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Research Paper

# Benchmarking techno-economic performance of greenhouses with different technology levels in a hot humid climate

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ABSTRACT

Greenhouse agriculture is expected to play a critical role in sustainable crop production in the coming decades, opening new markets in climate zones that have been traditionally unproductive for agriculture. Extreme hot and humid conditions, prevalent in rapidly growing economies including the Arabian Peninsula, present unique design and operational challenges to effective greenhouse climate control. These challenges are often poorly understood by local operators and inadequately researched in the literature. This study addresses this knowledge gap by presenting, for the first time, a comprehensive set of benchmarks for water and energy usage, $CO_2$ emissions ($CO_2e$) contribution, and economic performance for low-, mid-, and high-tech greenhouse designs in such climates. Utilising a practical and adaptable model-based framework, the analysis reveals the high-tech design generated the best results for economic return, achieving a 4.9-year payback period with superior water efficiency compared to 5.8 years for low-tech and 7.0 years for mid-tech; however, the high-tech design used significantly more energy to operate its mechanical cooling system, corresponding with higher $CO_2e$ per unit area (8.3 and 4.0 times higher than the low- and mid-tech, respectively). These benchmarks provide new insights for greenhouse operators, researchers, and other stakeholders, facilitating the development of effective greenhouse design and operational strategies tailored to meet the challenges of hot and humid climates.

## 1. Introduction

Growing human population, increasingly scarce natural resources, and shrinking arable land make clear the need for sustainable intensification of agricultural production. Sustainable intensification aims to increase agricultural productivity (yield per unit input of energy, water and nutrients) without detrimental impact on biodiversity, soil, and water (Cassman & Grassini, 2020). Greenhouse systems allow farmers an intensified option with a relatively high degree of control over the growing environment to enable optimal conditions for plant growth. Compared to open-field, greenhouses have the potential to reduce the water usage by 50–90% (Barbosa et al., 2015; Czyzyk et al., 2014, pp. 325–332) and also increasing yield productivity. Greenhouses will become more critical for reliable crop production in the context of accelerating climate change, which drives multiple adverse effects on agriculture like unpredictable weather, decrease in water quality, soil erosion, and ocean acidification. As a result, new opportunities are opening to the greenhouse industry, especially in hot, water-scarce regions such as the Arabian Peninsula (AP) which have historically been unproductive for agriculture (Goddek et al., 2023).

The agriculture industry in the AP is constrained by harsh environmental conditions. Arable land comprises only 1.53% of total land area (FAOSTAT, 2020), and the average level of water stress (*i.e.*, freshwater withdrawal as a proportion of available freshwater resources) is 1055%, while the global average is 18.4% (FAO & UN Water, 2021). Protected agriculture, and specifically greenhouse crop production, is seen as critical to alleviate the disproportionate water demand of the agricultural sector in the AP (World Economic Forum, 2023). Most of the coastal areas in the AP region are representative of an extreme climate

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $A_r$ | Area (horizontal) of roof, m$^2$ |
| $A_s$ | Area of sidewalls, m$^2$ |
| $B$ | Energy absorbed by structure/ground, % |
| $C_4$ | Empirically derived constant, W s m$^{-3}$ Pa$^{-1}$ |
| $e_{fan}$ | Fan efficiency, % |
| $e_{mtr}$ | Motor efficiency, % |
| $G_E$ | Transpiration conductance, m s$^{-1}$ |
| $h$ | Air head loss, Pa |
| $I_{plant}$ | Solar energy available in plant zone, W |
| $k$ | Crop specific transpiration parameter |
| $LAI$ | Leaf area index, cm$^2$ leaf area cm$^{-2}$ floor area covered by canopy |
| $m_{vent}$ | Moisture moved by ventilation, kg hr$^{-1}$ |
| $m_{infl}$ | Moisture moved by infiltration of air through cladding, kg hr$^{-1}$ |
| $m_{evapc}$ | Moisture contributed by evaporative cooling, kg hr$^{-1}$ |
| $m_{trsp}$ | Moisture contributed by transpiration from crop, kg hr$^{-1}$ |
| $m_{cnds}$ | Moisture removed by condensation on heat exchangers, kg hr$^{-1}$ |
| $m_{evapc}$ | Moisture contributed by evaporative cooling, kg hr$^{-1}$ |
| $m_{trsp}$ | Moisture contributed by transpiration from crop, kg hr$^{-1}$ |
| $m_{cnds}$ | Moisture removed by condensation on heat exchangers, kg hr$^{-1}$ |
| $m_{vent}$ | Moisture moved by ventilation, kg hr$^{-1}$ |
| $m_{infl}$ | Moisture moved by infiltration of air through cladding, kg hr$^{-1}$ |
| $q_{cool}$ | Heat exchange through mechanical cooling, W |
| $q_{conv}$ | Heat exchange through convection/conduction through cladding, W |
| $q_{fan}$ | Heat contributed by fan motor, W |
| $q_{infl}$ | Heat exchange due to conduction by air leakage through cladding, W |
| $q_{plant}$ | Heat exchange absorbed by plants, W |
| $q_{rad}$ | Heat exchange due to solar radiation, W |
| $q_{vent}$ | Heat exchange due to ventilation, W |
| $r_b$ | Aerodynamic resistance, s m$^{-1}$ |
| $r_s$ | Stomatal resistance, s m$^{-1}$ |
| $R_g$ | Outdoor global irradiance, W m$^{-2}$ |
| $R_n$ | Net radiation at crop level, W m$^{-2}$ |
| $T_a$ | Temperature ambient, °C |
| $T_i$ | Temperature at greenhouse entrance following cooling, °C |
| $T_o$ | Temperature of greenhouse interior temperature at discharge or air return, °C |
| $U_r$ | Thermal transmittance of roof, W m$^{-2}$ °C$^{-1}$ |
| $U_s$ | Thermal transmittance of sidewalls, W m$^{-2}$ °C$^{-1}$ |
| $V$ | Ventilation rate, m$^3$ s$^{-1}$ |
| $X$ | Water vapor concentration in the greenhouse, kg m$^{-3}$ |
| $X_{plant}$ | Water vapor concentration within crop canopy, kg m$^{-3}$ |
| $X_{sat}$ | Saturated water vapor concentration, kg m$^{-3}$ |
| $Y$ | Percentage of reflected irradiance that must be removed as heat, % |
| $\mathcal{E}$ | Ratio of latent to sensible heat |
| $\tau_{clad}$ | Transmissivity of cladding and dust (combined), % |
| $\tau_{esh}$ | Transmissivity of exterior shade screen, % |
| $\tau_{ish}$ | Transmissivity of interior shade screen, % |

*Abbreviations*

| | |
|---|---|
| ACH | Air changes per hour |
| AP | Arabian Peninsula |
| CAPEX | Capital expenditures |
| $CO_2$e | Carbon dioxide emissions |
| DLI | Daily Light Integral |
| NPV | Net Present Value |
| OPEX | Operating Expenses |
| PAR | Photosynthetic active radiation |
| SDGs | Sustainable Development Goals |

zone that is characterised by peak wet bulb temperatures greater than 35 °C. Other countries with similar climates and resource challenges are shown in Fig. 1 (Emu Analytics, 2021); such locations urgently require greenhouse design and operation to be robust to extreme heat and humidity. The combined population of the regions identified is currently close to 2.1 billion (United Nations Department of Economic and Social Affairs Population Division, 2022), and many of these countries are already vulnerable to food insecurity. Although water scarcity is not a universal issue across these regions, they are all impacted by the combined stressors of high humidity and heat. These conditions limit effective greenhouse climate control and exacerbate crop fungal and bacterial diseases (Moustafa et al., 1998).

Despite its harsh climate, the AP region has several environmental and market advantages for greenhouses, including plenty of open land, excessive photosynthetic active radiation (PAR), high potential for renewable solar power, and inexpensive labour. Coastal regions in the AP in particular are gaining attention for new greenhouse projects due to several factors: 1) the abundancy of marginal land that would otherwise not be suitable for agriculture; 2) proximity to reliable desalinated water supplies; and 3) proximity to many large cities, which cuts down transportation costs and associated greenhouse gas emissions. Many AP states also have plenty of excess capital to invest in state-of-the-art agricultural technologies including advanced greenhouse systems (Lefers et al., 2020).

The technology level of a greenhouse reflects its capability to create optimal growing conditions through the use of technology, ranging from basic structures that protect plants from external weather conditions (low-tech) to highly automated, controlled environments that maximise productivity and efficiency (high-tech). Greenhouse systems can generally be categorised by one of three levels of technology: low-, mid-, and high-tech. Table 1 outlines the key advantages and disadvantages for each level. Technology selection in greenhouses becomes particularly critical in hot-humid climates due to the extreme environmental conditions that can significantly affect crop growth, resource use efficiency, and overall sustainability.

Side-by-side comparisons of greenhouses with different technology levels highlight the impacts of various design aspects and operational strategies on cost-effectiveness, emissions, and adaptability to local climates. Such analyses drive informed decision-making related to greenhouse crop production systems, improving efficiency, profitability, and broader goals of sustainable food security. A small number of studies provide such side-by-side comparisons. Vanthoor et al. (2012) developed and validated a model-based method to produce optimal greenhouse designs in different climates, with the goal of achieving the best financial performance. Although proven to be robust and reliable for both cold and hot climates, the practicality of this method is limited by its complexity, requiring more than 100 model parameters and employing nearly 100 equations to arrive at the result of Net Financial Return. Page et al. (2012) used a life-cycle assessment approach to compare the carbon emissions impact and water usage of tomatoes grown in low-, mid-, and high-tech greenhouse systems and field production in Australia (near Sydney), and found that high-tech systems had the highest carbon footprint and lowest water footprint, mid-tech had the highest water footprint, and field production had the lowest

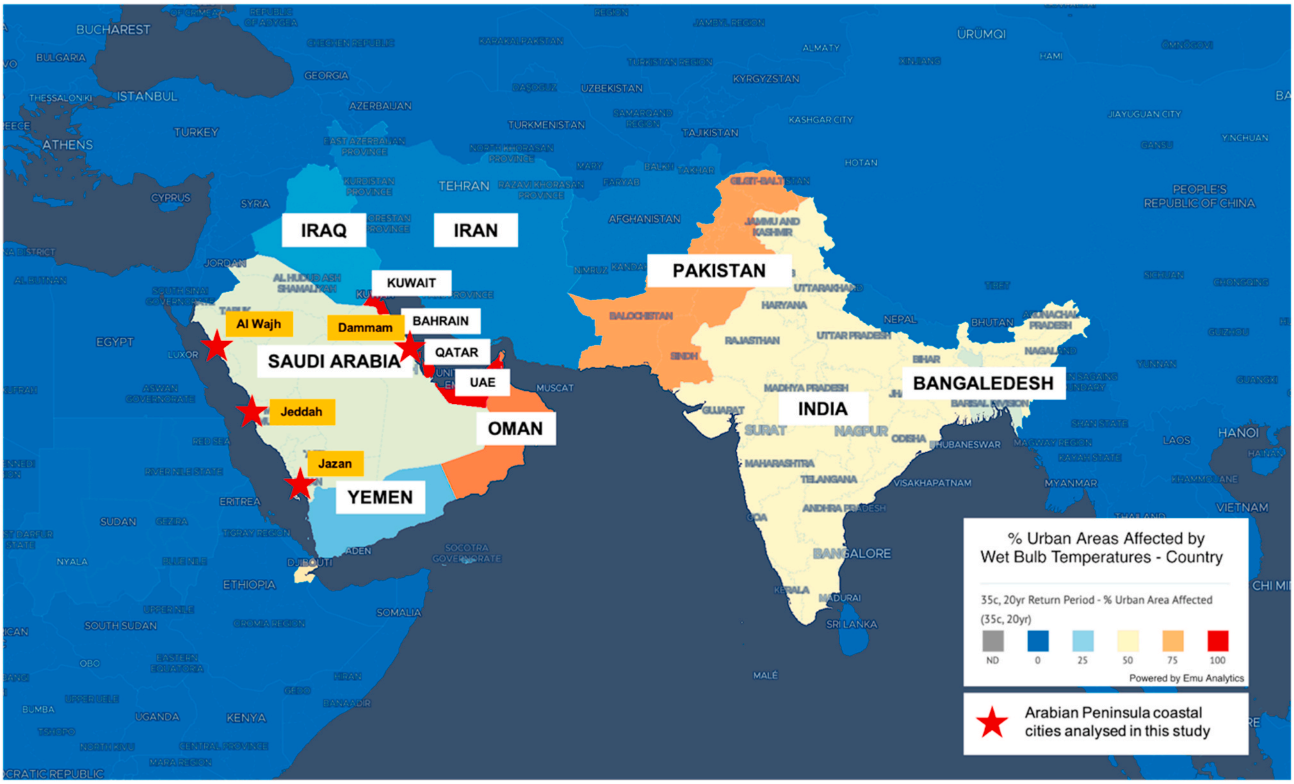


**Fig. 1.** Countries predicted to have a significant portion of urban areas at risk of peak wet bulb temperatures >35 °C in the next 20 years (Emu Analytics, 2021). Red stars indicate the coastal locations in the Arabian Peninsula that were analysed in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

carbon footprint. Zhou et al. (2021) evaluated the performance of low- and high-tech greenhouses for tomato production, both organic and conventional, in the Netherlands and Spain, through the lens of the United Nations Sustainable Development Goals (SDGs); the study found that high-tech, conventional systems had the best overall sustainability performance but fell short of the SDG7 “affordable and clean energy”, wherein low-tech systems performed better. In central Saudi Arabia (Riyadh), several experimental studies have been conducted comparing the resource use efficiencies of low-, mid-, and high-tech greenhouses systems in water and energy usage (Campen et al., 2020, 2023; Tsafaras et al., 2021).

While the aforementioned studies offer valuable insights through side-by-side comparisons of greenhouses with different technology levels, the applicability of their findings to hot and humid climates, such as those prevalent in the AP and many rapidly developing regions, remains limited. None of the aforementioned studies analyse in detail the interplay between outdoor humidity and greenhouse cooling system performance, a factor critical in hot humid climates but not adequately addressed in existing literature.

