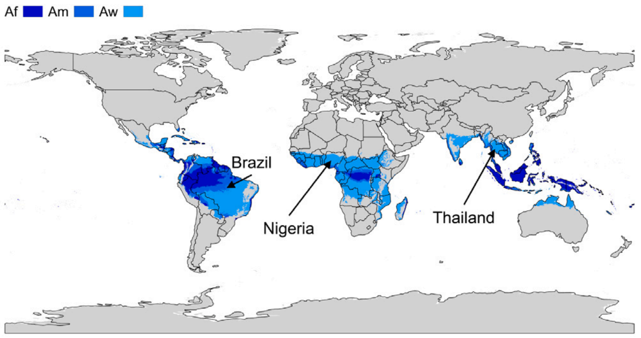

Fig. 5. Selected countries in Köppen climate Zone A (Tropical).

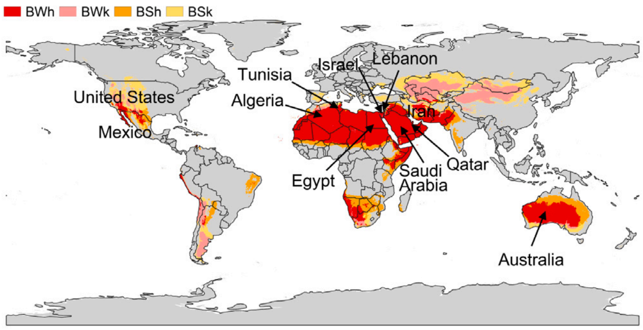

Fig. 6. Selected countries in Köppen climate Zone B (Arid).

Cooling is the main energy requirement in greenhouses, with air conditioning using about 64% of the total energy and LED lighting contributing 36% [18]. This shows the importance of improving cooling methods suited to tropical climates. Recent research has focused on using renewable energy together with smart control systems. For example, one system powered by solar panels and controlled by the Internet of Things (IoT) reduced electricity use from the grid by 30% and improved environmental control through real-time sensors and wireless communication [23].

Although grid-connected photovoltaic (PV) systems can reduce operating costs by more than 50% [24], using standalone PV with battery storage is still expensive due to high battery costs and system limitations. This leads to a high levelized cost of electricity, reaching up to 0.1718 USD/kWh. A more practical solution is to combine PV with smart grids and AI-based control systems, which can predict and manage energy demand more efficiently. Such hybrid systems offer a more sustainable option for greenhouse operations in tropical climates. Advanced control methods, such as fuzzy logic, have also shown strong results, with electricity use reduced by 58.78% and water consumption cut by 68.90% [25].

3.2. Zone B

Zone B primarily includes hot arid (BWh) regions such as the Sahara Desert, the Middle East, and central Australia, as illustrated in Fig. 6. These areas are characterized by extreme daytime temperatures in summer, often exceeding 40 °C, with some regions surpassing 50 °C. Annual precipitation is generally below 250 mm; for example, Qatar receives approximately 125 mm per year. These climatic conditions create several challenges for greenhouse operations, including high cooling energy demands, limited water availability, and intense solar radiation. A summary of microclimate modeling methods and key findings for Zone B is provided in Table 2.

3.2.1. Microclimate modeling in Zone B

In BWh climate zones, efforts to improve cooling efficiency have led to the development of regression-based prediction models that incorporate variables such as ambient temperature, cover transmittance, and ground soil thermal conductivity [26]. One such model was developed using a central composite design, with the maximum cooling load estimated through simulations conducted in EnergyPlus. The model achieved a coefficient of determination (R^2) of 0.996, indicating a high level of predictive accuracy. Among the crops studied, cucumbers required the least cooling energy, whereas lettuce had the highest demand. Subsequent findings revealed that tailoring crop selection to local climatic conditions can significantly reduce cooling energy consumption, highlighting the importance of integrating crop-specific cooling requirements into greenhouse energy management strategies [31].

Incorporating environmental variables into greenhouse design has also been shown to improve system performance. By integrating energy, humidity, and crop growth models, greenhouse structures and orientations have been optimized based on trade-offs between energy use, water demand, and plant productivity [32]. In addition, machine learning techniques have been applied to enhance climate prediction accuracy in greenhouse environments. Temperature forecasting using nonlinear autoregressive exogenous (NARX) models has demonstrated remarkable accuracy, with R^2 values reaching up to 0.9986 for internal greenhouse temperature prediction [34,35].

Ventilation modeling has been widely examined due to its critical role in regulating temperature and humidity within greenhouse environments [27]. It has been demonstrated that optimized ventilation strategies contribute to improved environmental uniformity [28]. Fan-and-pad cooling systems can reduce internal temperatures by as much as 25 °C; however, their efficiency significantly declines under peak summer conditions, reaching levels as low as 58% [29]. CFD simulations have also been employed to evaluate increased air exchange rates, which enhance cooling performance but result in elevated water consumption (222 L/day) and energy demand (3 kWh/day) [30]. These findings highlight the trade-offs between thermal regulation and resource consumption, reinforcing the need for integrated and sustainable approaches to greenhouse management in arid zones.

The economic feasibility of semi-solar greenhouse systems has been assessed using comprehensive exergoeconomic modeling techniques [33]. Results indicate that optimizing such systems requires balancing thermodynamic performance with economic viability, thereby emphasizing the importance of integrated techno-economic evaluation in sustainable greenhouse design.

While greenhouse-related studies in BWh climates primarily explore cooling strategies, solar energy integration, and advanced materials to mitigate extreme conditions, research in BSh (semi-arid) and BSk (cold semi-arid) zones focuses on microclimate regulation, greenhouse orientation, and passive environmental control to enhance sustainability and resource efficiency.

In BSh climate zones, greenhouse microclimate dynamics have been investigated through CFD simulations [36]. Results indicated that solar radiation and external air temperature are the dominant factors affecting internal temperature, whereas crop presence contributes minimally to humidity regulation. A centralized crop arrangement was found to reduce internal temperatures by approximately 2K, thereby enhancing temperature uniformity.

In BSk climates, an energy and mass balance modeling approach has been employed to predict greenhouse temperature and humidity [37]. The model demonstrated high predictive accuracy for temperature (R^2 = 0.96), while its accuracy for humidity was lower due to underestimation of transpiration and airflow dynamics. In the absence of active climate control, internal temperatures were observed to be 0.34 °C higher than ambient, and relative humidity increased by 15.7%, emphasizing the moderating effect of passive environmental regulation. Furthermore, light transmittance and heat transfer models have been proposed to evaluate the control performance of various greenhouse envelope materials.

Table 2

Summary of microclimate modeling approaches and key findings for greenhouse applications in Köppen climate Zone B.

Climate type	Focus area	Modeling approach	Key variables	Key findings	Reference
BWh	Cooling Load Modeling	Regression & EnergyPlus	Temperature, cover transmission, soil conductivity	Model achieved $R^2 = 0.996$; cucumber required least cooling, lettuce the most; crop type significantly impacts cooling demand	[26]
	Ventilation & Cooling	CFD, Ventilation modeling	Ventilation, temperature, water & energy use	CFD shows optimized ventilation improves temperature and humidity uniformity; fan-pad cooling reduces temperature by 15–25 °C, but has peak efficiency drop (58%–75%)	[27–30]
	Crop-Climate Optimization	Crop selection based on climate	Climate conditions, crop type	Climate-based crop selection reduced cooling load; supports crop-specific energy strategies for greenhouses	[31]
	Integrated Design Optimization	Multi-variable modeling	Energy, humidity, crop growth	Combining energy, humidity, and growth models optimizes structure/orientation; balances energy–water–crop needs	[32]
	Techno-Economic Evaluation	Exergoeconomic modeling	Thermodynamic & cost parameters	Optimization of semi-solar greenhouse design must weigh thermodynamic efficiency vs. economic cost; recommends multi-objective design	[33]
	Temperature Prediction	Machine learning (NARX)	Temperature time series	NARX model predicted greenhouse temperature with R^2=0.9986; ensures high forecasting accuracy for dynamic climate control	[34,35]
BSh	External conditions and the crop position	Numerical modeling (CFD)	Solar radiation, air temperature, crop layout	CFD showed centralized crop layout lowered temperature by 2 K and improved uniformity; solar radiation and ambient air temperature dominate thermal dynamics	[36]
BSk	Energy-Humidity Modeling	Energy & Mass Balance (Custom simulation)	Temperature, humidity, transpiration, airflow	Passive control led to temperature 0.34 °C and RH 15.7% higher than ambient; $R^2 = 0.96$ for temperature, but underestimated humidity due to transpiration or airflow	[37]

3.2.2. Passive design and device-assisted enhancements in Zone B

Advancements in cladding, nanotechnology, shading systems, subsurface cooling, desiccant-based climate control, and optical enhancements have significantly improved energy efficiency, water conservation, and climate adaptability in BWh greenhouses, enabling sustainable food production under extreme desert conditions.

In BWh climates, greenhouse passive design research focuses on optimizing cladding materials, such as plastics and glass, to enhance solar absorption and thermal regulation. The transmittance and thermal conductivity of these materials play a crucial role in maintaining stable internal temperatures, directly impacting cooling efficiency and overall energy consumption [38].

The optimization of plastic cladding materials has been a key area of focus in greenhouse energy research. Their optical and thermal properties have been extensively analyzed, showing that high solar transmittance enhances photosynthetic activity but increases cooling demand. In contrast, materials with low long-wave transmittance reduce nighttime heat loss, resulting in a 6.3% reduction in heating energy use and a 9.8% decrease in annual cooling load [39]. In related studies, the performance of different plastic film types have been evaluated. Diffusion films exhibited a 34% light scattering rate, while conventional films contributed to a 5 to 10 °C temperature reduction and a 3 to 5% increase in relative humidity within the greenhouse environment [40]. It has been demonstrated that the use of white plastic covers in combination with PV-powered evaporative cooling systems can result in a temperature reduction of 10 °C, with evaporative efficiency reaching 74% and water use efficiency improving by 19% [41].

In glass-covered greenhouses, the use of ULR-80 film, which transmits 85% of photosynthetically active radiation while blocking heat-generating wavelengths, has been shown to reduce cooling loads [42,43]. However, changes in light spectrum negatively affected eggplant and pepper yields, illustrating the trade-off between temperature control and crop productivity.

Shading strategies are also widely used for climate regulation in high-temperature environments. Black shade nets placed 20 cm above greenhouse roofs lowered internal temperatures by up to 8 °C, while slaked lime whitening achieved a cooling effect of 8.5 °C but significantly reduced light transmission, potentially limiting plant growth [44]. A water-injected polycarbonate shading system has been shown to absorb infrared radiation while transmitting visible light, reducing greenhouse temperatures by 3–4 °C and enhancing humidity retention [19].

Nanotechnology-based approaches have been explored for thermal management. Spectrally selective nanofluids applied to roofing materials filter specific light wavelengths, enhancing energy absorption and cooling efficiency [45–47]. A near-infrared spectral-separating semi-transparent solar water-heating roof was developed to absorb near-infrared radiation for passive cooling and thermal energy recovery [48]. This system reduced cooling loads by 17.4%, generated 59.66 L of fresh water per day, and provided dual functionality in climate control and energy recovery, though long-term durability remains a concern.

Other passive cooling strategies, such as subsurface heat exchangers, have also been explored in recent studies. Ground-air heat exchange has also been explored, with a horizontal earth-to-air system in Qatar achieving an 85.6% reduction in cooling loads and a 67.8% decrease in life-cycle cooling costs [49,50], demonstrating strong potential in arid climates. Similarly, seawater thermal exchange systems have been applied in coastal environments. A floating offshore greenhouse utilizing seawater thermal exchanger and solar energy maintained year-round temperatures between 20–30 °C and relative humidity between 60%–90%, while reducing energy use by 30%–40% [51].

Beyond cladding, shading and passive cooling, liquid desiccant air conditioning (LDAC) systems have been developed for water-efficient climate control. A closed-loop LDAC system achieved 63% water recovery through recirculation [20]. Further enhancement using nanofiltration (NF) membranes enabled continuous dehumidification and water recovery. This NF-LDAC system reduced irrigation demand by 50% in hot desert and semi-arid climates, and by 30% in tropical zones, significantly improving water sustainability [52].

Evaporative cooling systems have been studied. One configuration combining cooling pads, a water spray unit, and a blower achieved a temperature reduction of 7.7 °C, a 22% increase in relative humidity, and a cooling efficiency of 60.05% at a wind speed of 12 m/s [53]. However, higher wind speeds led to unstable humidity control, potentially affecting plant growth. Additionally, structural optical innovations have also been investigated. A greenhouse design incorporating a negative linear Fresnel lens and high-efficiency insulating walls demonstrated an 80% reduction in cooling demand while maintaining uniform light distribution, as shown by ray tracing simulations [54].

In BSh climate zones, optimizing greenhouse shape and orientation has been shown to improve energy efficiency. Simulations conducted in Marrakech, Morocco indicated that uneven-span structures with a 45 ° roof tilt and a −80 ° orientation (10 ° from east–west) increased winter solar gain by 10.61%, reducing heating costs by $\$90/\text{m}^2$ [55]. This passive optimization complements Fresnel-lens-based designs, further enhancing thermal performance and reducing auxiliary energy needs.

In BSk zones, optimization of direct evaporative cooling systems has focused on cooling pad materials. Cellulose pads achieved 37.6% cooling efficiency, loofah pads 38.9%, and shading nets 24.4% [56]. The addition of external shading nets increased cellulose pad efficiency to 45%. Loofah pads provided similar performance to cellulose while reducing water use, offering a cost-effective alternative.

3.2.3. *Operational optimization in Zone B*

Advancements in MPC-based control, data-driven optimization, and CO_2 utilization have significantly contributed to energy-efficient and environmentally sustainable greenhouse management in Zone B, enabling improved crop production, resource conservation, and reduced carbon footprints [57]. These strategies are particularly crucial in arid and semi-arid regions, where greenhouses face high cooling demands, water scarcity, and energy-intensive climate regulation [58].

MPC has proven effective for greenhouse climate regulation due to its rolling optimization mechanism, which continuously adjusts system parameters. Implementation of MPC has been shown to reduce energy consumption by 18%–25%, lower CO_2 emissions by 15.3%, and improve the efficiency of heating, ventilation, and air conditioning (HVAC), lighting, and water management systems [59,60].

In addition to MPC, data-driven control frameworks have been applied. A combined model integrating input-yield relationships with robust MPC (RMPC) improved both CO_2 fertilization and energy management strategies [61,62]. Maintaining CO_2 concentrations at 1050 ppm increased crop yields by 103.63%, while RMPC achieved temperature root mean square errors (RMSE) of 0.32 °C in winter and 0.60 °C in summer, resulting in 9.67–23.61% energy savings over conventional methods.

CO_2 concentration control is also critical for enhancing productivity and supporting carbon neutrality goals. A bioenergy carbon capture and utilization system enabled CO_2 fertilization while achieving net-negative emissions [63]. Maintaining CO_2 at 1200 ppm led to a 13.8% yield increase, a 28% reduction in irrigation demand, and negative emissions of 24.6 kg/m^2 annually, demonstrating the potential for integrating carbon capture into sustainable greenhouse operations.

3.2.4. *Renewable energy integration in Zone B*

In Zone B, PV technology enhances greenhouse performance by providing reliable electricity while reducing overheating and water loss. Compared to biomass and waste heat recovery, PV offers a more practical solution for high irradiance, arid regions. Based on transparency, greenhouse PV systems are classified as opaque or semi-transparent. Among them, semi-transparent and spectrum-selective designs are preferred for balancing energy output with crop light requirements and have drawn growing research interest. Since crop growth depends on daily light integral, optimizing PV coverage is essential. Light-demand classifications include high-light crops (e.g., tomatoes, sweet peppers) needing over 30 mol/m^2 day, medium-light crops (e.g., asparagus) 10–20 mol/m^2 day, and low-light crops 5–10 mol/m^2 day [64].

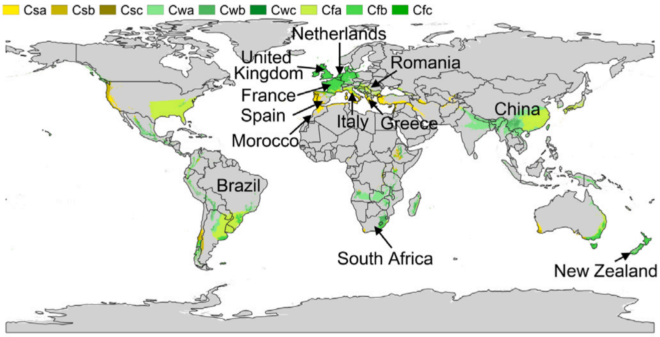

Fig. 7. Selected countries in Köppen climate Zone C (Temperate).

The impact of PV coverage on crop performance has been widely evaluated. A 25% PV coverage was shown to reduce energy use by 15.06% but also decrease tomato yield by 12.01% [65]. Optimization studies have addressed PV arrangement [66], coverage levels [67], and adaptive mounting systems [68] to minimize shading and maximize energy output. Photovoltaic blinds have been applied to reduce cooling loads by 45.5% while maintaining adequate light levels [69]. Dielectric mirror-integrated PV roofs have also been developed, achieving 25.4–28.9% cooling load reductions and generating 22.18 kWh/day of electricity [70].

By filtering sunlight through wavelength-selective layers, STPV systems tailor the transmitted spectrum to crop-specific needs while simultaneously generating electricity. Although photosynthetically active radiation (PAR) was reduced, tomato yields increased by 38% and plant height by 12%, while broccoli growth remained unaffected, demonstrating the potential of STPV to balance energy generation with plant development [71]. Organic photovoltaics (OPV) is a lightweight and flexible type of STPV technology, offer potential for greenhouse and building-integrated PV applications due to their low carbon footprint. However, their low efficiency (3%–15%) and short lifespan (3–10 years) limit widespread adoption [72]. Integrating thermochromic materials in OPV-based STPV greenhouses has been shown to reduce temperature fluctuations by 30% [73], while 68% PV transparency applied in greenhouses enables 135–200 kWh/m^2 of solar power generation without compromising crop growth [74].

Hybrid PV/T systems have also gained attention. One modeled configuration increased solar energy contribution to 85% and reduced fossil fuel use by 83% [75], though high equipment costs remain a limiting factor. Integrated systems combining PV, vapor compression cooling, and reverse osmosis desalination have shown a favorable balance of energy efficiency and economic viability in underground subtropical greenhouses [76].

Solar-biomass hybrid systems are used for polygeneration. A system integrating an internal combustion engine, organic Rankine cycle, and microbial desalination cell produced 215.3 kW of electricity, 118.45 m^3/day of freshwater, and 2.68 tons/day of CO_2 capture [77]. Another system combining solar thermal collectors with a biomass boiler achieved 54.92% solar energy coverage and a low operating cost of €2.70/m^2 per year [78], indicating strong economic potential.

Waste heat recovery has also been investigated as a sustainable heating strategy. An organic Rankine cycle-based system reduced heating demand by 30%–50%, with investment payback achieved within five years, offering a cost-effective option for applications in arid climates [79].

3.3. *Zone C*

C climate zones fall within the temperate belt and primarily include Mediterranean (Csa, Csb) and maritime (Cfa, Cfb) climates. As shown

Table 3
Summary of microclimate modeling approaches and key insights for greenhouse applications in C Climate Zones.

Climate type	Focus area	Modeling approach	Key variables	Key findings	Reference
Csa	Zoning Impact	Multi-zone modeling (TRNSYS)	Temperature distribution, heating load	Multi-zone model improved temp prediction; reduced heating energy error by 30% vs. single-zone	[80]
	Climate Influence	Steady-state energy balance	Latitude, climate classification, heating energy	Greenhouses need less heating than cold-climate zones; influenced by latitude	[16]
	Insulation Effects	MATLAB simulation	Insulation, internal temperature, heat loss	Insulated greenhouses 2–5 °C warmer at night; heat loss reduced by 23.8%	[81]
	CFD & FEM airflow analysis	CFD & FEM simulation	Airflow, wind speed, heating layout	CFD ensured uniform airflow; FEM optimized heating pipes; passive ventilation saved 25% energy	[82–86]
	Hybrid Energy System	EnergyPlus simulation (GCHP + PV)	Geothermal, PV, heating energy	Hybrid GCHP + PV system cut heating energy by 21%	[87]
	ML for Energy Prediction	Machine learning (SVM, ANN, GPR)	Thermal load, TES, HVAC, PV power	SVM reduced nRMSE by 30%–40%, ANN R>0.92 for HVAC, GPR R>0.96 for PV forecasting	[88,89]
Cfa	Heat Exchange Optimization	CFD + Particle Swarm Optimization	Heat exchange coefficient, shading	Shade screens reduced heat exchange coefficient by 12%–18%; improved thermal retention	[90]
	Light & Crop Effects	Greenhouse climate simulation	Solar radiation, transpiration, structure design	Light/crop layout affects temp; light balance crucial due to strong radiation & humidity	[91–93]
	Heat Pump & Container Model	TRNSYS + EnergyPlus	Water-to-water heat pump, life-cycle cost	Heat pump system reduced life-cycle cost by 9.45%; container model showed <3% annual error	[94,95]
Cfb	AI-based Crop Prediction	ML models (RBF, SVM, GPR)	Temperature, RH, PAR, CO_2 canopy temperature	RBF achieved R^2 = 0.98; precise crop yield prediction from environmental data	[96]

in Fig. 7, these zones are distributed across regions characterized by milder temperatures and more moderate solar radiation compared to the hot, arid conditions of Zone B. For instance, Mediterranean regions such as Barcelona (Csa) typically experience annual temperatures ranging from 10 °C to 25 °C, with an average annual precipitation of approximately 572 mm and about 2524 h of sunshine per year. Maritime climates, like that of Bordeaux (Cfb), are generally marked by narrower temperature ranges and higher annual rainfall, averaging between 850 and 1200 mm. A summary of the microclimate modeling methods and key findings for C-climate zones is presented in Table 3.

3.3.1. Microclimate modeling in Zone C

(1) Csa

Greenhouse energy modeling in Csa climates, which are characterized by hot, dry summers and mild, wet winters, has gained significant attention due to their distinct energy requirements.

TRNSYS-based studies demonstrate that multi-zone greenhouse models significantly enhance temperature distribution accuracy, reducing heating energy consumption errors by 30% compared to single-zone models [80]. These findings align with steady-state energy balance models, which highlight that latitude and climate classification strongly influence heating demand, with greenhouses in Csa climates requiring substantially less heating energy than those in colder zones [16].

To further refine heating strategies, insulation plays a key role in optimizing energy efficiency. In Csa zones, where temperature fluctuations between day and night are moderate. MATLAB-based simulations indicate that insulated greenhouses maintain nighttime temperatures 2–5 °C higher than transparent structure, reducing heat loss by 23.8% [81].