Furthermore, there are no experimental or modelling studies in the literature that report on the long-term techno-economic performance of greenhouses in hot humid climates; only a handful of studies report 2–3 days of performance of greenhouses in relevant climatic conditions. Mao et al. (2024) studied the performance of a closed cooling system in a commercial glasshouse in Wuhan, China over two days during the summer, wherein wet bulb temperatures typically exceed 30 °C and sometimes 35 °C. Xu et al. (2015) reported on the experimental performance of an evaporative cooling system in a glasshouse in Shanghai, China, comparing the effects of different shading strategies on cooling performance during several days in August. While such experimental data is valuable (in fact it is used to validate the physical modelling approach used in the current study), neither study reported on water and energy usage or any overall system efficiency metrics. This absence of relevant benchmarks for greenhouses in hot humid regions forces greenhouse operators and other stakeholders to navigate the unique challenges imposed by this climate type without practical information to guide the design and optimisation of their systems. Research too faces a bottleneck, as the absence of comprehensive performance data hinders the development of greenhouse models and technologies tuned to the conditions of such extreme environments.

Addressing this gap, this study presents the first comprehensive set of benchmarks for the techno-economic performance of low-, mid- and high-tech greenhouse designs in a hot humid climate. To determine these benchmarks, a novel model-based framework was developed and demonstrated with a case study in coastal Saudi Arabia. Three distinct greenhouse designs—negative-pressure, evaporatively cooled *low-tech*, a positive-pressure, evaporatively cooled *mid-tech*, and mechanically cooled ‘closed’ *high-tech*—were simulated over one year using historical climate data. The energy and water usage, financial performance, and $CO_2$ emissions impact of each design was quantified and compared against each other, in addition to experimental data reported in the literature. Various design and operational strategies that offer significant benefits for water and energy savings in this climate type were also investigated and discussed; these include suitable cladding materials, optimised shading and humidity capture. A local sensitivity analysis determined the relative impacts of different design and market factors on financial performance. Overall, this study aims to meet the urgent need for practical performance benchmarks and assessment tools for greenhouses in challenging hot humid climates, which can support stakeholders in making data-driven decisions that enhance the productivity and sustainability of greenhouse agriculture in such regions.

 

**Table 1**
Advantages and disadvantages of low-, mid-, and high-tech greenhouses located in hot humid regions.

| | Low-tech | Mid-tech | High-tech |
|---|---|---|---|
| **Disadvantages** | •Crop potential is limited by environmental conditions<br>•High water demand for cooling<br>•Highly susceptible to pests and diseases<br>•Chemical products for pest control are needed<br>•Environmental conditions can be non-homogenous due to design of evaporative cooling system<br>•Year-round production is virtually impossible | •Higher capital costs compared to low-tech<br>•Evaporative cooling efficiency is limited by outdoor climate conditions<br>•Year-round production is a major challenge<br>•Skilled labour is required for operation and maintenance | •High energy consumption required to operate closed cooling system<br>•Capital costs are the highest of the tech levels<br>•Highly skilled labour required for operation and maintenance, which can be difficult to source |
| **Advantages** | •Low energy consumption<br>•Low capital costs<br>•Less skilled labour required for operation and maintenance | •Trade-off between cost and productivity<br>•Positive pressure environment provides more protection from pests and diseases<br>•More homogenous indoor environment compared to low-tech<br>•More efficient use of water for evaporative cooling than low-tech | •Plant growth, yield, and fruit quality are optimised<br>•High water-use efficiency<br>•Crops are well-protected from pests and disease<br>•Less use of chemical products for pest control<br>•Year-round production is feasible<br>•Not limited by weather conditions<br>•Less limited by site conditions |

## 2. Materials and methods

### 2.1. Description of model-based assessment tool and performance measures

The overall structure of the model-based assessment method is shown in Fig. 2. The goal of developing this method was to use the same tool to accurately but efficiently quantify the resource use efficiency, financial performance, and environmental impact of a range of greenhouse designs, focusing on the climate control system, since this has the greatest impact on water and energy usage for greenhouses in hot climates (Gorjian et al., 2021; Rorabaugh, 2015).

Table 2 outlines the metrics used to evaluate the techno-economic performance of the modelled greenhouse systems explored in this study; these are the key outputs of the model-based assessment method shown in Fig. 2. Together these metrics quantify resource use efficiency, environmental impact (via $CO_2$ emissions) and financial performance of a given greenhouse design, which are key to ascertain its economic and environmental sustainability (Bathaei & Štreimikienė, 2023; Zhou et al., 2021). It should be emphasised that this methodology focuses on assessing the design and functionality of greenhouse structures rather than the crop production systems they support. To streamline the analysis, assumptions regarding yield productivity have been made (see Table 3 and Section 2.8).

### 2.2. Description of low-, mid-, and high-tech greenhouse designs

Fig. 3 shows the three greenhouse designs explored in this study, which represent three distinct technology levels: low-, mid-, and high-tech. These were designed based on typical greenhouse facilities in the AP region (Campen et al., 2020). The design parameters for each system are provided in Table 4. All three systems have the same footprint (a 5000 $m^2$ crop production area plus a 375 $m^2$ service area). The high- and mid-tech systems have the same architecture (6-m tall multi-span Chapel with polycarbonate sidewalls and polyethylene roof) and hydroponic growing system but differ in their cooling/ventilation system and shading designs.

### 2.3. Energy and humidity balance modelling

For this analysis, the primary goal of modelling the greenhouse climate was to determine the overall energy and water usage of varying greenhouse designs in hot humid conditions; to this end, a simplified modelling approach was used, based on the thermodynamic principles of energy and mass conservation. The greenhouse energy balance is based on the model first described in Aldrich and Bartok (1994), which has been experimentally validated in a hot climate with good results by Salazar-Moreno et al. (2019) and in a warm tropical climate by Ortiz et al. (2023). The energy balance model is described in EQ-1:

$$q_{vent,i} + q_{fan} + q_{infl,i} + q_{conv,i} + q_{rad} = q_{infl,o} + q_{plant} + q_{vent,o} + q_{cool} \qquad \text{EQ-1}$$

where heat gain is defined as: venting ($q_{vent,i}$), electric fans ($q_{fan}$), infiltration through cladding ($q_{infl,i}$), convection/conduction ($q_{conv,i}$) and global irradiance ($q_{rad}$). Heat loss from the system is defined as: infiltration out ($q_{infl,o}$), absorbed by plants ($q_{plant}$), venting out ($q_{vent,o}$), mechanical cooling ($q_{cool}$), as well as conduction (which was assumed negligible in this analysis since the outdoor temperature was almost always higher than the internal setpoint temperature).

Likewise, the greenhouse humidity balance is calculated according to Equation 2, described in Fitz-Rodríguez et al. (2010):

$$m_{vent,i} + m_{infl,i} + m_{evapc} + m_{trsp} = m_{vent,o} + m_{infl,o} + m_{cnds} \qquad \text{EQ-2}$$

Infiltration and exfiltration rates ($m_{infl,i}$ and $m_{infl,o}$) are considered to be a minimum of 1 air change per hour (ACH) The pad wet bulb efficiency of 80% is assumed to calculate the moisture contributed by evaporative cooling ($m_{evapc}$ , in kg $hr^{-1}$). Ventilation in and out ($m_{vent,i}$ and $m_{vent,o}$, both in kg $hr^{-1}$) depends on the technology level; these are equal to 0 for the closed high-tech system. Condensate capture ($m_{cnds}$) is only applicable to the high-tech system where condensate is collected on the chiller heat exchanger. Moisture due to plant transpiration ($m_{trsp}$, kg $hr^{-1}$) is calculated based on the energy absorbed by the plants and the latent heat of vaporisation for water (λ, 2260 kJ $kg^{-1}$ water) (Mahmood et al., 2022).

The greenhouse climate model was also validated by the authors of the current study against published performance data of commercial greenhouse facilities in hot humid conditions; the facilities included an evaporatively cooled, negative pressure system (Xu et al., 2015) and an air-conditioned closed system (Mao et al., 2024). The results showed strong agreement between the experimental values and modelled results for both designs, with an average relative error of 1.7% for the evaporatively cooled facility and 10% for the closed facility. More details on the energy and humidity balance calculations, assumptions, and validation results can be found in the Appendix.

### 2.4. Cooling load and cooling water usage

Historical meteorological data between 2016 and 2021 (Saudi General Authority for Statistics, 2023) was analysed for four coastal cities in Saudi Arabia (Table 5) to identify periods in which evaporative cooling was effective, considering suitable conditions for tomato production. For

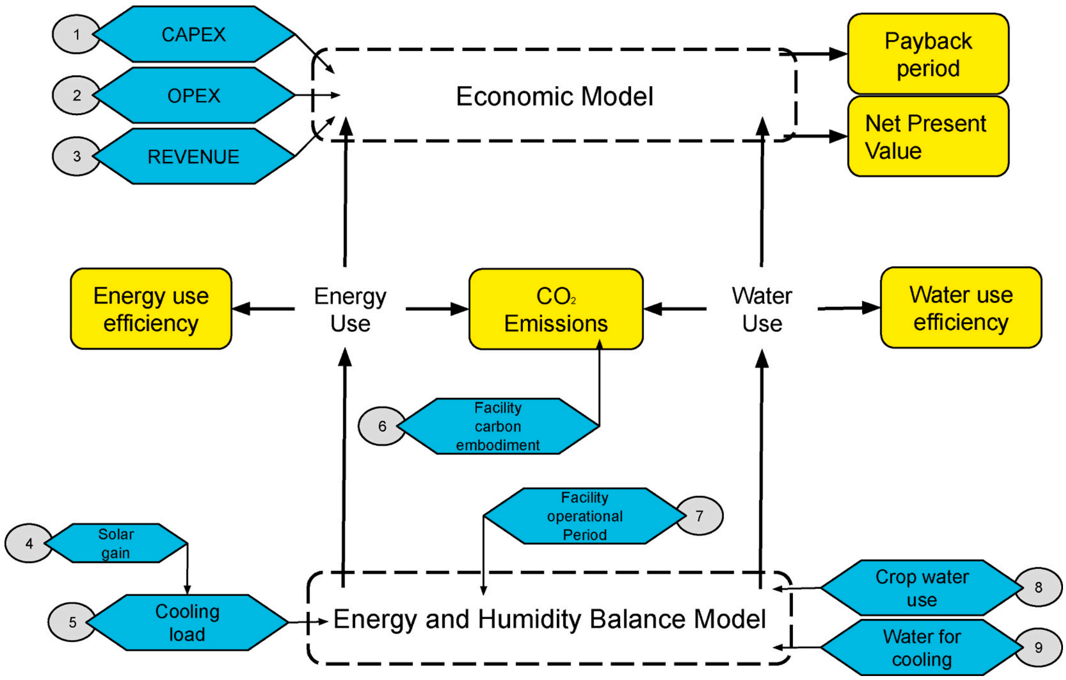


**Fig. 2.** Overview of the model-based assessment method for evaluating various greenhouse designs in hot climates. The key outputs are the performance measures (yellow boxes), which are derived from the greenhouse energy and humidity balance and economic models. The primary input parameters (blue hexagons) and supporting parameters (grey circles) utilised in these models are detailed in Table 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 2**
Performance metrics used to assess the techno-economic performance of the greenhouse designs explored in this study.

| Performance metric | Description | Units |
|---|---|---|
| **Payback period** | The time required to recover the initial capital cost of investment | years |
| **Net present value (NPV)** | The difference between the cash inflow and cash outflow over the project lifetime. | € $m^{-2}$ |
| **Water use efficiency** | Annual water usage per unit area | $m^3$ $m^{-2}$ $yr^{-1}$ |
| **Energy use efficiency** | Annual energy usage per unit area | kWh $m^{-2}$ $yr^{-1}$ |
| **$CO_2$ emissions** | Annual $CO_2$ emissions ($CO_2$e) contribution per unit area | $kg_{CO2e}$ $m^{-2}$ $yr^{-1}$ |

each dataset, the meteorological data was consolidated into hourly averages for each day of the year. A cutoff level was determined at a 5-day average of daytime enthalpy greater than 77 kJ $kg^{-1}_{dry\ air}$. At this level the internal temperature after the wet pad in an evaporative cooling system was around 28 °C and the exit temperature rose to 32 °C, recognised as the maximum temperature for greenhouse tomato production (Hahn & Rosentreter, 1995; Hochmuth, 2001). The model assumed that when the daytime enthalpy was above this cutoff level the greenhouse was shut down due to unsuitable crop growing conditions. Furthermore, the nighttime conditions during these shutdown periods did not allow for a sufficient drop between daytime and nighttime temperatures which is considered necessary to maintain high productivity in greenhouse tomato (Willits & Peet, 1998; The University of Arizona Controlled Environment Agriculture Center, 2000). The model assumed evaporative cooling to be unnecessary when the ambient wet bulb temperature was less than 20 °C (generally corresponding to dry bulb temperature lower than 26 °C). During these periods ventilation with outside air was adequate to maintain the target internal environment.

For the evaporative cooling systems featured in the low- and mid-tech designs, the model assumed that the cooling pad was not wetted when ventilation of outside air provided adequate internal temperature and humidity levels. Additionally, the model also minimised ventilation rates when the cooling pad was wetted since water consumption is directly proportional to ventilation rate (Teitel et al., 2008). The model adjusted ventilation rates such that the temperature of air between the cooling pad and exit did not exceed the temperature that can be tolerated by productive tomato plants (32 °C). Ventilation rates were also modelled to prevent excessive indoor humidity levels. These conditions were met based on a maximum ventilation rate of 60 ACH for the low-tech and 35 ACH for the mid-tech; these are within the range of typical ACH values for ventilated greenhouses in the region as reported by Ghani et al. (2020).