Computational approaches such as finite element method (FEM) and CFD modeling have been used to analyze the thermal environment and airflow distribution within greenhouses. FEM modeling has been applied to optimize heating pipeline configurations [82,83], while CFD simulations ensure uniform internal airflow, mitigating localized temperature variations [84,85]. Notably, models incorporating variable wind speeds demonstrate potential energy savings of up to 25% [86], which is particularly relevant in Csa climates, where passive ventilation strategies can be leveraged to further reduce energy consumption.

Hybrid energy systems have also been explored to enhance efficiency. EnergyPlus-based simulations of ground-coupled heat pump (GCHP) and PV systems indicate a potential reduction of approximately 21% in heating energy consumption [87]. Given the high solar radiation availability in Csa zones, such hybrid systems present a viable solution for sustainable greenhouse energy management.

Beyond physical modeling, machine learning techniques have been shown to be highly effective in forecasting greenhouse energy demands. Support vector machines (SVM) applied to short-term thermal load prediction reduced nRMSE by 30%–40%, stabilized state-of-charge fluctuations by 50%, and improved thermal energy storage (TES) efficiency [88]. The approach met 80% of heating demand, halved TES volume requirements, and minimized reliance on backup boilers, reducing both investment and operational costs while enhancing energy dispatch stability.

Artificial neural networks (ANNs) accurately predicted HVAC energy use during summer, with a Pearson correlation coefficient (R) of 0.9501 and normalized RMSE of 15.03%. Gaussian process regression also performed well in forecasting photovoltaic output, achieving R = 0.9422 and nRMSE = 13.61% over the same period [89]. These data-driven approaches complement conventional simulation based methods, supporting adaptive control strategies tailored to the dynamic climatic variability typical of Csa-classified regions.

(2) Cfa

Greenhouse energy modeling in Cfa climates, which are characterized by warm, humid summers and mild winters with consistent rainfall, focuses on managing high humidity, variable solar radiation, and seasonal temperature fluctuations. While these conditions are less extreme than in arid zones, they still present challenges for maintaining stable indoor environments. Most existing models focus on thermal performance, solar energy utilization, and heating efficiency, while offering limited attention to humidity control despite its importance in humid climates.

Heat exchange modeling has received particular focus in Cfa climates. A CFD-based simulation showed that using shade screens at night reduced the heat exchange coefficient by 12 to 18%, thereby improving thermal retention during cold periods [90]. Crop transpiration and optical properties were also found to affect internal temperature distribution in greenhouses, as demonstrated in a study on Shanghai facilities [91]. While Cfa regions receive high solar radiation annually, winter solar availability decreases with latitude, necessitating structural optimization for effective light capture and thermal gain [92]. To address overheating while maintaining adequate light, simulation tools have been developed to analyze the greenhouse light environment [93].

Heating system modeling has been explored by dynamic simulations. A TRNSYS-based model combining a water-to-water heat pump with a pellet boiler achieved a 9.45% reduction in life-cycle costs while improving heating efficiency [94]. In addition, an EnergyPlus based model for hydroponic container farms demonstrated an annual energy prediction error below 3%, confirming its reliability for long-term performance assessment in controlled environments [95].

Although Cfa climates are inherently humid, few studies have modeled indoor humidity dynamics in detail. This may be due to the alignment between ambient humidity levels and crop moisture requirements, reducing the perceived need for active humidity control. As a result, energy modeling in these regions has largely prioritized temperature regulation and energy efficiency. However, excess humidity can lead to condensation, disease pressure, and unstable microclimates, indicating a need for future models to integrate coupled heat and moisture transfer for more comprehensive environmental control.

(3) Cfb

The Netherlands has a temperate maritime climate with mild, wet winters and cool summers. As a result, Venlo-type glass greenhouses are widely used due to their efficiency in light transmission and environmental control. Supported by advanced greenhouse automation and environmental sensing systems, the country provides high-quality environmental data, improving the accuracy and applicability of AI-based models. Machine learning algorithms, including radial basis function (RBF) networks, SVM, and gaussian process regressors (GPR) were used to predict crop yield from time-series environmental data. Input features included air temperature, relative humidity, PAR, CO_2 concentration, and canopy temperature, reflecting dynamic microclimatic conditions. Among the models, the RBF network achieved the highest predictive performance, with an R^2 value of 0.98 [96].

3.3.2. Passive design and device-assisted enhancements in Zone C

(1) Csa

Passive and device-assisted strategies in Csa greenhouses have enhanced thermal stability and energy efficiency by improving cladding performance, optimizing heat exchange, and integrating solar energy storage. By mitigating summer overheating, retaining winter heat, and reducing energy demand, these solutions support climate-responsive and economically viable greenhouse cultivation.

For cladding materials, several energy-efficient options have been identified, including foam polyethylene [97], argon-filled double glazing [98], air-inflated double-layer claddings [99], and double reflective glass [100], all of which enhance thermal insulation and reduce energy consumption.

In heat exchanger applications, copper coil heat exchangers [21, 101] and multi-layer pipe systems [102] have demonstrated improved heat transfer efficiency, contributing to better thermal management.

Solar energy utilization has been optimized through various heat storage systems. Air-based solar heaters with multi-layer duct ventilation [103] and dual-medium (water and gravel) systems integrated with solar collectors and heat exchangers [104] enhance heating coverage and energy retention. Flat-plate solar collectors combined with water storage tanks and heat exchange networks leverage the thermosiphon effect for efficient energy transfer [105], while rock-bed thermal energy storage systems provide long-term heat retention for stable nighttime temperatures [106–108].

Water-based heat storage approaches, including heat pumps [109], CO_2 fertilization combined with passive water storage [110], and black plastic water sleeves for solar heating [111], further reduce 8.5%–42.5% energy loss in Csa greenhouses. Additionally, combined cooling, heating, and power (CCHP) systems offer integrated energy solutions, when the electricity to natural gas price ratio exceeds 3, the greenhouse can be profitable by selling electricity and even offsetting the cost of energy consumption [112].

Humidity control has received less attention, though heat pump dehumidifiers have been applied to prevent plant diseases while reducing energy use. However, their efficiency declines in low-temperature, dry conditions [113].

(2) Cfa

In Cfa climates, passive design and device-assisted strategies primarily focus on stabilizing temperature fluctuations and enhancing energy efficiency within greenhouse environments. Soil plays a crucial role in passive thermal regulation for plastic greenhouses, helping to buffer temperature changes and support plant growth [114]. Subsurface heating systems further optimize root-zone temperatures, contributing to stable thermal conditions for crops [115].

Water-based heat recovery technologies complement these efforts. A solid adsorption-based water-heat recovery system captures and reuses excess heat, improving overall thermal efficiency [116]. Cladding research has emphasized balancing solar radiation management with thermal control. Nanofluid spectral splitting coatings and transparent radiative cooling membranes mitigate overheating by selectively managing light transmission and heat dissipation [117,118]. The use of high-transmittance, low-thermal-gain materials tailored to specific crop needs further enhances light utilization while limiting unwanted heat accumulation [119]. Collectively, these approaches address the dual challenges of energy efficiency and microclimate stability in humid subtropical environments.

(3) Cwa

In Cwa climates, characterized by distinct wet and dry seasons and larger temperature swings, structural optimization plays a central role in energy management [120]. Studies have shown that asymmetrical overlapping roof designs reduce solar radiation intake by 14.2% in summer and increase solar gain by 8% in winter, improving seasonal energy balance. This configuration also decreases nighttime heat loss by 10.5%, effectively lowering heating demand during colder periods [121].

(4) Cfb

In Cfb climates, optimizing greenhouse passive design is essential for reducing energy consumption and enhancing crop productivity, particularly due to moderate temperatures and consistent rainfall patterns. One effective approach is the use of climate-specific greenhouse shells that dynamically adjust optical and thermal properties, achieving a 23%–37% reduction in heating energy use and a 7%–20% increase in crop yields [122]. Complementary to this, optimizing greenhouse geometry further improves energy efficiency. Reducing the roof slope ($\theta = 20\,^{\circ}$) and aspect ratio (0.55) suppresses natural convective heat transfer, minimizes nighttime heat loss, and enhances overall thermal performance [123].

3.3.3. Operational optimization in Zone C

(1) Csa

By integrating passive design with predictive control, operational optimization strategies in Csa greenhouses effectively balance solar energy utilization and temperature regulation, resulting in improved energy efficiency and stable crop production under dynamic climatic conditions. These approaches are particularly important in Csa climates, where high solar radiation and temperature fluctuations pose significant challenges for maintaining optimal growing environments. Multi-objective genetic algorithms (MOGA) have been applied to optimize passive design parameters, such as roof inclination, height, and orientation, to maximize solar gain while preventing overheating [124].

Beyond structural optimization, MPC has been employed to regulate heating water flow rates, air temperature, and overall energy consumption, achieving a 30% reduction in electricity use [125]. Furthermore, predictive control strategies have been developed for LED lighting systems, improving both energy efficiency and crop growth conditions [126].

(2) Cfa

In Cfa climate greenhouses, operational optimization primarily targets temperature and humidity regulation, as these factors critically impact energy consumption and crop performance [127–130]. However, most studies have addressed these variables independently, with limited integration of their combined effects.

To enhance energy efficiency, recent research has shifted toward multi-objective optimization frameworks that simultaneously account for multiple environmental factors. Deep reinforcement learning algorithms have been employed to reduce energy consumption by 28%–57% while maintaining optimal growing conditions [131,132]. Further advances in precision climate control integrate physics-informed neural networks with data-driven RMPC, achieving a 46.4% reduction in energy use while enhancing climate stability and enabling adaptive decision-making under dynamic conditions [133].

Beyond environmental control, operational optimization also considers system configurations and crop adaptability. Comparative studies evaluating open greenhouses, closed greenhouses, and plant factories under varying climatic conditions have identified the most energy-efficient setups for different scenarios [134]. Additionally, a climograph-based crop optimization method has been developed, aligning crop heat tolerance, environmental requirements, and cultivation cycles to minimize cooling loads and improve crop adaptability in Cfa zones [135].

(3) Cwa

Building on the climatic characteristics of Cwa regions, operational optimization has focused on enhancing energy efficiency and reducing production costs through advanced control and energy integration strategies. While MPC has been widely applied in Csa climates for regulating heating and lighting demands, its application in Cwa regions emphasizes multi-variable regulation, including temperature, humidity, CO_2 concentration, and light intensity, to address more variable environmental conditions [136]. To further improve sustainability, grid-connected PV systems have been integrated to supply renewable energy, lowering production costs and enhancing system resilience [137]. These approaches illustrate the importance of coupling demand-side climate control with renewable energy supply to achieve efficient and sustainable greenhouse operations in Cwa climates.

(4) Cfb

In Cfb climates, such as those in France and the United Kingdom, greenhouse control strategies have focused on improving energy efficiency and environmental stability under mild but variable weather conditions. In addition to the widely used MPC, IoT-based remote monitoring and AI-driven optimization have also been extensively explored. For instance, a multi-flow optimization framework integrating economic MPC with multi-energy MPC has been developed to coordinate heating, CO_2 fertilization, and thermal energy storage cycles, resulting in a 28% reduction in total energy consumption and a 6% decrease in CO_2 emissions compared to conventional rule-based control [138]. Furthermore, an IoT-based system combining physical modeling with closed-loop PI control achieved a 29.04% reduction in control error by precisely managing heating power, ventilation rates, and solar radiation gain [139]. These studies demonstrate the potential of integrating diverse control strategies to enhance operational efficiency and environmental regulation in Cfb greenhouses.

3.3.4. Renewable energy integration in Zone C

In Csa climates, characterized by high solar radiation and significant temperature fluctuations, renewable energy integration is critical for maintaining energy-efficient and stable greenhouse operations. Technologies such as PV, wind, geothermal, and hydrogen energy have been explored to optimize energy management, reduce carbon emissions, and enhance system resilience through intelligent control strategies.