### 2.5. Greenhouse energy usage and energy sources

The majority of energy usage in greenhouses located in extreme climates is related to climate control (Rorabaugh, 2015), estimated between 65 and 85% (Gorjian et al., 2021). Therefore, for evaporatively cooled, unheated greenhouses (the low- and mid-tech designs in this study), the ventilation rate can be used as a reliable indicator of overall greenhouse energy usage (Abdel-wahab, 1994; Teitel et al., 2008). For high-tech closed systems, in addition to high-pressure fans for ventilation, the primary energy consumption is the mechanical cooling system. Humidity and energy balances were used to determine the mechanical cooling demand based on hourly conditions. Another significant energy demand for greenhouses located near the coast is related to water desalination (Buchholz, 2021). A typical rate of 4 kWh $m^{-3}$ was used to determine the energy consumption from desalinated water production (Ghalavand et al., 2014). The smaller energy demands including irrigation pumping and operational lighting were assumed to be similar between the different technology levels and also have been shown to constitute a small fraction (1–2%) of the overall energy demand compared to cooling and water production (Buchholz, 2021); therefore, these were assumed negligible within the scope of this analysis. In terms of the source of electricity, the low- and mid-tech greenhouses operated solely on the main electrical grid. For the high-tech design, a 500 kWp

**Table 3**
General overview of input parameters for the model-based greenhouse assessment framework in this study.

| Main Parameter | Secondary Parameter | Definition | Notes | Value in this study | Unit | Reference |
|---|---|---|---|---|---|---|
| **1. CAPEX** | **1a. Structure** | Cost of greenhouse foundation, metal structure and cladding | Varies by technology level | See Table 14 | € $m^{-2}$ | Based on experience* |
| | **1b. PV system** | Cost of solar PV system and related equipment | Only included in high-tech design | 72 | € $m^{-2}$ | Based on experience* |
| | **1c. Cooling system** | Cost of cooling system | Varies by technology level | See Table 14 | € $m^{-2}$ | Based on experience* |
| | **1d. Auxiliary facilities** | Cost of service area offices, bathrooms, mechanical room, control system, biosecurity area, and supporting equipment | Same for all tech levels | 70 | € $m^{-2}$ | Based on experience* |
| | **1e. Water treatment system** | Cost of sea intake, pumping station, transmission, and RO treatment system | Varies by technology level | See Table 14 | € $m^{-2}$ | Based on experience* |
| | **1f. Brine infrastructure** | Cost of sea discharge, transmission piping and pumping | Varies by technology level | See Table 14 | € $m^{-2}$ | Based on experience* |
| | **1g. Appurtenances** | Cost of irrigation system, shading, cold storage, nursery, motorised carts, packaging machines, backup power | Varies by technology level | See Table 14 | € $m^{-2}$ | Based on experience* |
| **2. OPEX** | **2a. Maintenance** | Costs estimated at 1.5% of annual capital cost (CAPEX) | Varies by technology level | See Table 14 | € $m^{-2}$ $yr^{-1}$ | Kurklu (2022) |
| | **2b. Consumables** | Cost of seeds, fertilisers, and chemicals | | 4.5 | € $m^{-2}$ $yr^{-1}$ | Kurklu (2022) |
| | **2c. Labour** | Costs of labour based on Manager/Supervisor/Labourer per hectare ratio of 1/2/10; salaries based on local rates | Varies by technology level | See Table 14 | € $m^{-2}$ $yr^{-1}$ | Based on experience* |
| | **2d. Packaging & delivery** | Costs of packaging and delivery to local market; based on 0.23 € $m^{-2}$ $kg_{yield}^{-1}$ | Varies by technology level | See Table 14 | € $m^{-2}$ $yr^{-1}$ | Kurklu (2022) |
| | **2e. Water treatment and delivery** | Costs for maintenance, membrane replacement, and chemicals in RO system | Varies by technology level | See Table 14 | € $m^{-2}$ $yr^{-1}$ | Based on experience* |
| | **2f. Brine disposal** | Costs for maintenance and electricity related to disposal of brine from RO system | Varies by technology level | See Table 14 | € $m^{-2}$ $yr^{-1}$ | Based on experience* |
| | **2g. $CO_2$ enrichment** | Cost of enrichment; based on a usage rate of 150 $kg_{CO2}$ $ha^{-1}$ $hr^{-1}$ | Only included in high-tech | 9.91 | € $m^{-2}$ $yr^{-1}$ | Bao et al. (2018) |
| | **2h. Energy usage** | Costs of electricity; based on Saudi Arabia 2023 electricity prices, including subsidy for agricultural usage | | 0.06 | € $m^{-2}$ $yr^{-1}$ | Based on experience* |
| **3. Revenue** | **3a. Crop type** | Crop(s) grown in greenhouse system | Determines the yield productivity; see Section 2.9 for more details. | Cherry tomato | | Based on experience* |
| | **3b. Technology level** | Categorical description of greenhouse technology level; includes low-, mid-, or high-tech | Accounts for yield differences and operational period | Low-, mid-, or high-tech | | Based on experience* |
| | **3c. Yield increase due to $CO_2$ enrichment** | Average increase in yield due to atmospheric $CO_2$ enrichment compared to non-enriched system | Only for high-tech closed system | 30 | % | Karim et al. (2020) |
| | **3d. Farmgate price** | Price received by the grower from produce sale | | 6.4 | € kg $yield^{-1}$ | Based on experience* |
| | **3e. Seasonal price fluctuations** | Difference in farmgate price based on the season; depends on the local market | Commercial growers in the study region (Arabian Peninsula) reported a year-round flat rate from large supermarkets regardless of the season | Not applicable | % | Based on experience* |
| **4. Solar gain** | **4a. Transmittance factors** | Solar irradiance transmittance through greenhouse cladding, shade screen, and dust ($\tau_{clad}$, $\tau_{ish}$ $\tau_{esh}$) | Varies by technology level | See Appendix | % | Aldrich and Bartok (1994) |
| | **4b. Solar irradiance** | Averaged hourly global horizontal solar irradiance (GHI) | 5-year historical solar irradiance dataset used for each target location | See Table 5 | W $m^{-2}$ | European Commission (2022) |
| | **4c. Minimum DLI** | Minimum cumulative photosynthetic active radiation required by the crop to achieve high yields in commercial production | Determines the shading strategy | 30 | mol $m^{-2}$ $day^{-1}$ | Cruz and Gómez (2022) |
| | **4d. Building footprint** | Area occupied by greenhouse facility | | See Table 4 | $m^2$ | Based on experience* |
| **5. Cooling Load** | **5a. Cladding heat transfer (U)** | Convective and conductive heat transfer through the cladding; | See Appendix for more details on calculation | Varies | W $m^{-2}$ $°C^{-1}$ | Calculated |

(*continued on next page*)

**Table 3** (*continued*)

| Main Parameter | Secondary Parameter | Definition | Notes | Value in this study | Unit | Reference |
|---|---|---|---|---|---|---|
| | | depends on the type cladding material | | | | |
| | **5b. Heat from fans ($q_{fan}$)** | Heat contributed by fans; especially significant in positive-pressure designs (mid- and high-tech) | See Appendix for details on calculation | Varies | W | Calculated |
| | **5c. Solar energy absorbed by plants ($q_{plant}$)** | Portion of incident solar radiation that is absorbed by the plants | See Appendix for details on calculation | Varies | W | Calculated. Salazar-Moreno et al. (2019) |
| | **5d. Mechanical cooling** | Heat exchange via mechanical cooling; includes latent/sensible heat ratio of 2.916 and coefficient of performance (COP) of 3.0 | Only in high-tech system | Varies | W | Calculated |
| **6. Facility carbon embodiment** | **6a. Production stage** | $CO_2$ emissions related to the raw material extraction, processing, transport, and manufacturing of the structural materials | Materials considered include reinforced concrete, steel frame, aluminum, and plastic cladding material (polycarbonate/ polyethylene) | Varies | kg kg$CO_2$e | Orr et al. (2020) |
| | **6b. Transportation** | $CO_2$ emissions related the transport of materials to from the factory to the project site | Modes of transport include truck, sea, air, and rail; materials sourced from local, national, and international suppliers | Varies | kg kg$CO_2$e | Orr et al. (2020) |
| | **6c. Construction installation** | $CO_2$ emissions related to the on-site construction activities ('A5a') and the wasted materials related to construction ('A5w') | | Varies | kg kg$CO_2$e | Orr et al. (2020) |
| **7. Facility Operational period** | **7a. Air temperature** | Averaged hourly air temperature | 5-year historical dataset of air temperature for each study location | See Table 5 | °C | Saudi General Authority for Statistics (2023) |
| | **7b. Humidity** | Averaged hourly relative humidity | Used 5-year historical dataset of relative humidity for each study location | See Table 5 | % | Saudi General Authority for Statistics (2023) |
| | **7c. Air enthalpy threshold** | Shutdown period based on ambient air enthalpy exceeding the threshold value for more than 5 days | | 77 | kJ $kg_{dryair}^{-1}$ | Based on experience* |
| **8. Irrigation** | **8a. Cultivation system** | Hydroponic system with water recycling for mid- and high-tech; drip irrigation in soil for low-tech | Determines water recycling and evapotranspiration; see Section 2.6 for more details. | Hydroponic, soil-based drip | | Based on experience* |
| | **8b. Transpiration** | Water loss from crop canopy | See Appendix for more details. | Varies | kg hr$^{-1}$ | Calculated. Mahmood et al. (2022) |
| | **8c. Recycle rate** | Amount of irrigation water recycled; assumed 15% of irrigation rate | Only for mid- and high-tech (recirculating hydroponics) | Varies | kg hr$^{-1}$ | Calculated. Martinez-Granados et al. (2022) |
| | **8d. Drain-to-waste** | Portion of irrigation water drained to waste to maintain nutrient solution quality; assumed 10% of drain water | Only for mid- and high-tech (recirculating hydroponics) | Varies | kg hr$^{-1}$ | Martinez-Granados et al. (2022) |
| | **8e. Condensation capture** | Condensation captured on heat exchangers in mechanical cooling system; assumed 80% of transpiration and infiltration humidity | Only for high-tech | Varies | kg hr$^{-1}$ | Based on experience* |
| **9. Cooling water** | **9a. Ventilation rate** | Based on the minimum rate required to reach temperature and humidity setpoints | | Varies | m$^3$ hr$^{-1}$ | Calculated |
| | **9b. Wet bulb efficiency** | Capacity of evaporative cooling system to reach wet bulb temperature | | 80 | % | Based on experience* |

* Data based on information from Saudi greenhouse growers, local quotes from contractors, and/or expert knowledge of the authors of this study, who combined have decades of consulting, research, engineering, and growing experience in the Saudi greenhouse industry.

PV solar array covering 0.5-ha is included.

### *2.6. Water source and irrigation rates*

Near-coastal greenhouses in the AP have several options for their water supply, shown in Table 6. The CAPEX for seawater extraction with direct brine disposal into the sea is estimated to be 15% higher than that of near-shore extraction with near-shore injection wells. This estimate is based on a preliminary design done by the authors and local construction quotations. The water demand for evaporatively cooled greenhouses generally exceeds what can be feasibly supported by truck hauling. However, for a high-tech design that uses mechanical cooling, the relatively low water demand could be met by hauling. Utilising hauled water could enable locations further from the coast and the use of larger, centralised and more efficient treatment plants. The direct withdrawal and direct discharge to the sea is the only scenario considered in the economic analysis, as it represents the most economically conservative approach for large volumes. Table 6 includes the

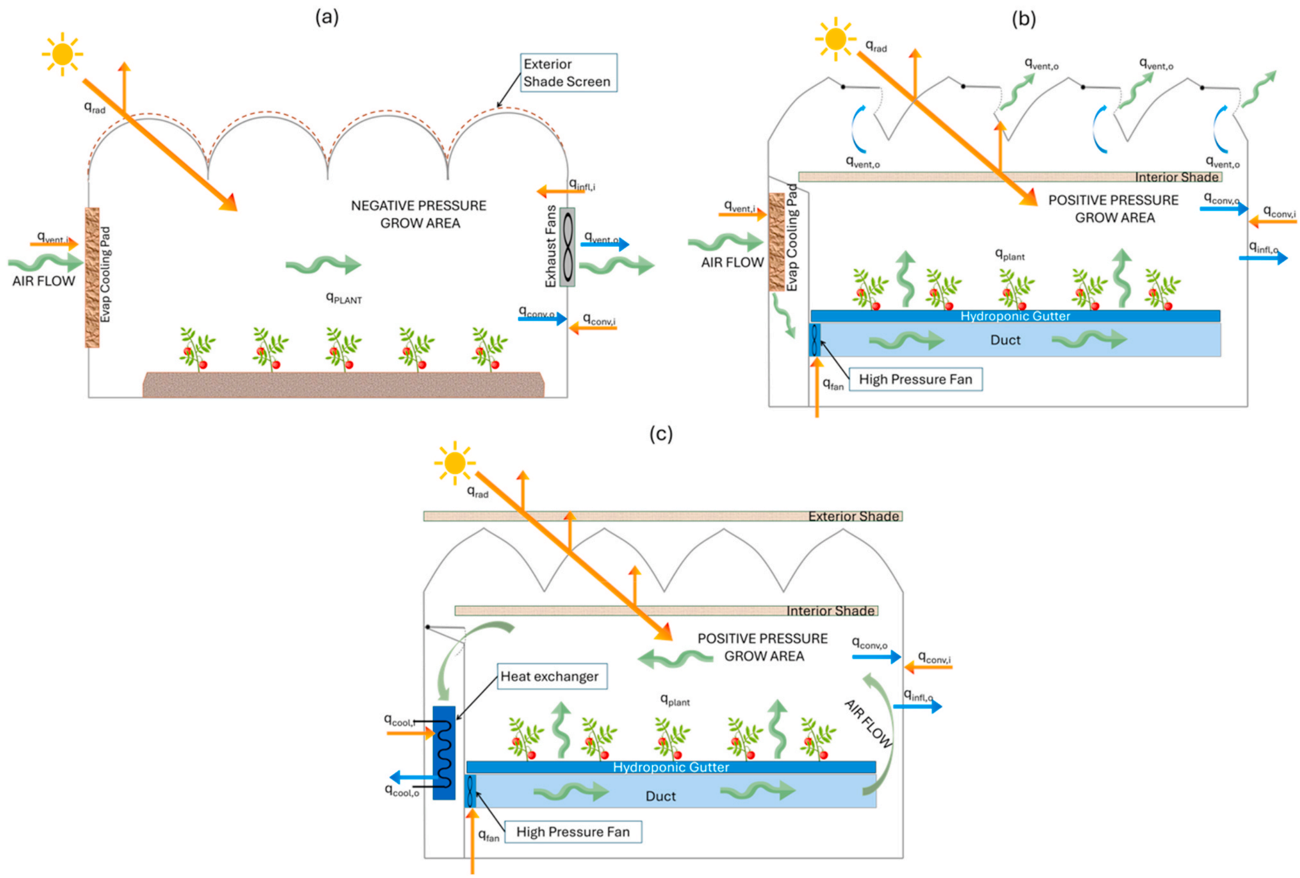


**Fig. 3.** Schematic designs for (a) low-tech (b) mid-tech and (c) high-tech greenhouse designs modelled in this study. Green arrows show air flow, blue arrows show outgoing energy transfer, and orange arrows show incoming energy transfer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

replacement cost to compare with hauled water. For calculating payback period, the costs of water and brine management do not include replacement to avoid double-counting replacement.