Among these, PV systems are the most extensively studied for greenhouse applications [140], providing on-site electricity generation while offering shading benefits when installed on greenhouse rooftops. This shading effect not only reduces overheating but also limits excessive humidity loss, contributing to a more stable microclimate [141]. Research on PV-integrated greenhouses has demonstrated both opportunities and challenges [142]. For example, a study in Morocco showed that 40% rooftop PV coverage lowered summer temperatures, creating favorable conditions for tomato cultivation [143]. However, reduced winter solar availability led to yield losses, a trend observed in other studies as well [144–146]. To mitigate this issue, adjustable-angle PV panels have been developed to optimize light availability during winter while maintaining energy production [145,147]. These findings highlight the need for flexible PV integration strategies that balance energy generation with crop light requirements across seasons.

Beyond conventional PV applications, vertical farm integration has also been explored in Csa regions to enhance land-use efficiency. While vertical farming offers higher yields per unit area, its substantial energy demands pose challenges for renewable integration. One study found that even with PV coverage 4.5 times the farm area, only 12% of the required energy could be supplied, indicating the necessity for additional energy sources [148].

OPV technology presents a promising alternative due to its lightweight, flexible, and semi-transparent properties. A study integrating OPV with a GCHP demonstrated that OPV provided 16% of total electricity demand, while the GCHP improved heating efficiency by 21% compared to conventional systems [149]. However, the widespread adoption of OPV is constrained by its lower efficiency and shorter lifespan, necessitating further material advancements.

Given the high and variable energy demands of modern greenhouses, standalone PV systems are often insufficient to meet operational needs, leading to the development of hybrid renewable energy systems. Various configurations have been explored, including PV–wind hybrids [150–152], PV–geothermal systems [153], PV–battery storage [154], and PV–hydrogen energy storage solutions [155]. These hybrid systems improve energy reliability and sustainability, addressing the limitations of single-source renewables in dynamic climatic conditions.

Beyond Csa climates, renewable energy integration in Cfb, Csb, Cfa, and Cwa regions follows similar technical pathways. Despite climatic differences, these zones consistently prioritize PV systems, biomass energy, and hybrid configurations to improve energy efficiency and sustainability in greenhouse operations. Research highlights shared strategies such as PV tracking, biomass integration, and advanced energy management, adapted to local conditions but grounded in common technologies.

In Cfb climates, research has emphasized dynamic PV tracking and CO_2 utilization to improve both energy efficiency and crop productivity. A solar-tracking PV system in the Netherlands improved seasonal light conditions and thermal regulation, increasing electricity output by 6.91% [156]. These outcomes align with results from variable-shading PV systems in Csa zones, highlighting the cross-regional benefits of dynamic PV optimization. Additionally, in the United Kingdom, CO_2 fertilization using anaerobic digestion byproducts enhanced crop yields by 50% and reduced emissions by 14%–67% [157], reflecting similar trends observed in Csa climates [140].

In Csb climates, a biomass–PV hybrid energy system developed in South Africa achieved significant reductions in annual CO_2 emissions (14,370 t) and operational costs [158], consistent with hybrid PV–wind-battery strategies explored in Csa regions [151].

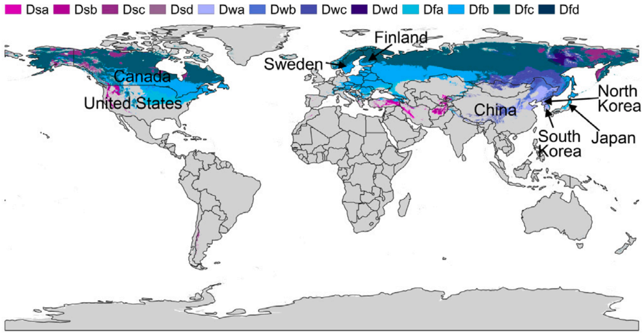

Fig. 8. Selected countries in Köppen climate Zone D (Continental).

For Cfa climates, semi-closed greenhouse systems integrating MPC and data-driven strategies achieved a 40.1% reduction in energy use and a 16.6% increase in crop yield. Photovoltaic generation met summer energy demands, while optimized heating reduced winter consumption by 25% [159].

In Cwa zones, modeling of PV-integrated greenhouses in Kunming, China, identified 40% PV coverage as optimal for balancing energy efficiency and climate regulation [160], mirroring findings from Csa regions [143].

3.4. Zone D

D climate zones, encompassing humid continental and subarctic climates and mapped in Fig. 8, are primarily located in Canada, Finland, and northeastern China. These regions experience pronounced interannual temperature variability, characterized by warm to hot summers and severely cold winters. In subarctic areas, average winter temperatures fall below −3 °C, with extremes dropping below −30 °C.

Humid continental climates (Dfa, Dwa) retain monsoonal influences, particularly in East Asia, while subarctic climates (Dfc, Dfd) experience more evenly distributed precipitation, with heavier snowfall during winter months. For example, Beijing (Dwa) records winter temperatures between −10 °C and −15 °C, occasionally dropping to −25 °C, while summer temperatures range from 20 °C to 30 °C. Annual precipitation generally falls between 500 and 700 mm, with an average annual sunshine duration of approximately 2490 h, subject to interannual variability.

3.4.1. Microclimate modeling in Zone D

A summary of the microclimate modeling methods and key findings for D-climate zones is presented in Table 4, consolidating the relevant studies discussed above.

(1) Dwa

In the Dwa climate zone, characterized by cold winters and warm summers, Chinese solar greenhouses (CSGs) are widely adopted, particularly in northern China. These greenhouses rely on the passive heat storage capacity of the north wall and soil to buffer against nighttime temperature drops [161]. Thermal storage modeling has therefore been a key research focus, with studies examining wall heat retention [162], the application of PCMs to enhance wall performance [163], and soil temperature dynamics for improving environmental control [164]. Optimizing cladding materials has further contributed to soil thermal stability, with temperature increases of approximately 2 °C reported [165]. Solar radiation modeling also plays a crucial role in improving greenhouse performance. For example, strategies such as enhancing the heat storage capacity of the north wall and adjusting the positions of insulation curtains on the south-facing roof have been shown to increase solar energy utilization by 14.7–41.1% and improve nighttime thermal stability [166]. These efforts underline the importance of thermal storage optimization in CSGs for winter energy efficiency.

Structural design significantly impacts greenhouse energy performance [167]. Modeling studies have highlighted the interaction between span and ridge height, where excessive span increases surface area and heat dissipation [168]. Simulation-based optimization combining mathematical modeling, 3D dynamic simulations, and finite element analysis has increased solar absorption by 5.4 MJ/m^2 and raised indoor temperatures by 3.1 °C while enhancing structural stability [169]. However, maintaining stability with larger spans often necessitates higher ridge heights, which expand greenhouse volume and exacerbate heat losses [170]. To address this, mathematical models integrating experimental data and CFD simulations have been developed to optimize the span-to-ridge height relationship. A ridge height-to-span ratio of 0.53 with a 4.2 m north wall height reduced heating demand by 9.8% and enhanced nighttime heat accumulation by 14.2% [171,172]. These findings emphasize the need for geometric optimization to balance energy efficiency and structural stability under extreme climate conditions.

In addition to thermal and structural considerations, the relationship between energy consumption and crop yield has been explored. Using TRNSYS-DVBES modeling, studies have predicted energy demand and strawberry yields, identifying optimal temperature (8–13 °C at night, 18–23 °C during the day) and humidity ranges (60%–75%) for maximizing productivity [173,174].

Environmental heterogeneity, particularly in light and temperature distribution, presents further challenges. Three-dimensional light modeling has revealed that upper canopy leaves intercept over 60% of solar radiation, leaving lower layers underexposed, underscoring the need for spatially resolved light optimization [175]. Similarly, temperature variability remains significant, with natural ventilation serving as a key regulation mechanism. Numerical simulations show that increasing the side window opening angle enhances airflow and reduces localized overheating [176].

Summer cooling strategies further impact energy dynamics. While passive methods such as ventilation and shading reduce energy use, they increase internal temperature fluctuations. In contrast, mixed systems combining fans, heat pumps, and air handling units provide greater thermal stability (maintaining 24 °C), albeit with higher energy consumption [177]. These findings highlight the ongoing challenge of balancing energy efficiency and environmental stability in greenhouse design and operation.

(2) Dfb

In Dfb climates, characterized by moderate summers and cold winters, greenhouse modeling has advanced in thermal environment prediction, energy optimization, and the development of high-density controlled environment agriculture (CEA-HD) systems. These climatic conditions require precise energy management to maintain stable microclimate throughout the year.

A notable example of cross-zone technology adaptation is the application of CSG concepts, originally designed for Dwa climates, to Manitoba, Canada. The SOGREEN model, validated with local field data, demonstrated potential for climate-specific greenhouse design. However, prediction errors of 1.9 °C for temperature and 7.0% for humidity indicate the need for further model refinement [178].

To improve energy optimization, TRNSYS combined with MOGA reduced temperature prediction errors to 1.6 °C, enhancing greenhouse climate control precision [179]. Alternative heating strategies, such as utilizing mining waste heat, lowered heating costs by 55% in low-electricity zones, though their economic feasibility remains sensitive to fluctuating energy prices [180].

With the increasing adoption of CEA-HD systems, where lighting accounts for 66.14% of energy use [182], modeling approaches have incorporated CFD-enhanced EnergyPlus calibration to improve thermal simulation accuracy and support optimized energy management [181].

Table 4
Summary of microclimate modeling approaches and key insights for greenhouse applications in D-Climate Zones.

Climate type	Focus area	Modeling approach	Key variables	Key findings	Reference
Dwa	Heat Storage & Soil Temp Modeling	Energy balance & empirical modeling, CFD	Wall/soil temp, PCM, cladding material	North wall & soil temp impact nighttime heat stability; PCM and materials improve performance	[161–165]
	Solar Radiation Optimization	Solar radiation modeling	Insulation curtain position, wall storage	Optimized wall and insulation improve solar use by 14.7–41.1%	[166]
	Structural Geometry Optimization	3D simulation, FEM, mathematical modeling	Span, ridge height, solar absorption	Optimized geometry boosts absorption by 5.4 MJ/m^2, indoor temp +3.1 °C; ideal ridge/span ratio is 0.53	[167–172]
	Energy-Yield Correlation	TRNSYS DVBES modeling	Temperature, humidity, yield	8–13 °C night, 18–23 °C day, RH 60%–75% optimize strawberry yield	[173,174]
	Light Distribution Modeling	3D light simulation	Solar radiation, canopy layer	Upper canopy receives >60% solar; lower shaded; need for light balancing	[175]
	Ventilation & Cooling	CFD + system modeling	Ventilation angle, temperature stability	Natural ventilation enhances flow; mixed systems stable at 24 °C but use more energy	[176,177]
Dfb	Greenhouse Adaptation & Heating	TRNSYS + MOGA + field validation	Energy use, heating method, prediction accuracy	CSG adapted to Canada; TRNSYS+MOGA reduced temp error to 1.6 °C; waste heat cut cost by 55%	[178–180]
	CEA-HD Simulation	CFD-enhanced EnergyPlus	Convective coefficients, lighting loads	Lighting = 66.14% of energy use; improved climate control via model calibration	[181,182]
Dsa	Passive Storage	Dynamic energy modeling	Wall/roof heat loss	Heat losses through walls, roofs, and floors account for approximately 63% of the total thermal loss	[183,184]

(3) Dsa

In Dsa climates, marked by arid summers and cold winters, greenhouse energy research focuses on solar energy utilization and heating optimization. Dynamic thermal modeling of an east–west oriented single-span greenhouse in northwest Iran improved winter light use by 8%, reducing heating demand [183].