The transpiration rates were calculated based on predicted energy absorption by plants divided by the latent heat of vaporisation (Mahmood et al., 2022). The modelled transpiration rate for the high-tech greenhouse throughout the year was 0.7–1.4 L plant$^{-1}$ day$^{-1}$ depending on the shading condition, which is aligned with values reported in the literature (Zhang et al., 2017). For all tech levels, irrigation rates were calculated based on the assumption that the irrigation rate is 120% of transpiration rate (Mahmood et al., 2022). The calculated irrigation rates for mid-tech greenhouses were consistent with an unpublished study conducted by the authors of a 9-month trial of a cherry tomato crop conducted near Jeddah in 2023. In that study, an average daily transpiration requirement of a mature cherry tomato plant in a recirculating hydroponic gutter system was measured to be 1.4 L plant$^{-1}$ day$^{-1}$, which agrees with other experimental studies on greenhouse tomato conducted in similar systems and climatic conditions ((Martínez-Ruiz et al., 2019; Trigui et al., 1999). A 25% drain recovery rate for recycling hydroponic solution was used for the mid- and high-tech designs, with 10% drained to waste, which is aligned with experiment values reported on recirculating hydroponic systems (Elvanidi et al., 2020; Martinez-Granados et al., 2022).

## 2.7. Shading strategy

Shading is an essential component of greenhouse climate control in hot regions like the AP. The high-tech design featured a retractable 40% external shade screen that can be partially closed, in addition to a 15% interior diffusion screen for light distribution. The modelled mid-tech greenhouse had an automated retractable 40% interior shade screen. The low-tech greenhouse had an exterior shade net (35%) that can be fixed directly on top of the roof during the hotter months but is not easily removed; this is a typical strategy used in low-tech systems in the region (Ahmed et al., 2016).

Some literature suggests that tomato yield will continue to increase proportional to the daily light integral (DLI) with no upper limit (Soussi et al., 2022). However, at higher DLI levels the internal greenhouse temperature is difficult to maintain within the optimal range, and the extra cooling demand and associated energy costs begin to outweigh any potential yield increase (Tsafaras et al., 2021). The model assumes a target DLI of 30 mol m$^{-2}$ day$^{-1}$ for greenhouse tomato, in agreement with values recommended in the literature (Cruz & Gómez, 2022; Palmitessa, Paciello, & Santamaria, 2020). The shading for all technology levels is optimised to reduce solar irradiance reaching the crop during the peak hours of the day while still providing the target DLI; this approach ensures that the low-, mid-, and high-tech systems receive the same amount of light throughout the year.

## 2.8. Crop type and yield estimation

Crop yields in greenhouses depend on many factors, including the outdoor climate, the greenhouse climate, the quality of the plant material and cultivation system, and management practices. Cherry tomato was selected as the production crop due to its popularity as a greenhouse crop and the availability of production and market data. The crop yield rates shown in Table 7 were based on the average values reported by local greenhouse operations at each technology level, which agree with

**Table 4**
Design features of the modelled low-, mid-, and high-tech greenhouses.

| Component | Low-tech | Mid-tech | High-tech |
|---|---|---|---|
| **Length (m)** | 40 | 60 | 60 |
| **Width (m)** | 63 | 83 | 83 |
| **Footprint ($m^2$)** | 5000 $m^2$ grow area (two 2500 $m^2$ structures) + 375 $m^2$ service area | 5000 $m^2$ grow area +375 $m^2$ service area | 5000 $m^2$ grow area +375 $m^2$ service area |
| **Height (gutter/ sidewall)** | 3 | 5 | 5 |
| **Height (ridge)** | 4 | 6 | 6 |
| **Structure** | Multi-span Tunnel | Multi-span Chapel | Multi-span Chapel |
| **Cladding** | Roof: Double polyethylene film ($U = 4.0$ W $m^{-2}$ $C^{\circ -1}$) Sidewalls: Double polycarbonate ($U = 3.6$ W $m^{-2}$ $C^{\circ -1}$) | Roof: Double polyethylene film ($U = 4.0$ W $m^{-2}$ $C^{\circ -1}$) Sidewalls: Double polycarbonate ($U = 3.6$ W $m^{-2}$ $C^{\circ -1}$) | Roof: Double polyethylene film ($U = 4.0$ W $m^{-2}$ $C^{\circ -1}$) Sidewalls: Double polycarbonate ($U = 3.6$ W $m^{-2}$ $C^{\circ -1}$) |
| **Cooling system** | Evaporative cooling, negative pressure | Evaporative cooling, positive pressure with high pressure fans and ducts under each gutter | Closed, mechanical AC system with chiller, high pressure fans and ducts under each gutter |
| **Climate control targets** | Daytime: 25–28 °C Nighttime: 17–22 °C | Daytime: 25–28 °C Nighttime: 17–22 °C | Daytime: 25–28 °C Nighttime: 17–22 °C |
| **Peak Ventilation Rate (air changes per hour)** | 60 | 35 | 0.75 |
| **Heating system** | None | None | None |
| **Shading** | Fixed exterior shade net (40%) added during hot months of operation | Retractable interior screen (up to 40%) | Retractable exterior shade screen (up to 40%), interior diffusion screen (15%) |
| **Growing system** | High-wire cherry tomato, soil, non-recirculating irrigation (planting density = 2.8 plants $m^{-2}$) | High-wire cherry tomato, recirculating hydroponic (planting density = 2.8 plants $m^{-2}$) | High-wire cherry tomato, recirculating hydroponic (planting density = 2.8 plants $m^{-2}$) |
| **$CO_2$ enrichment** | None | None | Automated $CO_2$ air enrichment system (setpoint = 1000 ppm) |
| **Water source** | RO-treated seawater equivalent | RO-treated seawater equivalent | RO-treated seawater equivalent |
| **Electricity source** | Grid connection | Grid connection | 500 kWp Solar PV system to supplement grid connection |
| **Condensation capture and reuse** | None | None | Reuse of condensation on heat exchangers |

production values from the region reported in the literature (Estidamah, 2021; Kurklu, 2022). The annual revenue was based on the wholesale price for cherry tomato, determined by averaging values reported to the authors by several producers in Saudi Arabia as well as comparison to supermarket prices (Estidamah, 2021). The high-tech system operated year-round with planting staggered in different zones to maintain a consistent production rate. Each greenhouse system can generate high-quality produce, if well-managed; variations in quality, during periods when target climate control conditions cannot be met, are reflected in differences in yield between each technology level in Table 7.

**Table 5**
Summary of historical climate conditions in four coastal cities in Saudi Arabia. Maximum and minimum temperatures and humidity levels are based on hourly conditions for a 5-year period (2016–2021) (European Commission, 2022; Saudi General Authority for Statistics, 2023).

| City | Month | Min T (°C) | Avg T (°C) | Max T (°C) | Min RH (%) | Avg RH (%) | Max GHI (W $m^{-2}$) |
|---|---|---|---|---|---|---|---|
| **Jazan** | January | 17 | 30 | 36 | 29% | 66% | 861 |
| | February | 24 | 30.3 | 36 | 49% | 68% | 956 |
| | March | 24.5 | 30.7 | 37 | 27% | 69% | 998 |
| | April | 25 | 31 | 37 | 27% | 67% | 1033 |
| | May | 25.7 | 31.4 | 38 | 24% | 64% | 1024 |
| | June | 26 | 31.6 | 41 | 25% | 64% | 1003 |
| | July | 26 | 30.3 | 34 | 41% | 70% | 1002 |
| | August | 26.8 | 30.6 | 34.3 | 27% | 67% | 1000 |
| | September | 27 | 31.1 | 35 | 25% | 65% | 1006 |
| | October | 27 | 31 | 35 | 40% | 69% | 978 |
| | November | 27 | 31.4 | 35 | 38% | 68% | 884 |
| | December | 27.6 | 31.5 | 35.7 | 25% | 65% | 795 |
| | **Annual average** | | **30.9** | | | **67%** | |
| **Jeddah** | January | 15 | 24.2 | 34 | 8% | 54% | 796 |
| | February | 15 | 24.8 | 37 | 7% | 51% | 945 |
| | March | 16 | 26.5 | 40 | 9% | 54% | 1047 |
| | April | 18 | 29.1 | 41 | 9% | 49% | 1099 |
| | May | 21 | 32 | 46 | 5% | 48% | 1066 |
| | June | 23.8 | 32.8 | 48 | 5% | 52% | 1053 |
| | July | 26 | 34 | 43 | 9% | 48% | 1061 |
| | August | 27 | 34 | 49 | 17% | 54% | 1041 |
| | September | 26 | 32.8 | 46 | 6% | 62% | 1022 |
| | October | 24 | 31.1 | 43.4 | 4% | 60% | 968 |
| | November | 19 | 28.5 | 37 | 13% | 57% | 863 |
| | December | 18.8 | 26.2 | 36.1 | 7% | 54% | 781 |
| | **Annual average** | | **29.7** | | | **54%** | |
| **Al Wajh** | January | 9 | 19.9 | 32 | 14% | 54% | 800 |
| | February | 11 | 21 | 34 | 9% | 52% | 895 |
| | March | 12 | 23.1 | 37 | 10% | 57% | 1037 |
| | April | 14 | 25.5 | 39 | 5% | 60% | 1098 |
| | May | 18.6 | 28.9 | 47.6 | 7% | 62% | 1114 |
| | June | 21.6 | 30.3 | 44 | 11% | 66% | 1105 |
| | July | 23.4 | 31 | 40 | 12% | 71% | 1063 |
| | August | 25 | 31.5 | 39.2 | 24% | 73% | 1066 |
| | September | 22 | 30.3 | 44 | 18% | 75% | 1021 |
| | October | 19 | 28.6 | 41 | 6% | 66% | 933 |
| | November | 15 | 25.3 | 38 | 10% | 57% | 810 |
| | December | 13 | 22.2 | 35 | 8% | 52% | 735 |
| | **Annual average** | | **26.5** | | | **62%** | |
| **Dammam** | January | 5 | 16.9 | 29 | 6% | 57% | 780 |
| | February | 3 | 17.9 | 32 | 8% | 55% | 902 |
| | March | 8 | 22.4 | 41 | 3% | 48% | 993 |
| | April | 12 | 27.3 | 43 | 5% | 40% | 1037 |
| | May | 20 | 33 | 46 | 3% | 29% | 1050 |
| | June | 22 | 36.7 | 50 | 2% | 22% | 1074 |
| | July | 28 | 37.6 | 49 | 3% | 33% | 1028 |
| | August | 26 | 36.9 | 49 | 4% | 37% | 1033 |
| | September | 22 | 34.2 | 48 | 5% | 45% | 1028 |
| | October | 17 | 29.8 | 44 | 5% | 51% | 934 |
| | November | 11 | 23.9 | 36 | 10% | 56% | 752 |
| | December | 7 | 18.8 | 32 | 7% | 59% | 735 |
| | **Annual average** | | **28** | | | **44%** | |

### 2.9. $CO_2$ enrichment strategy

$CO_2$ enrichment has been demonstrated to benefit greenhouse crops in improved yields, nutrient-, and water-use efficiency (Jin et al., 2009; Li et al., 2018); however, the supply and delivery of $CO_2$ may be inefficient and prohibitively expensive. Since the utilisation of $CO_2$ by plants for photosynthesis coincides with incident solar radiation, there is a tradeoff in open/semi-open greenhouse crop production systems between ventilating for cooling and maintaining optimal $CO_2$

**Table 6**
Cost of desalinated seawater (including brine disposal and capital replacement cost). Estimates were based on preliminary design by the authors and quotes from local contractors.

| Water source and brine management technique | Cost (€ $m^{-3}$) |
|---|---|
| Near-shore well extraction with local RO system, near-shore brine injection wells | 1.47 € + 1.01 € = 2.48 € |
| Extraction from sea with local RO system, disposal of brine to sea | 1.89 € + 1.01 € = 2.90 € |
| Truck-hauled desalinated water | 2.94 € |

**Table 7**
Yield and revenue values used for economic analysis.

| Description | Low-tech | Mid-tech | High-tech |
|---|---|---|---|
| **Expected Yield * (kg $m^{-2}$ $yr^{-1}$)** | 11.0[a] | 15.0[b] | 31.0[c] |
| **Sales price (€ $kg^{-1}$)** | 5.89[d] | 5.89[d] | 5.89[d] |

* All values are adjusted to operation period (day $yr^{-1}$) discussed in Section 3.1.
[a] Based on values reported by local growers. Range of values from literature include 9.7–13.3 kg $m^{-2}$ $yr^{-1}$ (Singh et al., 2021; Romero-Gàmez et al., 2017).
[b] Range of values from literature include 15.0–21.2 kg $m^{-2}$ $yr^{-1}$ (Campen et al., 2023).
[c] Based on values reported by local growers. Range of values from literature include 30.0–33.6 kg $m^{-2}$ $yr^{-1}$ (Estidamah, 2021; Kurklu, 2022).
[d] Based on values reported by local growers. Range of values from literature 1.94–9.84 € $kg^{-1}$ (assuming farmgate price is equal to half of the market/retail price) (Campen et al., 2023).

concentrations. This is particularly problematic for greenhouses in hot regions, where ventilation is used continuously during most of the year for climate control. In this study, the closed high-tech greenhouse (without ventilation) featured an automated $CO_2$ enrichment system using 150 kg $ha^{-1}$ $hr^{-1}$ to generate an enriched internal environment between 800 and 1000 ppm (Bao et al., 2018). This is assumed to result in a 30% increase in yield, a conservative value based on the literature, which reports 15–63% increases in yield for tomato (Karim et al., 2020; Kimball et al., 1979). The mid- and low-tech designs do not have $CO_2$ enrichment because it is impractical to enrich the air at the required ventilation rates.

### 2.10. $CO_2$ emissions

This analysis quantified both the energy and water footprints, as well as the climate change impact from $CO_2$ emissions ($CO_2$e) of each greenhouse technology level. For greenhouses operating in extreme climates where active climate control is essential throughout the year, the primary differentiating factors in $CO_2$e are energy usage and the carbon embodied in construction materials such as concrete, steel, aluminium, and cladding (Ntinas et al., 2017). By concentrating on these elements, this study targets the most critical sources of emissions that are influenced by the choice of greenhouse design. Other environmental impacts related to the production and usage of other inputs (fertilisers, pesticides, materials) and transportation were determined to be similar between the low-, mid-, and high-tech systems; furthermore, these factors have been shown to have much lower $CO_2$e impact (on the order of 5–10%) compared to energy usage and structure for greenhouses in extreme climates (Torrellas et al., 2012). Therefore, these factors were not considered in this analysis. The carbon embodiment was calculated based on the methods described in Orr et al. (2020). The lifecycle stages A1 (‘production’) through A5 (‘construction complete’) were considered, in addition to replacement of the cladding materials. The replacement schedule was assumed to be 10 years for polycarbonate and 3 years for polyethylene. Greenhouse electricity usage related to climate control and water desalination was converted to a $CO_2$e equivalent based on 1.11 kg$CO_2$e $kWh^{-1}$ (U.S. Energy Information Administration, 2022) for petroleum-based electricity generation. The $CO_2$ used for enrichment applications was not included in the emission summation because it would be collected from a point source and its use does not result in any net $CO_2$ increase in the atmosphere.

### 2.11. Economic model and sensitivity analysis

The capital expenses (CAPEX) for all designs were determined by considering the purchase and installation of equipment related to the greenhouse foundation, structure, cladding, cooling system, growing system, shading, climate control system, growing/harvesting system, electrical system, solar PV, water treatment system and brine disposal. The economic analysis assumed that the land was already owned by the greenhouse operator, so the purchase of land was not considered in the CAPEX. The operational expenses (OPEX) were determined by considering both fixed and variable costs; the fixed costs included maintenance and salaries and were estimated based on local rates. Variable costs included all costs related to labour wages, plant materials (*e.g.*, seeds), substrate, fertilisers, pest management, electrical consumption, water production, brine disposal, liquified $CO_2$ for enrichment, and packaging and delivery of the product. The sources used to determine these costs are noted in Table 3.

To assess the relative importance of various factors on greenhouse economic performance, a local sensitivity analysis was conducted in which each parameter of interest was varied ±30% to determine the impact on payback period for each technology level. The parameters and assumed values used in the sensitivity analysis are shown in Table 8.

## 3. Results

First, a comparative analysis is provided of the modelled results for energy and water consumption of the low-, mid-, and high-tech systems and experimental values reported in the literature. Then, the resource-use efficiencies of each technology level resulting from key design factors such as cooling systems and shading strategies are analysed. Following this, the environmental and economic performance of each technology level is presented and discussed, followed by a side-by-side comparison of each technology level in the performance measures (Table 2). The section concludes with a sensitivity analysis showing the relative impact of various operational and market parameters on the payback period for each technology level.

### 3.1. Comparison of modelled energy and water consumption with other studies

Table 9 compares the estimated water and energy usage from this model with results from previous greenhouse tomato studies. This comparative analysis revealed a notable gap in experimental research on greenhouse tomato production in hot humid climates for extended

**Table 8**
Values for various factors used in sensitivity analysis of economic model.

| Factor | Value in Sensitivity Analysis | | |
|---|---|---|---|
| | Scenario A | Scenario B | Scenario C |
| All Tech Levels | | | |
| Sales price of cherry tomato (€ $kg^{-1}$) | 4.12 | 5.89 | 7.65 |
| Cost of water (€ $m^{-3}$) | 0.58 | 0.83 | 1.08 |
| Cost of electricity (€ $kWh^{-1}$) | 0.04 | 0.06 | 0.07 |
| **Low-Tech** | | | |
| Capital (€ $m^{-2}$) | 168 | 240 | 312 |
| Yield (kg $m^{-2}$) | 7.7 | 11 | 14.3 |
| **Mid-Tech** | | | |
| Capital (€ $m^{-2}$) | 294 | 420 | 547 |
| Yield (kg $m^{-2}$) | 10.5 | 15 | 19.5 |
| **High-Tech** | | | |
| Capital (€ $m^{-2}$) | 434 | 621 | 806 |
| Yield (kg $m^{-2}$) | 40.3 | 31 | 21.7 |

**Table 9**
Comparison of modelled greenhouse water and energy consumption to other greenhouse tomato studies with comparable facility designs. Note that '-' means that the data is either not reported or cannot be meaningfully compared to the results of the current study.

| | Current Study | Al-Ibrahim et al. (2006) | Sabeh et al. (2006) | Lefers et al. (2016) | Campen et al. (2020) | Tsafaras et al. (2021) | Campen et al. (2023) |
|---|---|---|---|---|---|---|---|
| Study location | Jeddah, Saudi Arabia | Riyadh, Saudi Arabia | Tucson, Arizona, USA | Thuwal, Saudi Arabia | Riyadh, Saudi Arabia | Riyadh, Saudi Arabia | Riyadh, Saudi Arabia |
| Study type | Simulation | Experimental | Experimental | Simulation | Experimental | Experimental | Experimental |
| Climate type | Hot-humid | Very hot-dry | Hot-dry | Hot-humid | Very hot-dry | Very hot-dry | Very hot-dry |
| Operational period | Oct–Jun | Jan–Dec | Mar–Oct | – | Jul–Mar | Feb–Dec | Jan–Dec |
| Irrigation (soil-based) (L $m^{-2}$ $day^{-1}$) | 3.0 | – | 3.2 | – | 4.1 | 3.2 | 4.4 |
| Evaporative Cooling (L $m^{-2}$ $day^{-1}$) | 6.9 | – | 5.9 | – | 8.7 | 17.6 | 11.2 |
| Total water consumption (L $m^{-2}$ $day^{-1}$) | 9.9 | – | 9.1 | – | 12.8 | 20.8 | 15.6 |
| Electrical Energy (kWh $m^{-2}$ $day^{-1}$) | 0.05 | 0.07 | – | – | – | – | 0.10 |
| Operational period | Oct–Jun | – | – | 15–16 August (1 day) | Jan–Dec | Feb–Dec | Jan–Dec |
| Irrigation (hydroponic) (L $m^{-2}$ $day^{-1}$) | 3.1 | – | – | – | 4.7 | 4.1 | 3.3 |
| Drain recovery (L $m^{-2}$ $day^{-1}$) | −0.47 | – | – | – | −1.3 | – | – |
| Evaporative cooling (L $m^{-2}$ $day^{-1}$) | 6.4 | – | – | 8.6 | 6.3 | 10.2 | 6.3 |
| Total water consumption (L $m^{-2}$ $day^{-1}$) | 9.0 | – | – | – | 9.7 | 14.3 | 9.6 |
| Electrical energy (kWh $m^{-2}$ $day^{-1}$) | 0.16 | – | – | – | – | – | 0.08 |
| Operational period | Jan–Dec | – | – | – | Jan–Dec | Feb–Dec | Jan–Dec |
| Irrigation (hydroponic) (L $m^{-2}$ $day^{-1}$) | 2.7 | – | – | – | 5.2 | – | 3.8 |
| Drain recovery (L $m^{-2}$ $day^{-1}$) | −0.40 | – | – | – | −1.4 | – | – |
| Condensation Recovery (L $m^{-2}$ $day^{-1}$) | −1.8 | – | – | – | −3.2 | – | −3.3 |
| Total water consumption (L $m^{-2}$ $day^{-1}$) | 0.49 | – | – | – | 0.55 | – | 0.5 |
| Electrical energy (kWh $m^{-2}$ $day^{-1}$) | 1.01 | – | – | – | 1.86 | – | 1.64 |

durations. This lack of data both justifies the current study and constrains comparisons. In lieu of this information, a model-based greenhouse study conducted in the target climate zone (Lefers et al., 2016) is included, in addition to five experimental studies conducted in hot but drier climates like Riyadh, Saudi Arabia and Tucson, Arizona.

Overall, the differences in water and energy usage between the current study and other studies follow an expected trend considering the differences in climatic conditions and some key design distinctions with the low-, mid-, and high-tech models in this study. The low-tech system in the current study used less water and electricity than in Riyadh, where lower humidity and higher summer dry bulb temperatures increase crop transpiration and evaporative cooling needs. Sabeh et al. (2006) reported on a low-tech system in Tucson, Arizona, which is dry like Riyadh but cooler by 4–6 °C on average; Tucson's peak dry bulb temperatures are also lower than Jeddah by 1–2 °C on average (European Commission, 2022). These conditions explain the slightly higher irrigation and lower evaporative cooling demand compared to the low-tech system in this study.

For mid-tech, the irrigation water use was lower than values reported by Campen et al. (2020) and Tsafaras et al. (2021), likely due to the glass cladding increasing light transmission and thereby crop transpiration. Campen et al. (2020) was the only study to report on drainage recovery rate, which was nearly three times higher than this study; this can be attributed to the increased irrigation and the higher drainage and reuse rates (28% drainage rate with 100% reused, compared to 25% drainage rate with 10% drained-to-waste in this study). The average water consumption for evaporative cooling in the mid-tech was about 26% lower than that reported by Lefers et al. (2016) for a simulated mid-tech greenhouse near Jeddah during one day in peak summer. The overall water consumption of the mid-tech system was 6–7% lower than values reported by Campen et al. (2020) and Campen et al. (2023), but 37% lower than Tsafaras et al. (2021), which was based in the same facility as Campen et al. Energy use was higher compared to Campen et al. (2020) likely due to the higher ventilation rate and reduced evaporative cooling efficiency in Jeddah compared to Riyadh.

For high-tech, the current study estimated 38–46% lower energy consumption than Campen et al. (2020) and Campen et al. (2023), attributable to higher dry bulb temperatures in Riyadh as well as the higher convection/conduction losses of the glass cladding compared to the double-walled polyethylene roof and polycarbonate sidewalls in this study. Furthermore, the exterior screen in the model high-tech system reduced energy consumption considerably, while the high-tech system in Riyadh did not use any shading. Higher crop transpiration in the Riyadh facility resulted in higher irrigation rates, drainage recovery, and condensate capture compared to the current study.

### *3.2. Evaporative cooling system performance in different coastal locations in Saudi Arabia*

Greenhouse cooling system performance depends largely on the local conditions; especially for greenhouses with evaporative cooling (low- and mid-tech) it is the basis for energy and water productivity in hot climates. Table 10 and Fig. 4 show a wide range in the modelled performance of evaporative cooling for the four coastal locations based on historical weather conditions. Jazan, with the highest average wet bulb temperatures of the four locations studied, is the least suitable for

**Table 10**
Modelled greenhouse evaporative cooling system performance in different coastal sites in Saudi Arabia.

| Location | Coast | Shutdown period (days) | Shutdown range | Annual average daytime wet bulb (°C) |
|---|---|---|---|---|
| **Jazan** | Red Sea | 239 | 5 April – 29 November | 26.1 |
| **Jeddah** | Red Sea | 106 | 28 June – 12 October | 22.4 |
| **Al Wajh** | Red Sea | 127 | 8 June – 14 October | 21.7 |
| **Dammam** | Arabian Gulf | 0 | n/a | 18.4 |

evaporatively cooled greenhouses: the low- and mid-tech greenhouses are suitable only for 35% of the year. Dammam is the best location for evaporative cooling, with year-round operation possible. The climate between Al Wajh and Jeddah is similar; in these locations, evaporative cooling is possible for nearly two-thirds of the year, with the shutdown period corresponding with the highest humidity levels from June–October.

Jeddah was selected as a median condition for a more in-depth analysis. As shown in Fig. 5, the indoor environment created by evaporative cooling exceeded target conditions during the peak period of 106 days. Fig. 5 also shows that evaporative cooling can be turned off, at least during the nighttime, for some period during the cooler months of November–April.

### 3.3. Water consumption

Table 11 shows modelled results for the water consumption in each greenhouse design. The water consumption for evaporative cooling in the low-tech was only 9% higher than the mid-tech despite a 35% higher ventilation rate in the low-tech; this is explained by the taller mid-tech structure requiring more ventilation to generate the same air exchange rate. This discrepancy illustrates the importance of keeping evaporatively cooled greenhouses at a minimum practical height for growing systems in humid climates where evaporative cooling system efficiency is low. Conversely, in an experimental study comparing water usage between low- and mid-tech greenhouses of similar design to this study but in the very dry and hot climate of Riyadh, Campen et al. (2020) reported a 29% reduction in water usage for evaporative cooling in the mid-tech compared to the low-tech. Both cases show the critical role local climate conditions play in the performance of evaporative cooling systems, regardless of the greenhouse technology level.

#### 3.3.1. Condensation recovery from heat exchangers of high-tech greenhouse

For the high-tech design, humidity and energy balances were used to determine the amount of moisture expected to be removed from the air via condensation as recirculating air passes the chiller heat exchanger. The modelled results showed condensate capture rates of 600–1250 L $m^{-2}$ $yr^{-1}$. Humidity capture via condensation from both the internal greenhouse environment (from crop transpiration) and infiltration from the outdoor air is a significant advantage for high-tech greenhouses and helps substantially reduce the system's water consumption, as this water can be reused for irrigation. During periods of the year when the absolute humidity level is high (August and September in Jeddah), high-tech systems could harvest enough water from the atmosphere to supply the full water demand for the greenhouse (0.28 L $m^{-2}$ $day^{-1}$). This could be accomplished by allowing enough humid outside air to infiltrate that would then be condensed on the heat exchangers. However, this approach would increase the energy demand, and thus increase the cost of water supply to approximately 46 € $m^{-3}$.

### 3.4. Greenhouse energy requirements

As shown in Table 12, the low-tech has the lowest energy demand with the majority used for water desalination, while the mid-tech had a higher energy demand than the low-tech due to the high-pressure fans. In the high-tech system, 91% of the energy demand was due to mechanical cooling. The overall energy demand for the high-tech far exceeds the other technology levels, even with the solar PV supplementing its energy demand.