Energy and mass balance modeling revealed that heat losses through walls, roofs, and floors account for 63% of total thermal loss, highlighting the need for effective insulation and renewable heating integration [184]. To address this, solar heating, heat pumps, and other renewable sources have been proposed to reduce fossil fuel dependence.

3.4.2. Passive design and device-assisted enhancements in Zone D

(1) Dwa

- Geometry and wall thermal storage enhancement

The optimization of greenhouse geometry, including adjustments to roof angle, ridge height, and wall dimensions, contributes to improved solar energy capture, reduced surface heat loss, and enhanced indoor thermal stability. A globalized design framework developed for Dwa climates demonstrated that adjusting the angle of the front roof, the height of the ridge and the north wall allowed unheated cultivation in high-latitude regions, improving thermal stability and reducing the loss of energy at night [185]. Similarly, shape optimization of CSGs increased minimum nighttime temperatures by 2 °C, enhanced solar energy capture by 22%, and significantly reduced coal consumption and carbon emissions [186]. These findings underscore the importance of geometric adaptation in improving passive heat retention and energy efficiency in cold climates.

In addition to optimizing the overall greenhouse configuration, enhancing the thermal storage capacity of wall structures is critical for sustaining nighttime temperatures and minimizing heating demands in Dwa greenhouses.

Research on wall thermal storage has focused on layering structures and improving materials to enhance insulation and heat retention. Multilayer insulated walls maintained nighttime greenhouse temperatures at 10.1 °C, sustaining a maximum indoor–outdoor temperature difference of 38 °C and reducing heat loss through the south roof by 26.3% [187]. A prefabricated multilayer wall system incorporating expanded polystyrene insulation increased heat storage by 24.95% and heat release by 41.72%, sustaining discharge for over six days [188].

Material selection also significantly affects thermal storage. Compared to traditional rammed earth walls, concrete-layered walls improved heat storage capacity by 38%, which subsequently raised nighttime temperatures by 2.5 °C and reduced heat loss by 13.9% [189]. The straw block walls provided resistance to mold and improved thermal humidity conditions, increasing nighttime temperatures by 1.2 °C and lowering humidity by 5.3% [190]. In extreme cold regions, combining PCM and expanded polystyrene layers proved effective in reducing heating energy demand [191].

- Thermal management and optimization of greenhouse cladding

Optimizing greenhouse cladding systems, particularly in terms of insulation performance, light regulation, and integrated energy functions, plays a critical role in reducing heat loss, managing solar gain, and maintaining stable microclimates within Dwa climate regions. In CSGs, the south roof contributes 70%–80% of total heat loss, which can be reduced by up to 86.4% through optimized insulation blankets [192]. Despite these improvements, water vapor condensation remains a significant contributor, accounting for 41.1–48.4% of heat losses, emphasizing the need for materials with better permeability and refined irrigation strategies. Roof components exhibit high thermal transmittance (U-values up to 4.35 W/m^{2}K), responsible for approximately 78.2% of heat loss [193].

To improve insulation performance, double-layer cladding systems have been developed. Combining PVC films with a thermal buffer zone raised nighttime air and soil temperatures by nearly 7 °C compared to single-layer configurations [194]. Additional insulation layers further enhanced solar energy capture by 3.9–9.5 MJ and stabilized internal temperatures [195]. Cotton insulation combined with plastic films maintained indoor temperatures above 12 °C under external −18.6 °C conditions [196]. In multi-span greenhouses, multilayer energy-saving screens reduced energy use by up to 60% [197,198], underscoring the effectiveness of layered insulation strategies in minimizing winter heating demand.

Beyond insulation, advanced optical materials have been incorporated into greenhouse cladding to balance heat retention and crop-relevant solar transmission [199,200]. For instance, anti-reflective coatings on spectrally selective layers increased transmittance at key wavelengths, improving crop exposure to photosynthetically active radiation [201]. Dimmable panels adjusted light transmittance (35–57.87%), producing 9 kWh/m^2 of electricity while lowering indoor temperatures by 3–5 °C [202]. In a related approach, compound parabolic concentrator (CPC)-based solar roofs achieved a thermal efficiency of 32.2%, contributing to both improved winter heating and enhanced light distribution within the greenhouse [203].

To further enhance thermal stability, PCM have been integrated into greenhouse cladding systems, offering additional heat buffering and release capacity [204]. For instance, a 45 mm PCM layer increased nighttime temperatures by 1–2 °C and stabilized diurnal fluctuations [205]. Transparent PCM-embedded claddings achieved a greater effect, raising nighttime temperatures by 4 °C [206]. Additionally, PCM combined with thermal screens reduced heating demand by 16.4%, with particularly notable performance in east–west oriented greenhouses [207]. Beyond passive storage, coupling thermally responsive claddings with intelligent control systems enables dynamic regulation of heat and light transfer, further improving energy efficiency and supporting crop productivity.

In summary, integrating insulation layers, optical materials, PV systems, and PCM-based storage within cladding designs offers a comprehensive approach to managing heat loss and solar gain in Dwa greenhouses, ensuring stable microclimates and energy-efficient operation.

- Active and hybrid thermal management

Active thermal management systems are critical for improving greenhouse energy efficiency and stabilizing microclimates. Among these, solar collectors (SCs) are widely applied across Dwa regions due to their high thermal efficiency and cost-effectiveness [208–210]. At inlet water temperatures below 13.8 °C, SC systems raise nighttime temperatures by 3.2 °C, maintaining levels above 6.9 °C [211]. Integrating SCs with sliding-cover greenhouses further enhances cold resistance, elevating nighttime temperatures by 3 °C during extreme events [22].

To enhance heat retention and utilization, SCs are often integrated with thermal storage systems. For example, a dual-receiver solar collector combined with a water-cycle heat storage–release system maintained nighttime temperatures above 9 °C, achieving a 70.2% collection rate even during consecutive cloudy days [212]. Similarly, SCs paired with an active-passive ventilation wall and latent heat storage supplied 11.83 GJ of heat during winter, raising nighttime temperatures at the north wall, air, and soil by 7.5 °C, 1.8 °C, and 1.5 °C, respectively [213]. A north-roof water storage system integrated with SCs further improved nighttime heat release by 19.56% and reduced heat losses, achieving an average heat flux of 0.21 W/m^2 [214]. Furthermore, coupled heat-humidity regulation systems expanded the functionality of SC-based designs. For example, narrow-slot SCs combined with solid desiccants reduced nighttime humidity by 12.9% while increasing air temperatures by 1.2 °C [215].

In addition to conventional SC configurations, solar-assisted thermal systems such as solar water walls and water curtains demonstrated comparable nighttime temperature improvements of 3.3–3.6 °C. These systems also offered benefits including humidity reduction and economic feasibility, with payback periods as short as 1.4 years [216,217].

Beyond heating the air in the greenhouse, solar energy has been applied to soil heating and sterilization [218]. A combination of CPCs and PV/T systems achieved 60.4% efficiency, providing both electricity generation and thermal self-sufficiency [219]. CPC-based solar soil sterilization raised surface soil temperatures to 59 °C and 48.6 °C at 0.15 m depth, while reducing CO_2 emissions by 410.82 kg, demonstrating energy-saving and carbon-reduction potential [220].

Complementary to solar-based systems, heat pumps and waste heat recovery units offer flexible energy supplementation. Multifunctional air conditioning systems utilizing waste heat raised nighttime temperatures by 2.8 °C, reduced humidity by 13.2%, and covered 95% of heating demand under cloudy conditions, achieving 13%–23% energy savings [221]. Dual-source heat pumps leveraging internal heat sources improved COP by 23%–26% and maintained nighttime temperatures at 12.7 °C [222]. Air-source heat pumps (ASHPs) combined with water storage sustained a COP of 2.2 even at ambient temperatures of −13 °C [223]. However, limited summer cooling capacity led to internal temperature peaks of 30 °C, indicating a need for further system refinement [224,225].

Finally, hybrid systems integrating active and passive components provide additional thermal stability. Integrating PCMs with micro heat pipe arrays improved heat transfer efficiency, increasing storage capacity by 95.35% and raising nighttime temperatures by 1.75 °C [226]. Similarly, underground energy migration systems and vertical heat exchange pipes combined with PCMs raised nighttime temperatures by 1.36–5 °C and achieved COP values up to 5.14 [227,228]. Ventilated walls combining PCM storage with SCs raised nighttime temperatures by 0.8–1.4 °C [229,230]. More advanced setups incorporating air-channel heat exchangers, PCM walls, and PV/T hybrids achieved temperature increases of 1.6–4.2 °C, with COP values reaching 5.59 [231]. Furthermore, systems coupling underground heat exchange with solar assistance maintained nighttime temperatures at 12.8 °C and humidity at 83.6%, ensuring stable microclimates [232].

(2) Dfb

In the Dfb climate zone, TES systems are widely employed to enhance greenhouse heating and reduce fossil fuel reliance. A borehole TES combined with heat pumps stored surplus summer heat for winter use, stabilizing thermal supply and mitigating temperature fluctuations [233]. Similarly, a rock bed TES captured daytime solar heat and released it at night, raising nighttime temperatures by 7 °C and lowering daytime peaks by 5 °C, thus reducing diurnal temperature swings and improving crop conditions. Energy analysis showed it stored up to 103 kWh daily (6.2–10.6% of solar input), with a heating COP of 1.4–3.0, indicating good efficiency [234].

In addition, solar energy integration with advanced insulation and control strategies further enhances energy efficiency. A low-temperature heating system combining water curtain heating with liquid foam insulation minimized heat loss and enabled effective use of low-grade waste heat at outdoor temperatures down to −19 °C [235]. Meanwhile, thermochromic materials for solar regulation achieved 13% energy savings and 20% CO_2 reduction compared to conventional glazing, highlighting their potential for intelligent greenhouse applications [236].

Beyond heat management, humidity control and air management systems contribute significantly to overall efficiency. Integrating LED lighting with mechanical refrigeration dehumidifiers, liquid desiccant dehumidification, and heat recovery ventilation got 10.6–15.4% energy savings through optimized control strategies [237]. Among these methods, heat recovery ventilation provided the best balance between energy consumption and dehumidification capacity [238].

(3) Dsa

In the Dsa climate zone, characterized by high solar radiation and large diurnal temperature variations, research has focused on thermal insulation measures and passive solar greenhouse design to improve energy efficiency and maintain stable microclimates. One effective approach involves thermal curtains, which reduce nighttime heat loss and enhance indoor climate stability. In a comparative study, thermal curtains increased indoor temperatures by 1.3 °C and relative humidity by 10%, while reducing heat energy consumption by 21%, fuel costs by 21%, and CO_2 emissions by 29.5 kg/night [239].

In addition, passive solar greenhouse structures, incorporating a 1-meter underground foundation and soil-based north walls, have been shown to enhance thermal storage and reduce heat loss. Evaluations of various wall materials, including brick, concrete, wood, and metal, demonstrated a 30% reduction in annual heating demand, with monthly heating needs as low as 126 MJ/m^2 compared to 796 MJ/m^2 in the least efficient configuration [240].

3.4.3. Operational optimization in Zone D

(1) Dwa

The Dwa climate zone, characterized by cold winters and large diurnal temperature variations, poses significant challenges for greenhouse energy management. Intelligent control and multi-objective optimization are crucial for balancing microclimate stability, energy efficiency, crop productivity, and carbon reduction. Recent advances integrate predictive control, dynamic scheduling, and optimization algorithms to improve greenhouse performance across multiple scales.