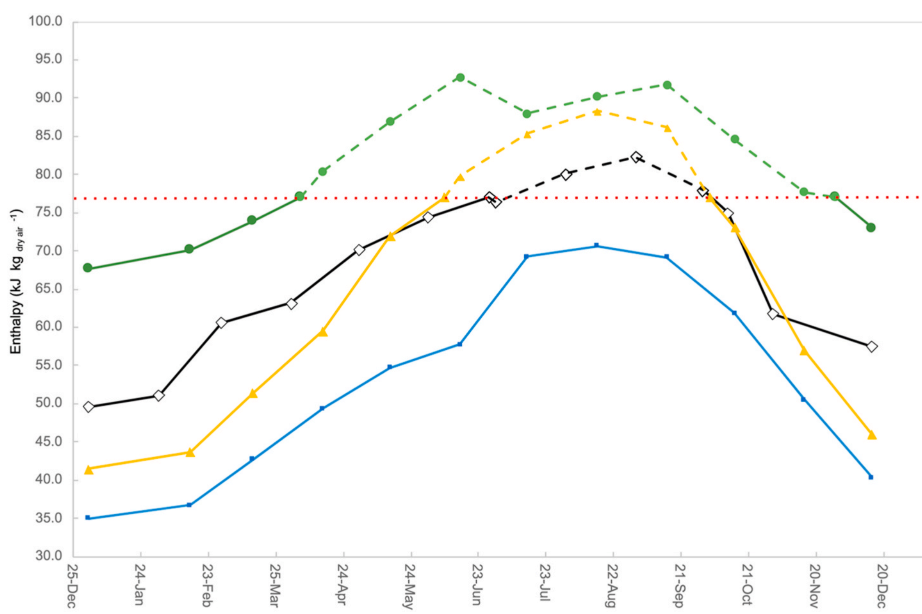


**Fig. 4.** Comparison of average monthly daytime ambient enthalpy for coastal sites in Saudi Arabia. Solid lines (Jazan, Al Wajh, Jeddah, Dammam) are periods when climate was suitable for evaporative cooling; dashed lines (Jazan, Al Wajh, Jeddah) are periods of the year when climate was not suitable for evaporative cooling, defined in this study as 5-day average enthalpy exceeding 77 kJ $kg_{dryair}^{-1}$ ().

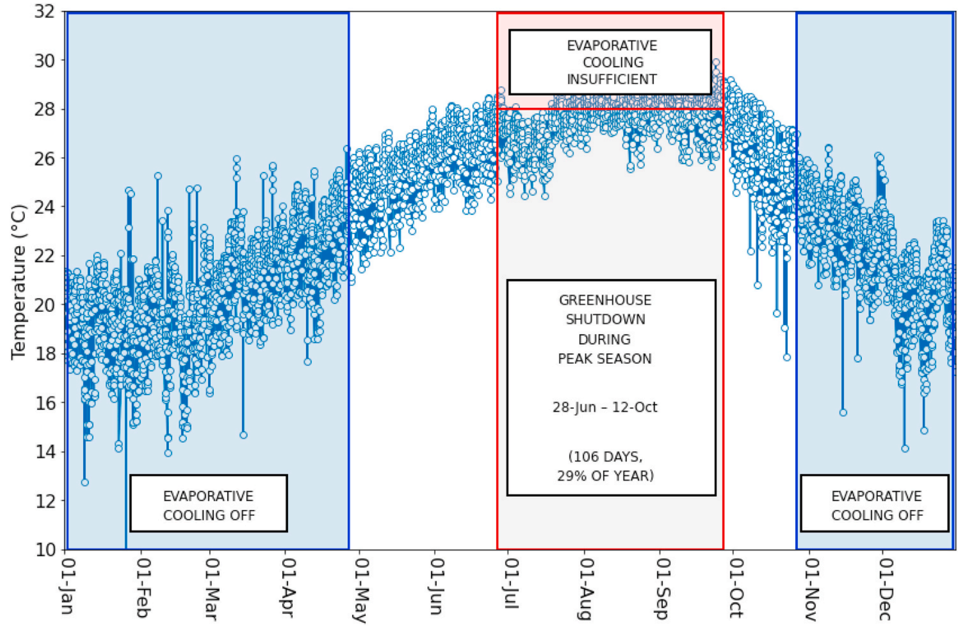


**Fig. 5.** Simulated greenhouse internal conditions (inside next to the cooling pad). Analysis is based on 5-year historical meteorological data for Jeddah, Saudi Arabia (Saudi General Authority for Statistics, 2023); shutdown period is based on enthalpy during daytime hours (6:00–18:00).

**Table 11**
Comparison of water requirements of the low-, mid-, and high-tech for each month in Jeddah, Saudi Arabia.

| Parameter | Low-Tech | Mid-Tech | High-Tech |
|---|---|---|---|
| Days of operation (days $yr^{-1}$) | 259 | 259 | 365 |
| Transpiration [a] (L $m^{-2}$ $day^{-1}$) | 2.47 | 2.59 | 2.25 |
| Irrigation (L $m^{-2}$ $day^{-1}$) | 2.97 | 3.10 | 2.70 |
| Recycled irrigation (L $m^{-2}$ $day^{-1}$) | 0.00 | −0.47 | −0.40 |
| Evaporative Cooling (L $m^{-2}$ $day^{-1}$) | 6.91 | 6.37 | 0 |
| Humidity capture from infiltration[b] (L $m^{-2}$ $day^{-1}$) | Negligible | Negligible | −0.06 |
| Humidity capture from transpiration [c] (L $m^{-2}$ $day^{-1}$) | 0 | 0 | −1.74 |
| Average daily water consumption (L $m^{-2}$ $day^{-1}$) | 9.88 | 9.01 | 0.49 |
| Total annual water consumption ($m^3$ $m^{-2}$ $yr^{-1}$) | 2.56 | 2.34 | 0.18 |

[a] Transpiration is not included in the calculation of water consumption but affects the humidity capture rate from internal environment in the high-tech greenhouse.
[b] Condensate captured by the heat exchangers from the infiltration of humid outdoor air through the greenhouse cladding, based on 1 air change per hour.
[c] Condensate captured by the heat exchangers from the humid air inside of the greenhouse resulting from canopy transpiration.

**Table 12**
Average energy requirements for modelled low-, mid-, and high-tech greenhouses in Jeddah, Saudi Arabia.

| Parameter | Low-Tech | Mid-Tech | High-Tech |
|---|---|---|---|
| Days of operation (days $yr^{-1}$) | 259 | 259 | 365 |
| Fans (kWh $m^{-2}$ $day^{-1}$) | 0.012 | 0.12 | 0.087 |
| Mechanical cooling (kWh $m^{-2}$ $day^{-1}$) | – | – | 0.920 |
| Energy usage for desalination (kWh $m^{-2}$ $day^{-1}$) | 0.040 | 0.036 | 0.0020 |
| Solar PV (kWh $m^{-2}$ $yr^{-1}$) | – | – | −0.50 |
| Average daily energy consumption (kWh $m^{-2}$ $day^{-1}$) | 0.051 | 0.16 | 0.51 |
| Total annual energy consumption (kWh $m^{-2}$ $yr^{-1}$) | 13.3 | 40.9 | 186 |

### *3.4.1. Plastic versus glass as greenhouse cladding material*

Cladding selection is a key design decision for all greenhouses but especially in extreme climates like the AP; excessive DLI for at least 9 months of the year minimises the need for cladding with high transmittance such as glass. Based on modelled results for the high-tech design, a double-wall polyethylene cladding with a U-value of 3.5 W $m^{-2}$ °$C^{-1}$ will result in an annual energy savings of 8.6% in comparison to glass (U-value of 6.0 $m^{-2}$ °$C^{-1}$). Polyethylene is lighter weight than glass, resulting in a lighter steel structure and foundation being required to support the roof. This, combined with the cladding material itself being less expensive, reduces the capital costs for polyethylene greenhouses in addition to the carbon footprint (Maraveas, 2019). The drawback of polyethylene is that it has a much shorter lifetime than glass (3–4 years vs. 20–25 years) which means the cladding must be replaced multiple times during the lifetime of the greenhouse.

### *3.4.2. Shading strategies*

Fig. 6 shows the impact of various shading strategies on water and energy usage in each greenhouse technology level. Modelled results showed that an exterior screen is the most effective for energy reduction because it reduces solar irradiance before it enters the envelope of the greenhouse where it can be trapped as heat. Fig. 6a shows that an adjustable exterior screen would reduce energy consumption for cooling in the high-tech greenhouse by 32% annually (a savings of 32,200 € $yr^{-1}$ $ha^{-1}$) while still meeting a target DLI of 30 mol $m^{-2}$ $day^{-1}$. This result is consistent with the conclusions of Abdel-Ghany et al. (2015) in which external screens were identified as the best option for thermal control in an arid climate.

Heavy interior shading is well-suited for mid-tech greenhouses which ventilate from the roof, as the irradiance that is blocked by the shade is readily removed by roof ventilation. As shown in Fig. 6b, the interior screen resulted in 12% reduction in water usage for the mid-tech design compared to no shading. The internal shade system must be properly designed so that it does not negatively interfere with ventilation; with adequate roof ventilation, the vertical temperature gradient will keep heat from moving into the crop canopy. Interior screens are not suitable for high-tech designs because the irradiance that is reflected by the screen is trapped as heat within the structure. This heat must be removed to maintain cooling levels and so eliminates any benefit in

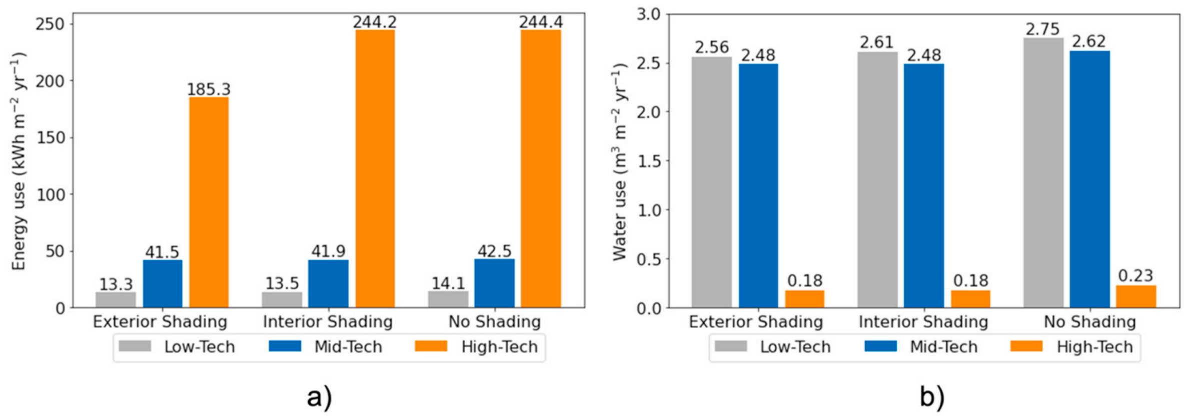


**Fig. 6.** Impact of exterior shading, interior shading, and no shading on the (a) energy usage and (b) water usage for each greenhouse technology level.

reducing energy requirements.

For the low-tech design, the modelled results showed that any shading more than 35% will reduce internal DLI below the target of 30 mol $m^{-2}$ $day^{-1}$. A 50% exterior screen would result in a DLI of 23 mol $m^{-2}$ $day^{-1}$ during the hotter months of operation in Jeddah. An exterior shade cloth fixed only on the second half of the structure could reduce the increase in temperature from inlet to outlet without requiring excessive ventilation rates and corresponding higher water consumption (Kittas et al., 2003); however, the non-homogenous light conditions across the growing area may have negative agronomic consequences.

### 3.4.3. *Dust accumulation on greenhouses*

Dust accumulation on greenhouse cladding is a significant issue in the AP region, estimated to cause up to 30% shading (Manor et al., 2005). Some local growers contend that dust accumulation during the hotter periods is an effective (and free) shading strategy. Modelled results show that for the high-tech system, blocking 25% transmittance by dust would have a similar positive reduction in cooling energy demands as a retractable exterior screen. In this scenario the target DLI was reached except during the lowest light period (December–February); during these months the dust should be cleaned off the cladding. However, the combination of a retractable exterior screen with dust was not effective: PAR was reduced by the dust in the off-peak hours, so during peak hours the exterior shade could not be deployed for a long duration if DLI targets were to be reached. In reality, it is unlikely that dust serves as a comparable substitute for retractable shade screens since maintaining a consistent and desirable shading level via dust accumulation is impractical.

## 3.5. *$CO_2$ emissions*

The $CO_2$e related to energy and water usage and structural carbon embodiment of each greenhouse design are shown in Table 13. The majority of $CO_2$e from all levels is related to energy consumption during operations, while only 2–16% of total emissions over the 20-year project lifetime were due to the carbon embodiment of structure. The high-tech greenhouse system contributed 2.3 times more $CO_2$e than the mid-tech, and nearly 5 times more than the low-tech system, due to the relatively high energy requirement of the mechanical cooling system (and the year-round operational period enabled by it). Interestingly, in the low-tech design, nearly two-thirds of the total $CO_2$e were related to energy requirements for water production.

In Section 3.4.1 the advantages of plastic cladding over glass in the high-tech system in terms of energy efficiency were explained; the differences in $CO_2$e are even more significant. Despite the need to replace polyethylene and polycarbonate cladding multiple times during the project lifetime, the overall carbon embodiment of the plastic-clad high-tech system is only 40% of a high-tech glass-clad system due to the substantially lower steel and concrete quantities needed for the lighter structure. In addition, the energy savings of plastic over glass resulted in an equivalent 8.6% lower $CO_2$e during operations.

**Table 13**
$CO_2$ emissions ($CO_2$e) related to energy usage, water usage, and structure over the 20-year project lifetime for each greenhouse technology level. Note that the energy offset from the PV system is included in calculation of emissions for the high-tech design.

| Parameter | Low-tech | Mid-tech | High-tech |
|---|---|---|---|
| **Building carbon embodiment** ($ton_{CO2e}$) | 575 | 950 | 1000 |
| **Operations - Electricity for cooling** ($ton_{CO2e}$) | 677 | 6631 | 41,021 |
| **Operations - Electricity for water RO** ($ton_{CO2e}$) | 2273 | 2078 | 160 |
| **Lifetime $CO_2$ emissions** ($ton_{CO2e}$) | 3525 | 9659 | 42,181 |
| **Annual $CO_2$ emissions per unit area** ($kgCO_2e$ $m^{-2}$ $yr^{-1}$) | 14.8 | 43.5 | 206 |
| **$CO_2$ emissions per unit tomato yield** ($kgCO_2e$ $kg_{yield}^{-1}$) | 1.34 | 2.90 | 6.64 |

Most studies report $CO_2$e impact in terms of yield ($kgCO_2e$ $kg_{yield}^{-1}$), directly linking the environmental impact to productivity. The overall $CO_2$e for the low- and mid-tech designs were very close to values reported by Ntinas et al. (2017), which quantified the carbon footprint of several types of heated (not cooled) greenhouses in Germany and Greece. The average impact for a similar operational period was 2.09 $kgCO_2e$ $kg_{yield}^{-1}$, compared to an average of 2.12 $kgCO_2e$ $kg_{yield}^{-1}$ for the low- and mid-tech greenhouses in this study. Page et al. (2012) reported 1.86 $kgCO_2e$ $kg_{yield}^{-1}$ of a heated/cooled high-tech greenhouse in Australia, 72% lower than that of the high-tech design system in this analysis. This difference can be largely explained by the significantly higher yield productivity for greenhouse tomato in Page et al. (2012) compared to this study—57 kg $m^{-2}$ and 24 kg $m^{-2}$, respectively. In addition, the more moderate climate in the study location (Sydney, Australia) lowers the energy requirement for climate control, in turn reducing the associated $CO_2$e.

## 3.6. *Economic performance*

As shown in Table 14, the low-tech greenhouse had the lowest CAPEX, but also the lowest revenue and the highest water consumption. Water system infrastructure comprised 30% of the capital cost of the low-tech greenhouse. The high CAPEX of the mid-tech design was compensated by only a moderate increase in yield compared to the low-tech greenhouse; this disadvantage is illustrated in the relatively long payback period of the mid-tech greenhouse (7.08 years) compared to the high- and low-tech (4.86 and 5.84 years, respectively). The high-tech greenhouse had the highest CAPEX, however its year-round

**Table 14**
Economic performance of modelled low-, mid-, and high-tech greenhouses.

| Parameter | Low-Tech | Mid-Tech | High-Tech |
|---|---|---|---|
| **CAPEX (€ m$^{-2}$)** | | | |
| Structure and cladding | 37.00 | 74.00 | 74.00 |
| Service area with packaging | 64.00 | 64.00 | 64.00 |
| Cooling system | 11.00 | 92.00 | 230.00 |
| Appurtenances | 58.00 | 139.00 | 163.00 |
| Water source/RO/Brine disposal | 70.00 | 52.00 | 23.00 |
| Solar PV | 0.00 | 0.00 | 66.00 |
| **Total CAPEX** | **240** | **420** | **620** |
| **OPEX (€ m$^{-2}$ yr$^{-1}$)** | | | |
| Seed/Fertiliser/Chemical | −4.14 | −4.14 | −4.14 |
| Labour | −10.47 | −10.47 | −14.72 |
| Energy consumption | −0.73 | −2.17 | −10.24 |
| Packaging and delivery | −2.53 | −3.45 | −7.13 |
| Maintenance | −3.60 | −6.31 | −9.32 |
| Water consumption | −1.65 | −1.51 | −0.12 |
| Brine disposal | −0.52 | −0.47 | −0.04 |
| $CO_2$ enrichment | 0.00 | 0.00 | −9.12 |
| **Total OPEX** | **−23.65** | **−28.52** | **−54.81** |
| **Revenue (€ m$^{-2}$ yr$^{-1}$)** | 64.77 | 88.32 | 182.53 |
| **Net profit (€ m$^{-2}$ yr$^{-1}$)** | 41.12 | 59.80 | 127.71 |
| **Payback period (years)** | 5.84 | 7.03 | 4.86 |
| **Present value (€ m$^{-2}$)** | 372 | 469 | 1279 |

production resulted in a net present value 2.7 times higher than mid-tech and 3.4 times higher than low-tech.

Campen et al. (2023) reported on the economic performance for low-, mid-, and high-tech systems in Riyadh; the total CAPEX for the low-, mid-, and high-tech was 65, 125, and 350 € m$^{-2}$, respectively, 27–56% lower than the CAPEX estimates in the current study. This difference is mostly attributable to the additional appurtenances, water desalination infrastructure, and solar PV (for the high-tech) included in the facility designs for the current study; these were not accounted in the analysis by Campen et al. (2023). The annual OPEX for the low- and high-tech in Campen et al. (2023) were virtually the same as the current study, while the mid-tech had lower annual OPEX (21 € m$^{-2}$ yr$^{-1}$ compared to 28.5 € m$^{-2}$ yr$^{-1}$ in this study); this difference can be explained by a lower electricity consumption for the mid-tech system in Campen et al. (2023) (see Table 9). In a review paper, Jemai et al. (2022) concluded that high-tech closed greenhouses in arid regions offer higher economic returns than lower-tech options. Conversely, Campen et al. (2023) showed the high-tech to have the longest payback period; importantly, this study was conducted in Riyadh, an inland desert location, where evaporative cooling is much more cost-effective, therefore strengthening the performance of the low- and mid-tech designs.

### 3.7. Overall performance and sensitivity analysis

Fig. 7 summarises the performance of the low-, mid-, and high-tech designs according to the performance measures described in Table 2. The high-tech system, despite higher initial costs, provided the quickest return on investment due to the year-round operations enabled by its closed cooling system and higher yield productivity. The water use efficiency of the high-tech system was 13.0 times higher than the mid-tech and 14.2 times higher than the low-tech, indicating the heavy burden of evaporative cooling on water usage in this climate type. The water savings in the high-tech system came at the cost of high energy usage, using 14 times more kWh per m$^{-2}$ than the low-tech, and 4.7 times more than the mid-tech, corresponding with a higher $CO_2$e contribution. Note that the energy and $CO_2$e performance of the high-tech system considered the energy usage offset from the solar PV array; the 0.5-ha PV offsets less than half of the total energy usage of the 1-ha facility.

The results of the sensitivity analysis are shown in Fig. 8. Changes in produce sales price and crop yields had the biggest impact on the payback period. A 30% increase in electricity or water costs had little impact on the payback period (this is typical of the other operational costs as well). A two-fold increase in electricity cost resulted in a 4%, 10%, 9% increase in payback period of low-, mid-, and high-tech systems, respectively. Due to the narrow profit margins for the mid-tech greenhouse, its financial performance was very sensitive to yield and produce sales price. The payback period for the high-tech greenhouse was more sensitive to yield and produce sales price than to increases in capital or operational costs. Vanthoor et al. (2012) compared a range of technology levels in southern Spain; similarly, they found the financial performance for both low-tech and high-tech was most sensitive to market prices and yields. However, the lower-tech system was found to

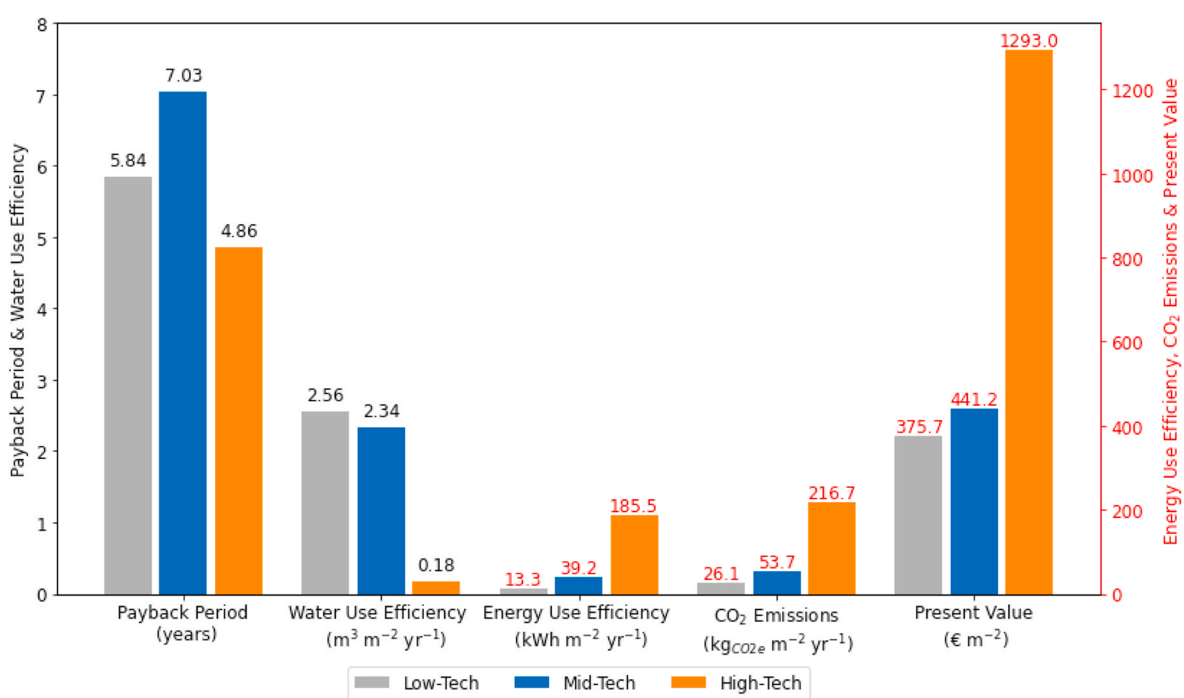


**Fig. 7.** Comparison of low-, mid-, and high-tech greenhouse systems according to performance measures.

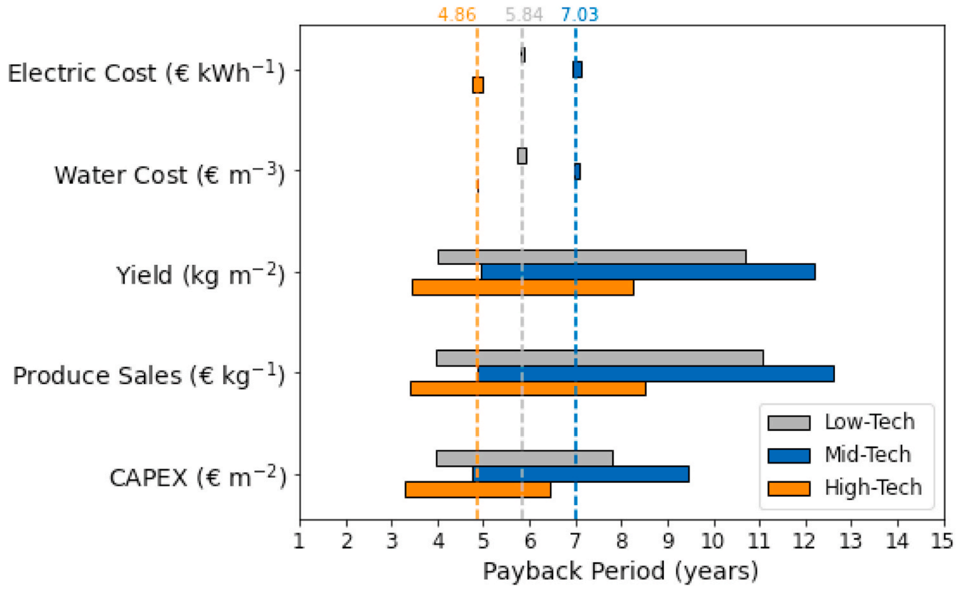


**Fig. 8.** Results of sensitivity analysis for (a) low-tech, (b) mid-tech, and (c) high-tech greenhouses. Each parameter was varied by ±30% of base scenario value to show the impact on the payback period.

have the best financial performance for southern Spain conditions; this difference is explained by the more moderate climatic conditions which enable greenhouse production to have reduced resource input for climatic control.

## 4. Discussion

The key takeaways from this analysis are summarised here.

- **Knowledge gaps for greenhouses in hot humid climates.** There is a notable lack of research as well as practical information related to greenhouse design and performance in hot, humid climates characterised by regular high wet bulb temperatures. These conditions, prevalent in much of the Arabian Peninsula (AP) and many other densely populated regions, represent major challenges for conventional greenhouse climate control. Optimised design and operational strategies are required to make greenhouse crop production a financially and environmentally viable industry in such contexts.
- **Alignment of modelled results with experimental data.** The modelled water and energy usage for the low-, mid-, and high-tech designs showed close alignment with experimental data reported in the literature, indicating the validity of the modelling approach used in this study. The discrepancies observed between modelled and experimental results were primarily attributable to local climatic variations and differences in facility design.
- **Limitations of evaporative cooling systems.** In the studied locations, evaporative cooling systems in both the low-tech (negative pressure) and mid-tech (positive pressure) designs failed to maintain target climatic conditions for much of the year. In such climates with regularly high wet bulb temperatures (see Fig. 1), the efficiency of water usage in greenhouses equipped with evaporative cooling is significantly compromised. This limitation undermines the viability of using greenhouse agriculture as a sustainable method for local food production in water-scarce areas like the Arabian Peninsula. To address this concern, closed cooling systems (as featured in the high-tech design in this study) should be implemented.
- **'Glasshouse' does not equal 'high-tech greenhouse'.** Contrary to the purported view that glass cladding is the best option for greenhouses if it can be afforded, polyethylene results in a ~9% energy savings and lower embodied $CO_2$ emissions while being significantly cheaper and easier to install than glass; in other words, 'glasshouse' is not an appropriate synonym for 'high-tech greenhouse'.
- **Mid-tech upgrades probably not worth the cost.** This analysis revealed that the additional investment required for mid-tech greenhouse systems does not yield proportional economic benefits, due to the limited effectiveness of evaporative cooling in regions that regularly experience high wet bulb temperatures. This finding underscores the importance of evaluating the cost-benefit ratio of technological upgrades in greenhouse operations in the context of local climatic conditions.
- **Shading strategies are not 'one size fits all'.** This analysis showed significant reductions in water and energy consumption due to shading across different technology levels, though the optimal shading strategy varied by technology level. In the high-tech closed design, external shading cut energy use by 32% annually, translating to savings of approximately 32,702 € per hectare per year in Saudi Arabia. In the mid-tech design, which featured roof ventilation, both internal and external shading provided comparable benefits in terms of water and energy savings. In the low-tech system, which was not operational during the peak summer months due to ineffective evaporative cooling, any shading beyond 35% diminished daily light integral (DLI) below the desired threshold.
- **Water desalination is a major expense, especially for low-tech.** Compared to other regional greenhouse studies, our analysis showed higher CAPEX across all technology levels. This increase is primarily due to the inclusion of water desalination infrastructure costs in the economic model. These costs, often overlooked or excluded, represent a significant investment; incorporating these expenses provides a more accurate financial assessment of establishing and operating greenhouses in regions like the AP where desalination is becoming increasingly necessary to access freshwater supplies.
- **Energy-intensive closed cooling makes high-tech worst emitter.** $CO_2$ emissions contributions from greenhouses mostly come from energy usage related to cooling, rather than embodied $CO_2$ emissions in the facility, which only comprises 2–16% of total emissions over a 20-year project lifetime. The high-tech was the highest emitter by far, even with a 0.5-ha PV array to supplement its energy requirement, due to the high-energy demand of its closed cooling system.
- **High-tech design showed the quickest payback.** Greenhouses of various technology levels were shown to be techno-economically viable in an extreme hot humid climate; the calculated payback

periods for the low-, mid-, and high-tech designs were 5.84, 7.03, and 4.86 years, respectively, which can be considered within the planning horizon for most growers/investors.
- **Market stability is key to financial viability.** Consistent with other greenhouse techno-economic studies, the sensitivity analysis showed yield productivity and market prices to have the largest impact on economic return. Overall, the mid-tech design was the most sensitive to fluctuations among the technology levels due to its high initial CAPEX and relatively narrow profit margins. The high-tech system was the most robust to variable conditions on account of high and consistent revenue from year-round production, enabled by a closed mechanical cooling system.