At the microclimate level, MPC has outperformed traditional PID methods. In a solar-assisted underground air heat exchanger, MPC enhanced temperature stability by 10.56%, reduced overshoot time by 29.7%, and lowered energy consumption [241]. Similarly, wireless sensor network-based control optimized heating and lighting setpoints, cutting heating energy use by 3.94% and lighting electricity by 7.88%, supporting low-carbon operations [242].

Multi-objective optimization further refines environmental control. Techniques such as rolling horizon optimization and reduced-order modeling improved crop yields by 43% while reducing energy use by 13.8% [243]. Additionally, CFD-based optimization using NSGA-II algorithms enhanced temperature uniformity and optimized CO_2 distribution and shading coefficients [244].

At the system level, energy scheduling ensures efficient resource allocation. Mixed-integer linear programming coordinated energy flows between building microgrids and rooftop greenhouses under equipment constraints [245]. In photovoltaic aquaculture greenhouses, distributionally robust optimization reduced operational costs by 74.83% and carbon emissions by 33.75% [246]. Similarly, a solar-biomass integrated system optimized load management for low-carbon operations [247]. Intelligent control also enhances renewable energy integration. A multi-energy system combining solar, wind, and biomass, optimized via an adaptive genetic algorithm, maintained temperature within ± 0.5 °C, humidity within $\pm 1\%$ RH, and CO_2 fluctuations within $\pm 2.5\%$, ensuring environmental stability and energy efficiency [248].

In parallel, intelligent energy management improves operational efficiency. Agent-based modeling optimized heating, lighting and ventilation schedules in the greenhouse–livestock systems, reducing operational costs by 50.68% and enhancing renewable energy utilization [249]. In aquaponic systems, RMPC reduced energy consumption by 11.73% in summer and 8.49% in winter while improving peak load regulation [250].

Investment optimization supports long-term feasibility alongside technical advancements. Multi-criteria decision-making applied to agri-photovoltaics (APV) systems with integrated storage balanced economic, environmental, and social objectives, improving land use efficiency, reducing emissions, and enhancing system viability [251].

(2) Dfb

The Dfb climate zone, with harsh winters and large variations in diurnal temperature, demands advanced greenhouse control strategies to improve heating uniformity, energy management, waste heat recovery, and load regulation. Compared to Dwa regions, research in Dfb climates emphasizes coordinated control across greenhouse clusters and long-term energy efficiency.

In heating optimization, a dual-side air supply system reduced internal temperature variation by 10 °C, minimized nighttime fluctuations, and enhanced heating efficiency and crop growth uniformity, outperforming top-side air supply configurations, which led to uneven heat distribution [252].

For energy management, distributed optimization across greenhouse clusters coordinated heating, lighting, and CO_2 supply, reducing peak electricity demand by 17.5% and increasing renewable energy utilization by 12.3% [253]. Stochastic optimization applied to PV-combined heat and power (CHP)-storage systems further reduced natural gas consumption by 24.7% and improved renewable self-consumption by 12.3%, enhancing sustainability in cold-climate greenhouses [254].

In waste heat recovery, dynamic Pinch analysis integrated with underground thermal storage and heat pumps cut primary energy use by 57% and cooling demand by 82% during high-temperature seasons [255]. Ventilation waste heat recovery further improved storage efficiency, achieving a 55% recovery rate [256].

For load regulation, aggregated load control strategies optimized lighting, humidification, and temperature, reducing peak electricity demand and enhancing renewable energy integration [257]. Additionally, nonlinear MPC reduced operational costs by 20.2% and climate parameter deviations by 4.2%, improving environmental stability [258].

3.4.4. Renewable energy integration in Zone D

(1) Dwa

In the Dwa climate zone, renewable energy integration significantly enhances greenhouse energy efficiency and crop production. APV systems and PV/T configurations are both central to this strategy. Off-grid APV integrated with mist cooling improved mushroom yields by 14.3% and individual plant weight by 26.3% through optimized microclimates (18–25 °C, 80%–95% RH) [259]. Sky illuminance models optimized APV shading layouts to balance energy harvesting and crop illumination [260]. Dynamic APV designs, such as reverse-tracking systems, increased canopy PAR by 53.06%, while conventional tracking benefited shade-tolerant crops like lettuce [261]. APV also effectively maintained grape yield and quality by adjusting harvesting schedules under controlled shading [262].

Advanced APV systems further enhance greenhouse environmental control [263]. Spectrally separated concentrating APV reduced internal temperatures by 3–5 °C, increased biomass by 13%, and produced 10.86 kWh/m^2 over 50 days [264]. Nanofluid-based full-spectrum solar systems achieved high photothermal efficiency (73%) and substantial annual energy outputs (358.9 kWh/m^2) with short payback periods (0.76 years) [265].

PV/T systems provide another key solution by capturing waste heat for simultaneous electricity and thermal generation, suitable for cold-season heating. Micro heat pipe PV/T systems achieved notable efficiencies (8.3% electrical, 40.93% thermal) [266], while Fresnel lens-based PV/T reached combined utilization rates of up to 55% [267]. However, PV/T performance depends heavily on thermal management and climate variability.

Hydrogen fuel cells represent an alternative renewable energy approach, converting chemical energy into electricity and providing heat and CO_2 enrichment, thus improving greenhouse energy efficiency and crop growth [268]. A hydrogen-based CHP system attained a comprehensive energy utilization of 73.36%, but broader adoption remains constrained by high hydrogen production and storage costs [269].

Hybrid renewable energy systems that combine biomass boilers and water-source heat pumps offer cost-effective heating for high-demand greenhouses. Triple-hybrid configurations (biomass, heat pumps, solar thermal) maximize renewable utilization and adaptability to seasonal temperature fluctuations [270]. PV-integrated thermal concentrators further enhance flexibility, accelerating greenhouse defrosting and extending operational periods [271]. ASHP systems integrated with PV improved nighttime temperatures by 5.3–7.3 °C, significantly benefiting strawberry yields and photosynthesis [272]. However, hybrid systems face challenges from control complexity and high initial investments.

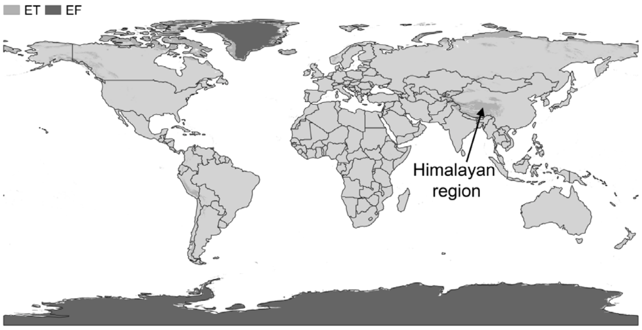

Fig. 9. Regions in Köppen climate Zone E (Polar).

(2) Dfb

Although both Dfb and Dwa zones share similar renewable energy goals for greenhouse operations, their technological strategies diverge due to different climatic conditions. The Dfb zone, characterized by colder winters and reduced sunlight, emphasizes technologies that enhance light transmission and thermal management, such as semi-transparent PV/T systems, container-sized agricultural units (CSAUs), and biomass-based polygeneration systems.

Like Dwa, Dfb greenhouses adopt PV optimization, active heating, and biomass energy to meet energy demands. For instance, optimizing a rooftop PV system for a Venlo-type greenhouse in Harbin, China, generated 35.8 MWh annually with a payback period of 3.02 years and a carbon reduction of 11,202 kg, while maintaining shading below 25% [273].

STPV systems are used in both Dfb and Dwa zones, though their primary functions differ: in Dwa zones, they mainly modulate excess solar radiation, while in Dfb zones, they enhance light transmission for crop productivity under limited sunlight. In Dfb, semi-transparent PV/T systems with thermal collectors raised greenhouse air temperatures by 6–8 °C and generated 6–7 kW of electricity, supporting stable year-round production [274]. However, their lower electrical efficiency compared to opaque PV remains a challenge.

In extreme cold, CSAUs offer a compact alternative to open-field cultivation, replacing up to 1020 m^2 of farmland with just 30 m^2 of stacked space. A renewable-powered CSAU model combining biomass, PV, wind, and waste-to-energy technologies could supply vegetables to 24.4% of the global population, though high initial costs and system standardization remain barriers [275].

STPV greenhouses in Canada reduced heating energy use by 12%, though supplemental lighting demand increased by 84%. Current systems meet 43.7% of lighting needs, with future potential could exceed total needs, but long payback periods remain a barrier [276].

For biomass energy, polygeneration systems based on dual-fluidized bed gasification provide heating, electricity, and CO_2 fertilization. One system with 8000 kW capacity achieved a net present value of 17.6 million Canadian dollars and an internal rate of return of 20.2%, though economic viability remains sensitive to hydrogen prices [277].

3.5. Zone E

This review identified only one relevant study on greenhouse energy consumption in Zone E (polar and alpine climates, see Fig. 9), indicating a significant research gap. This scarcity is largely attributable to the extreme environmental and operational challenges associated with greenhouse cultivation in these regions, where heating constitutes the primary energy demand.

The identified study, conducted in the Himalayan highlands, investigated a hybrid renewable energy system integrating solar, geothermal, and wind power to address these demands [278]. The proposed configuration reduced heating requirements by 35% through geothermal integration and mitigated nighttime heat loss by 50% by thermal energy storage, including PCMs and underground storage. Despite these advances, the study underscored significant barriers to implementation, primarily high capital costs and performance instability under extreme climatic variability.

This evident research gap calls for further investigation into economically viable hybrid renewable systems for Zone E. Key areas include modular system design to lower initial investment, development of advanced PCMs with enhanced thermal conductivity, and integration of multi-functional storage solutions. Additionally, greenhouse design must evolve to incorporate high-performance insulation, adaptive glazing technologies, and responsive control systems to ensure microclimate stability while minimizing energy inputs in these harsh environments. For a summary of climate-specific strategies, refer to Table A.1 in the Appendix.

4. Discussion

4.1. Adaptation strategies to extreme weather events

As each Köppen climate type corresponds to distinct weather extremes, such as extreme heat, cold, humidity, or seasonal variability, it also dictates unique challenges for greenhouse energy management. Table 5 summarizes representative adaptation strategies for greenhouses across major climate zones, highlighting the alignment between extreme weather conditions and the deployment of passive design solutions, renewable energy integration, and advanced thermal control technologies. This climate classification-based approach provides a global perspective on tailoring energy solutions to climate-specific demands.

4.1.1. Climate-zone-specific adaptation strategies

This subsection synthesizes adaptation strategies for representative Köppen climate types. For each major climate group, we summarize the dominant extreme-weather challenges identified in the reviewed studies and the main bundles of technologies that have been deployed in practice or tested in simulations.

Tropical Savanna Climates (Aw)

Tropical savanna climates, such as in southern Nigeria, experience year-round high temperatures and distinct wet-dry seasons. These conditions create persistent cooling demands in greenhouse systems.

Given abundant solar radiation but limited wind resources, PV systems combined with battery storage are the predominant energy solution [24]. While effective in ensuring energy reliability, heavy storage dependence constrains scalability.

Arid Desert Climates (BWh)

In arid desert climates, such as Qatar and Algeria, extreme heat and water scarcity drive high greenhouse cooling and irrigation demands. To address these, spectrally selective nanofluids have been applied in cooling systems, effectively lowering indoor temperatures and reducing energy consumption [47]. Solar-powered floating greenhouses further mitigate irrigation challenges by utilizing local water bodies for passive cooling and water recycling [51]. Additionally, bioenergy systems with carbon capture enhance resource efficiency by recycling CO_2 for crop growth [63].

Subtropical Humid Climates (Cfa)

Subtropical humid climates, such as those in southern China and South Korea, experience extreme summer heat combined with prolonged high humidity. These conditions lead to elevated cooling and dehumidification demands in greenhouse environments.

Transparent radiative cooling films and PV systems help mitigate heat stress while improving energy efficiency in greenhouse operations [198,261].

Table 5
Adaptation strategies for the extreme weather.

Climate type	Countries/Regions	Extreme weather challenge	Adaptation strategies	Reference
Tropical (Aw)	Nigeria, Thailand	High humidity and consistent high temperatures.	Hybrid renewable energy systems combining PV and wind; Smart greenhouses with adaptive cooling.	[23,24]
Arid Desert (BWh)	Qatar, Algeria, Egypt	Extreme heat and water scarcity.	Spectrally selective nanofluids for heat reduction; APV systems; Seawater heat exchangers.	[47,51,54]
Subtropical Humid (Cfa)	South Korea, South of China	High summer temperatures and humidity.	Mechanical cooling and ventilation systems; Solid desiccant dehumidification; Transparent radiative cooling films.	[116,117]
Temperate Oceanic (Cfb)	UK, Netherlands	Mild temperatures and high humidity.	CCHP with anaerobic digestion; dynamic PV systems with smart controls.	[112,138]
Mediterranean (Csa)	Italy, Greece, Spain	Hot summers and significant heating demands in winter.	Dynamic insulation systems; PV-integrated APV greenhouses; Passive solar heating with energy storage.	[16,99,110]
Monsoon-Influenced Humid Continental (Dwa)	Northern China, South Korea	Dry, cold winters with peak heating loads.	Building envelope with PCM; Solar collectors; Thermal storage systems; Heat pump	[185,187,191], [209,224]
Humid Continental (Dfb)	Finland, Sweden, Romania	Long cold winters with high energy demands for heating.	Seasonal thermal storage using boreholes; Low-temperature heating with water curtains; Hybrid energy systems integrating solar, biomass, and wind.	[233], [235,275]
Polar and alpine climates (ET/EF)	Himalayan region	extreme cold, with the warmest monthly temperature remaining below 10 °C.	Geothermal and wind energy; PCM and underground heat storage.	[278]

Temperate Oceanic Climates (Cfb)

Temperate oceanic climates, such as those in the United Kingdom and the Netherlands, feature mild temperatures year-round but consistently high humidity. These conditions require reliable humidity control and supplemental heating in greenhouse operations.

CCHP systems integrated with anaerobic digestion for CO_2 reuse can significantly improve energy efficiency [112]. Additionally, IoT-based environmental monitoring and MPC enhance climate regulation and resource optimization [138]. However, the complexity and high initial costs of such systems may hinder adoption in small-scale operations, indicating a need for more scalable and cost-effective solutions.

Mediterranean Climates (Csa)

Mediterranean climates, such as those in Spain and Italy, are marked by hot, dry summers and mild, wet winters. These seasonal extremes create dual energy demands for both cooling and heating in greenhouse operations.

Passive solar heating and dynamic insulation technologies help increase nighttime temperatures and reduce heat loss and CO_2 emissions [99,110]. STPV systems further improve performance by balancing crop lighting with electricity generation [74,149]. However, seasonal fluctuations in solar availability may reduce efficiency, highlighting the need for adaptive energy strategies that respond to changing climatic conditions.

Continental Monsoon Climate (Dwa)

Continental monsoon climates, such as those in northern China and South Korea, are characterized by hot summers and long, dry, cold winters.

Greenhouse operations in these regions face particularly high heating demands during the winter season. To meet these demands, systems often combine solar thermal collectors, heat pumps, and thermal energy storage technologies [187,209,224]. PCM embedded in the building envelope further improves insulation and stabilizes indoor temperatures under extreme winter conditions [191].

Humid Continental Climates (Dfb)

Humid continental climates, such as those in Finland and Romania, are marked by long, cold winters and moderate summers. These conditions result in consistently high heating demands for greenhouse operations during the winter months.

Seasonal thermal energy storage, including borehole systems, enables the capture of summer heat for winter use, enhancing energy resilience [233]. Hybrid insulation strategies, such as combining water curtains with foam insulation [235], and integration of renewable sources like solar and wind further support energy efficiency and enable CO_2 enrichment for improved crop productivity [275]. Nonetheless, system complexity and high upfront costs remain key barriers, highlighting the need for simplified and modular solutions suited to cold climate contexts.

Polar and Alpine Climates (ET/EF)

Polar and alpine climates, such as those in the Himalayan region, are defined by extreme cold, limited solar availability, and prolonged winters. These conditions lead to exceptionally high heating demands in greenhouse systems, particularly in isolated or high-altitude areas.

A hybrid renewable approach that integrates solar, geothermal, and wind energy with thermal storage shows promise in reducing heating demand under extreme climatic conditions [278]. However, high capital costs, reduced system reliability in severe cold, and logistical constraints hinder large-scale implementation.

4.1.2. cross-climate consistency and strength of reported outcomes

Across climate zones, several consistent patterns emerge in the performance of greenhouse energy strategies. In heating-dominated continental and cold climates, envelope-oriented measures such as multilayer claddings, energy-saving screens, and thermal storage repeatedly show substantial and robust reductions in heating demand, with agreement between field studies and validated simulations. By contrast, in temperate and humid climates, many of the reported benefits stem from advanced control and semi-closed configurations, which deliver double-digit energy savings while stabilizing temperature, humidity, and CO_2, but are still evaluated mainly in a limited number of demonstration sites.

In hot-arid and tropical climates, cooling and water-oriented strategies consistently reduce peak cooling loads and freshwater use, yet the underlying evidence base is more heterogeneous and often relies on short-term or single-site studies. Polar and alpine regions remain represented by only one integrated case. Even within the same climate group, reported gains for similar strategies vary widely, reflecting differences in greenhouse design, crop requirements, local energy prices, and study duration. Overall, drawing on the qualitative evidence assessment in Section 2.5, most high-strength evidence currently concentrates in Zones C and D, whereas Zones A, B, and E are dominated by exploratory simulations and prototypes. This imbalance highlights both where recommendations are relatively robust and where further field-validated and multi-site research is needed.

4.1.3. Mechanistic pathways linking climate, technology, and operation

The climate-zone summaries above can also be interpreted through common mechanistic pathways that link climatic drivers to greenhouse energy demand and, in turn, to preferred technology packages. In hot-arid climates, very high solar gains, large diurnal amplitudes, and low humidity produce strong cooling needs under severe water constraints; it is therefore consistent that spectrum-selective envelopes, evaporative and desiccant cooling, and renewable-powered water-energy systems are repeatedly proposed, as these directly target the coupled thermal and water stresses. In humid subtropical and monsoon-influenced climates, persistent high humidity means that dehumidification and disease prevention become as critical as temperature control, which explains the emphasis on semi-closed configurations, desiccant-based systems, and advanced controllers that can decouple humidity and CO_2 management from simple ventilation.

In temperate and cold climates, long heating seasons and frequent sub-zero conditions make conductive and infiltration heat losses dominant in the energy balance. As a result, envelope insulation, thermal mass, and seasonal storage emerge as primary levers, often complemented by solar thermal or heat-pump systems. Across all zones, these examples illustrate a common sequence from external drivers (temperature regime, humidity, solar resource, water availability) to characteristic load profiles and then to specific combinations of passive measures, active control, and renewable integration. Making this chain explicit helps move beyond a purely categorical classification. It also provides a basis for extrapolating findings to new locations and for linking climate-based analyses with the techno-economic and multi-dimensional evaluation perspectives discussed in Sections 4.2 and 4.3.

4.2. Techno-economic and life-cycle perspectives

A truly sustainable greenhouse energy strategy must balance energy efficiency and carbon mitigation with economic viability and life-cycle impacts. Only a subset of the reviewed studies quantified capital and operating costs, payback periods or levelized cost of energy, and even fewer performed full life-cycle assessment (LCA) of greenhouse structures and energy systems. However, the scarcity and inconsistency of techno-economic and LCA data currently limit cross-study comparison and underscore the need for integrated four-dimensional evaluation covering energy, productivity, economics and life-cycle sustainability. Accordingly, the following subsection proposes a unified set of indicators to support cross-climate comparison and decision-oriented evaluation.

4.3. Toward a unified multi-dimensional evaluation framework

A key finding of this review is the lack of consistency in the use of performance indicators across studies on greenhouse energy systems. Although a variety of metrics such as coefficient of performance, energy consumption per unit area, and energy saving rate are commonly used, they are often applied independently and without a standardized framework. As shown in Table 6, comprehensive sets of indicators are seldom adopted, and both definitions and measurement approaches differ significantly across studies. This inconsistency limits the comparability of results across regions and hinders the development of widely applicable greenhouse energy strategies.

To address this challenge, we propose the development of a unified, multi-dimensional performance evaluation framework for greenhouse energy systems. This framework should integrate four core domains: (1) Energy performance, including unit energy use, efficiency metrics, and thermal demand; (2) Crop productivity, such as yield per area and yield per energy input; (3) Economic viability, including payback period and life-cycle cost savings; and (4) Life-cycle sustainability, encompassing energy use and emissions across construction, operation, and decommissioning stages.

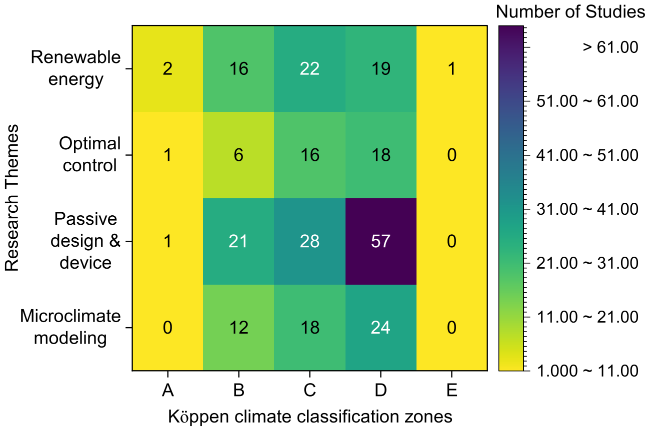

Fig. 10. Research distribution by climate zone and theme.

While this review does not establish a complete evaluation model, it consolidates commonly used indicators, particularly in life-cycle analysis and economic assessment. Establishing a standardized framework will be crucial for benchmarking future innovations and advancing net-zero, climate-specific greenhouse systems across diverse climatic and socioeconomic contexts.

4.4. Future research directions for greenhouse energy systems

As greenhouse systems face increasing climatic variability and decarbonization pressures, future development must move toward integrated, net-zero, and resilient solutions. Building on recent trends, this section outlines key directions: passive-active synergy, renewable energy integration, AI-based control, regional adaptation, and unified performance evaluation. These priorities reflect a shift from isolated innovations to coordinated, climate-specific strategies.

4.4.1. Climate-specific synergy of passive and active strategies

Climate-specific integration of passive design and operational control is key to effective greenhouse energy strategies. As shown in Fig. 10, studies in extreme climates, such as very cold or hot-arid zones, predominantly focus on passive solutions, including multilayer glazing, PCMs, insulation, and selective coatings. These strategies help stabilize internal environments under harsh conditions. However, passive measures provide fixed gains and lack adaptability. In temperate zones, where environmental fluctuations are more moderate and structural constraints are fewer, dynamic control becomes essential. Intelligent systems, such as AI-based controllers and MPC, enable real-time regulation of ventilation, shading, irrigation, and heating, responding adaptively to weather forecasts and crop growth data to optimize energy use.

The future of greenhouse energy systems lies in the climate-specific integration of passive design and operational optimization. This vision emphasizes technical optimization without considering initial investment constraints, providing a conceptual foundation for advancing greenhouse sustainability across diverse climate zones.

4.4.2. Scaling renewable energy integration for net-zero emissions

Renewable energy is playing an increasingly central role in greenhouse energy systems by reducing fossil fuel dependence and enhancing system resilience. Across different climate zones, various technologies, including solar photovoltaics, solar thermal, geothermal, biomass,

Table 6
Overview of key evaluation indicators for greenhouse energy systems.

Indicator	Definition/Description	Unit	Typical application/ Energy system	References
Coefficient of Performance (COP)	Energy efficiency indicator for heating/cooling equipment	–	Heat pumps, solar-assisted heating	[208,222,225]
CO_2 Emission Reduction	Reduction of CO_2 emissions compared to conventional systems	kg or t CO_2	Renewable-based systems like solar and heat pumps	[138,157,158]
Crop Yield Increase	Relative improvement in agricultural output due to energy/environmental interventions	%	Evaluating productivity impact of heating, CO_2 enrichment, and climate control systems	[63,122,157]
Energy Consumption per Unit Area	Energy consumption normalized by greenhouse area	kWh/m^2 or MJ/m^2	Comparison across greenhouse types and climates	[9,197]
Energy Efficiency	Ratio of output energy to input energy; measures system efficiency	%	Integrated systems with solar, heat pumps, and thermal storage	[75,269]
Energy Saving Rate	Proportion of energy saved compared to traditional systems	%	Energy retrofitting, PV-T systems	[70,86]
Heat Loss	Heat lost due to conduction and other losses in the system	W or MJ/h	Evaluation of insulation and structural thermal design	[81,192,278]
Life Cycle Cost (LCC)	Total cost from construction to operation and maintenance	\$ or ¥	Economic-energy performance assessment	[50,94]
Payback Period	Time required to recover initial investment through energy savings	Years	Feasibility analysis of renewable energy investments	[217,265,273]

wind, hydrogen, and battery storage, are being integrated to address diverse heating, cooling, and electricity demands.

Achieving net-zero greenhouse operations requires not only scaling these technologies but also advancing their efficiency, reliability, and adaptability to local conditions. In colder climates, geothermal storage ensures stable winter heating; in arid zones, solar–PV hybrids offset cooling loads; and in temperate regions, agrivoltaic systems balance energy generation with crop lighting requirements.

Future research should focus on improving the efficiency and affordability of renewable energy systems. It should also develop climate-specific integration frameworks that match energy solutions with local environmental and operational conditions. Moreover, coordination across technology, policy, and market levels will be crucial to accelerate the transition to net-zero and climate-resilient greenhouse systems.

4.4.3. *AI in greenhouse energy systems*

AI technologies are enhancing greenhouse energy management by improving precision, adaptability, and decision-making. In particular, machine learning models are increasingly being used to predict environmental conditions and energy demands, providing accurate data-driven models for system optimization. These models enable greenhouses to anticipate changes in weather patterns, crop requirements, and energy availability, forming the basis for intelligent control.

Beyond modeling, reinforcement learning has gained attention as a promising approach for real-time decision-making in greenhouse environments. RL-based controllers learn optimal strategies for regulating ventilation, shading, heating, and irrigation by continuously interacting with the greenhouse system and adjusting operations to maximize performance objectives such as energy efficiency and crop yield.

Future research should focus on climate-specific AI frameworks to adapt greenhouses to local conditions. Reliable simulations will be essential for validating these solutions prior to deployment. Integrating IoT-based real-time monitoring with AI will support practical implementation and promote sustainable industry growth.

4.5. *Limitations*

This review has several limitations. The search relied primarily on the Web of Science Core Collection and English-language journal articles, which may have excluded relevant studies from other databases or languages. The 2019–2024 window prioritized recent advances and may underrepresent earlier seminal work. Substantial heterogeneity in greenhouse types, crops, baselines, and outcome definitions precluded formal meta-analysis and required a structured narrative and semi-quantitative synthesis. The evidence base is geographically skewed toward East Asia, which may limit external validity. Moreover, the Köppen classification, while useful for global comparison, provides only a coarse representation of climate and does not fully capture microclimatic variability. Future research should address these constraints through harmonized multi-site benchmarking and expanded field validation across underrepresented climates.

5. Conclusion

This review systematically synthesizes greenhouse energy strategies within the framework of the Köppen climate classification, offering a climate-responsive perspective that extends beyond conventional geographic or purely thematic reviews. By aligning evidence with climate zones, we clarify how local meteorological constraints shape energy demand, technology selection, and operational priorities in protected agriculture, thereby supporting regionally optimized pathways for countries spanning multiple climate types.

The analysis yields four key insights. First, climate-based categorization enhances the strategic relevance of greenhouse energy research by enabling stakeholders to identify shared challenges and transferable solutions across similar climatic regions, which supports more targeted design and policy interventions. Second, the evidence indicates distinct climate-specific leading solution sets rather than only broad research priorities. In arid climates (Zone B), the most frequently reported pathways combine solar-driven hybridization with cooling and water-saving packages, including spectrum-selective shading and cover materials and water-efficient evaporative or desiccant-based schemes. In cold and continental climates (Zone D), research converges on thermal-retention and storage-oriented solutions such as enhanced envelopes, thermal screens, and latent or seasonal thermal energy storage coupled with solar-thermal or geothermal assistance. In temperate climates (Zone C), the comparative advantage increasingly shifts toward advanced operational control, particularly model predictive control, including economic or robust variants, and data-driven or reinforcement-learning-based approaches. These approaches are often integrated with renewable supply and storage to manage multi-variable trade-offs among heating, ventilation, humidity, CO_2, and yield. Tropical (Zone A) and polar (Zone E) regions remain comparatively underrepresented, highlighting feasibility, cost, and data availability barriers that warrant dedicated investigation.

Third, greenhouse energy research can be more clearly structured into three primary strategy classes, namely passive and device-assisted enhancements, active operational optimization, and renewable energy integration. These classes are enabled by microclimate modeling and decision-support tools that inform system design and real-time control rather than serving as standalone solutions. These findings emphasize the need for integrated packages that couple structural measures with intelligent, climate-aware operation. Fourth, despite notable progress, cross-study comparability remains constrained by fragmented evaluation practices. Future assessments should adopt a unified multidimensional framework that jointly considers energy use, crop productivity, economic viability, for example life-cycle cost and payback, and

Table A.1
Greenhouse energy strategy highlights across Köppen climate classification.

Climate type	Microclimate modeling	Passive design and device-assisted	Operational optimization	Renewable energy integration
Aw	N/A	Cooling dominates energy use (64%), followed by LED lighting (36%); highlights need for optimized, intelligent cooling strategies [18].	Fuzzy logic control cut electricity use by 58.8% and water use by 68.9% [25].	IoT-based PV system cut grid power use by 30% and enhanced control via real-time sensing [23].
BWh	NARX models achieved high temp prediction accuracy (R^2 = 0.9986) for greenhouse climate [34,35].	NIR-selective solar roof cut cooling loads by 17.4%, produced 59.7 L/day fresh water, aiding cooling and energy recovery [48].	RMPC with yield-CO_2 model cut temp RMSE to 0.32–0.60 °C, saved 9.7–23.6% energy, and doubled yield at 1050 ppm CO_2 [61,62].	PV roofs with dielectric mirrors cut cooling loads by 25%–29% and generated 22.2 kWh/day [70].
BSh	CFD showed solar and ambient temperature dominate; centralized crops lowered temp by 2K [36].	Uneven-span with 45 ° tilt and −80° orientation boosted winter solar gain by 10.6%, cutting heating costs by $90/m^2 [55].	N/A	N/A
BSk	Energy-mass balance model predicted temp accurately (R^2 = 0.96); but without active control, temp raised 0.34 °C, RH raised by 15.7% [37].	Shading nets raised cellulose pad efficiency to 45%; loofah pads offered similar cooling with lower water use [56].	N/A	N/A
Cwa	N/A	Asymmetrical roofs cut summer solar gain by 14.2%, raised winter gain by 8%, and reduced night heat loss by 10.5% [121].	MPC targets temperature, RH, CO_2, and light to manage highly variable conditions [136].	Modeling in Kunming showed 40% PV coverage best balanced energy efficiency and climate control [160].
Cfa	EnergyPlus model for hydroponic farms showed <3% annual error, enabling reliable long-term assessment [95].	Spectral coatings and radiative membranes reduced overheating by managing light and heat selectively [117,118].	Deep reinforcement learning cut energy use by 28%–57% while maintaining optimal climate via multi-objective control [131,132].	Semi-closed system with MPC cut energy use by 40.1%, raised yield by 16.6%; PV met summer needs, heating cut winter use by 25% [159].
Cfb	RBF networks (R^2 = 0.98) predicted yield from time-series microclimate data; supported by rich sensing and automation [96].	Adaptive greenhouse shells cut heating energy by 23%–37% and boosted yields by 7%–20% [122].	Economic-multi-energy MPC cut energy use by 28% and CO_2 emissions by 6% vs. rule-based control [138].	Solar tracking PV improved winter light, reduced summer heat, and raised power output by 6.9% [156].
Csa	SVM-based load prediction cut nRMSE by 30%–40%, halved TES size, met 80% heating demand, and reduced boiler reliance [88].	Dual-medium (water-gravel) systems with solar collectors improved heating coverage and energy retention [104].	MPC optimized heating flow and air temp control, reducing electricity use by 30% [125].	Adjustable-angle PV panels optimized winter light use while sustaining energy output [147].
Dwa	Modeling optimized span-to-ridge ratio (0.53) reduced heating demand by 9.8% and improved heat retention by 14.2% [171,172].	Dual-receiver solar collector kept night temps >9 °C with 70.2% collection rate during cloudy periods [212].	Rolling horizon and reduced-order models raised yield by 43% and cut energy use by 13.8% [243].	Micro heat pipe PV/T systems yielded 8.3% electrical and 40.9% thermal efficiency, aiding cold-season heating [266].
Dfb	TRNSYS+MOGA reduce temp error to 1.6 °C [179];	Rock bed TES cut diurnal swings (−5 °C day, +7 °C night), stored 103 kWh/day [234].	Distributed optimization across clusters cut peak demand by 17.5% and raised renewable use by 12.3% [253].	Renewable-powered CSAUs replaced 1020 m^2 farmland with 30 m^2 stacked space, potentially feeding 24.4% of global population [275].
Dsa	Energy-mass balance showed 63% of heat loss via envelope, stressing insulation and renewable heating needs [184].	Thermal curtains raised temp by 1.3 °C, cut heat use by 21% and CO_2 by 29.5 kg/night [239].	N/A	N/A
ET/EF	N/A	N/A	N/A	Hybrid solar–geothermal–wind system cut heating needs by 35% and night heat loss by 50%, but faced cost and stability challenges [278].

environmental sustainability, including life-cycle impacts. This will enable fair benchmarking of both technology packages and control algorithms across climate zones.

Future research should strengthen cross-climate comparative studies using standardized metrics and open benchmarking protocols, expand evidence for underrepresented climate zones, and advance integrated digital and physical solutions combining AI, IoT, and hybrid renewable and storage systems. Close collaboration among engineers, agronomists, economists, and policymakers will be essential to translate these insights into scalable, climate-adaptive greenhouse systems. By explicitly aligning energy strategies with climatic diversity, this review provides a roadmap for designing resilient, low-carbon protected agriculture that can contribute to global food security under a changing climate.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT for language refinement and grammatical corrections. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Climate-specific greenhouse energy strategies

See Table A.1.

Data availability

Data will be made available on request.

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