Looking forward, there are several *emerging technologies* that have potential to significantly improve the techno-economic performance of greenhouses in hot-humid climates.

- **Heat-blocking cladding** absorbs and/or reflects the NIR wavelengths which contribute most to heat production inside the greenhouse and transmits PAR wavelengths (Baeza et al., 2020; Mishra et al., 2023). This selective wavelength filtering reduces the shading and cooling requirement which can result in significant water and energy savings and also enhance crop quality (Lamnatou & Chemisana, 2013). Several heat-blocking cladding products are now commercially available, at a price point that makes them applicable to all tech levels. The ongoing challenge is to ensure the longevity and durability of these materials, which should match or even exceed conventional greenhouse cladding options.
- **Integration of solar PV** can help to offset the high energy usage in high-tech greenhouses and improve the sustainability of the facility; however, a large area is required for PV to be sufficient for greenhouse energy demands. The energy demand of the high-tech system (1.01 kWh $m^{-2}$ $day^{-1}$ on average) indicates that a roughly equivalent area of solar PV in the study location (Jeddah, Saudi Arabia) is required to fully meet its energy demand. The global horizontal solar irradiance in Jeddah over the course of the year ranges between 5 and 7.5 kWh $m^{-2}$ $day^{-1}$ (European Commission, 2022). In these conditions, assuming an average PV system efficiency of 20%, with a performance ratio of 80%, the PV system generates on average 1 kWh $m^{-2}$ $day^{-1}$. Although this would lower the land productivity of the system, it could be argued that the reduction in $CO_2$ emissions is more valuable. It is important to keep in mind that the advantage for cooled greenhouses in hot climates is that the highest energy usage (for cooling) coincides with highest PV energy production; the opposite is true for heated greenhouses in cold climates.
- **'Hybrid' cooling systems** use positive-pressure evaporative cooling during periods of the year when outdoor conditions are suitable and closed mechanical cooling during the rest of the year. Although not yet widely implemented in the AP region, hybrid systems are gaining popularity as energy saving cooling solutions in hot-humid regions (Shi et al., 2023) and can reduce the energy requirements for high-tech greenhouse systems significantly. However, these benefits may be outweighed by increased water usage for evaporative cooling and increased capital expense due to the incorporation of both cooling systems, including roof vents. For the modelled high-tech greenhouse system in this study, operating in an evaporative cooling mode during suitable outdoor conditions (see Fig. 5) would reduce the energy consumption by 46% (0.28 kWh $m^{-2}$ $day^{-1}$) but would increase water consumption by 360% (1.78 L $m^{-2}$ $day^{-1}$). These significant trade-offs indicate that the benefits of hybrid cooling systems are locally dependent and may not be economically or environmentally justified in extremely freshwater-scarce regions such as the AP region.

## 5. Conclusion

As interest and investment in greenhouse agriculture expands globally, benchmarks and practical tools are required to assess the profitability and sustainability of greenhouse design alternatives, to ensure they are locally suitable and maximally resource use efficient. In this study a model-based method was developed and applied to compare low-tech (evaporatively cooled, negative pressure), mid-tech (evaporatively cooled, positive pressure), and high-tech 'closed' greenhouse designs in the extreme hot, humid climate of coastal Saudi Arabia.

The current study concentrated on identifying and analysing the major factors that impact the techno-economic viability of greenhouse systems in this challenging climate. These primary factors included energy and water usage efficiencies, $CO_2$ emissions contribution, CAPEX and OPEX, and the resulting financial returns from different technological setups. While this approach provides a robust understanding of the key drivers of technical and economic performance related to the greenhouse design, it is important to consider the potential cumulative impact of some minor factors that could tip the results in a different direction.

Some notable limitations of the current study include: 1) reliance on modelled data; 2) consideration of only one crop type (tomato); 3) simplified representation of yield as a static input rather than a dynamic model; 4) limited scope of environmental impact assessment, which only considered $CO_2$ emissions; 5) simplified economic model which excluded land costs, depreciation and interest; and 6) locally specific economic data to Saudi Arabia.

To address these limitations, future research should include further validation of the modelling methods used in this study, through experimental trials conducted in relevant climatic conditions, in which overall energy and water use is continuously monitored. Future studies should also consider incorporating multiple crop types with different growth cycles, environmental needs, and economic values. Integrating a dynamic yield model that adjusts for varying environmental conditions and management practices would provide more accurate estimates, especially for water usage and revenue. Expanding on the crop production system aspects would also enable a comprehensive life cycle assessment, which would better capture the environmental impact of the entire greenhouse crop production system. In terms of the economic analysis, incorporating land acquisition costs, accounting for depreciation and interest, and adapting the economic model to various regional settings would improve the robustness and applicability of the financial assessments, making them more useful for potential investors and policymakers.

This study underscores the need for targeted interventions to optimise greenhouse agriculture for regions like the AP, in which greenhouses are already regarded as the most water-smart method for local crop production. Especially since many stakeholders in the AP have access to sufficient capital, it is recommended to promote advanced greenhouse technologies such as closed cooling systems and optimised shading systems due to their enhanced water productivity and economic benefits. Subsidies, incentives, and training programs especially for younger generations should be provided to facilitate the adoption and successful operation of these advanced facilities. Moreover, integrating renewable energy sources in greenhouse operations is crucial to mitigate their higher energy demands and related environmental impact. Finally, the development and dissemination of objective guidelines and benchmarks, including the current study, are essential to assist stakeholders in making informed decisions about appropriate greenhouse technologies, which can simultaneously support profitability and environmental stewardship in these challenging climates.

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## CRediT authorship contribution statement

Conceptualisation, W.H. and R.W.; Methodology, W.H. and R.W.; Investigation, W.H., R.W., Z.L., A.B., C.V., and D.A.; Visualisation, W.H., Z.L., A.B., R.W.; Writing – Original Draft, R.W., W.H., Z.L., and A.B.; Writing – Review and Editing, R.W., W.H., Z.L., A.B., P.D., M.Q., M.T., and A.A.; Funding Acquisition, R.A.W., M.T., R.W., and D.A.; Supervision, R.A.W. and M.T.

## 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

Further details related to the numerical modelling of the greenhouse energy and humidity balances, which form the basis of techno-economic assessment framework introduced in this study, are described here. Validation of the energy balance model for both an evaporative cooling and a mechanical closed cooling system with experimental data from commercial facilities in hot humid climatic conditions is then presented. All parameters, assumed values and sources used in the model are summarised in Table A1 at the end of this section.

### *Energy balance modelling*

This greenhouse energy balance model used in this study was first described in Aldrich et al. (1994), and has been applied and validated in many subsequent studies for different climatic conditions, including cold and temperate climates (Dimitropoulou, Maroulis, & Giannini, 2023), a hot climate (Salazar-Moreno et al., 2019), and a warm humid climate (Ortiz et al., 2023); the latter two studies demonstrated strong prediction efficiency (89% and 86%, respectively).

For the energy balance, a combination of convection and conduction through the cladding of the greenhouse ($q_{conv,i}$, W) is calculated in EQ-A1 (Salazar-Moreno et al., 2019):

$$q_{conv,i} = A_r\, U_r\, (T_a - T_i) + A_s\, U_s\, (T_a - T_o) \quad \text{EQ-A1}$$

The temperature on the inside of the roof was considered to be the highest temperature in the greenhouse, represented by the exit temperature ($T_o$) for a ventilated system, or the return air temperature in a closed system. The same value was used for thermal transmittance of the roof ($U_r$) and sidewalls ($U_s$), both in W $m^{-2}$ °$C^{-1}$. In this analysis $q_{conv}$ was always positive since the outside temperature ($T_a$) is always warmer than the inside temperature during active cooling.

Inefficiencies in fan motors ($e_{fan}$ and $e_{mtr}$) will contribute heat ($q_{fan}$, W) to a system as per EQ-A2 (ASHRAE, 1996):

$$q_{fan} = V \bullet \frac{h \bullet C_4}{e_{fan} \bullet e_{mtr}} \quad \text{EQ-A2}$$

$q_{fan}$ increases as the back-pressure on the fan ($h$, Pa) and ventilation ($V$, $m^3\ s^{-1}$) increases. $C_4$ is a constant equal to 0.9 W s $m^{-3}$ $Pa^{-1}$. $q_{fan}$ is more significant in mid-tech and high-tech which operate a large number of high-pressure fans for circulation and/or ventilation.

Solar radiation ($q_{rad}$) is the largest contributor to the daytime cooling load in hot climates, and is calculated in EQ-A3:

$$\mathrm{q_{rad}} = \mathrm{R_g A_r}(\tau_{\mathrm{esh}}\tau_{\mathrm{clad}}) \bullet [\tau_{\mathrm{ish}}(1\text{-B}) + \mathrm{Y}(1\text{-}\ \tau_{\mathrm{ish}})] \quad \text{EQ-A3}$$

As shown in EQ-A3 different portions of outdoor global irradiance ($R_g$, in W $m^{-2}$) are reflected as it passes through different barriers, including the external shade screen ($\tau_{esh}$), the cladding with or without dust ($\tau_{clad}$), and the internal shade screen ($\tau_{ish}$). A portion of the irradiance that passes through these barriers is assumed to be absorbed by the structure ($B$) (Aldrich et al., 1994). A portion of the irradiance that is reflected from the interior shade screen is assumed to be trapped above the screen as heat and contributes to the cooling load ($Y$).

The solar radiation reaching the plant level $I_{plant}$ (in W $m^{-2}$) is calculated by EQ-A4:

$$\mathrm{I_{plant}} = \mathrm{R_g A_r}[\tau_{\mathrm{esh}}\ \tau_{\mathrm{clad}}\tau_{\mathrm{ish}}\ (1\text{-B})] \quad \text{EQ-A4}$$

The amount of heat energy absorbed by the crop plants $q_{plant}$ (in W $m^{-2}$) is calculated by EQ-A5:

$$\mathrm{q_{plant}} = \mathrm{G_E}\lambda(\mathrm{X_{plant}}\text{-X}) \quad \text{EQ-A5}$$

This value deducts from the heat energy contributed by $q_{rad}$.

Transpiration conductance ($G_E$, in m $s^{-1}$), the latent to sensible heat ratio (Ɛ), stomatal resistance ($r_s$, in s $m^{-1}$), and net radiation at plant level ($R_n$, W $m^{-2}$) are given in EQ-A6, EQ-A7, EQ-A8, and EQ-A9. Aerodynamic resistance ($r_b$, in s $m^{-1}$) is a constant ranging from 200 to 300 s $m^{-1}$. The saturated water vapor concentration ($X_{sat}$, kg $m^{-3}$) and canopy water vapor concentration ($X_{plant}$, kg $m^{-3}$) are given in EQ-A10 and EQ-A11.

$$G_E = \frac{2LAI}{(1+\varepsilon)r_b + r_s} \quad \text{EQ-A6}$$

$$\varepsilon = 0.7584e^{0.0518T_a} \quad \text{EQ-A7}$$

$$r_s = \left(82 + 570e^{\frac{-kR_n}{LAI}-}\right) \backslash\backslash\backslash \left(1 + 0.023(T_a - 20)^2\right. \quad \text{EQ-A8}$$

$$\mathrm{R_n} = 0.86\left(1\text{-e}^{(-0.7\mathrm{LAI})}\right)\mathrm{I_{plant}} \quad \text{EQ-A9}$$

$$X_{plant} = X_{sat} + \varepsilon \frac{r_b R_n}{2LAI\lambda} \quad \text{EQ-A10}$$

$$X_{sat} = 5.563e^{0.0572T_a} \quad \text{EQ-A11}$$

*Humidity balance modelling*

The greenhouse humidity balance was calculated according to EQ-A12 which is based on the approach described in Fitz-Rodríguez et al. (2010):

$$m_{vent,i} + m_{infl,i} + m_{evapc} + m_{trsp} = m_{vent,o} + m_{infl,o} + m_{cnds} \quad \text{EQ-A12}$$

The infiltration and exfiltration rates ($m_{infl,i}$ and $m_{infl,o}$) are assumed to be a minimum of 1 ACH. For the low- and mid-tech evaporatively cooled systems, a cooling pad wet bulb efficiency of 80% was assumed in order to calculate the moisture contributed by evaporative cooling ($m_{evapc}$). Ventilation in and out ($m_{vent,i}$ and $m_{vent,o}$) is dependent on the technology level and is equal to 0 for the closed high-tech design in this study. Condensate capture ($m_{cnds}$) is only applicable in the high-tech system where condensate is collected on the chiller heat exchanger.

Moisture contributed due to plant transpiration ($m_{trsp}$, in kg $hr^{-1}$) is calculated based on the energy absorbed by the plants and the latent heat of vaporisation for water (λ, 2260 kJ $kg^{-1}_{water}$) and is calculated in EQ-A13 (Mahmood et al., 2022):

$$m_{trsp} = \frac{3.6\, q_{plant}}{\lambda} \quad \text{EQ-A13}$$

*Validation of greenhouse climate model in hot humid climates*

The modelling approach used for the evaporatively cooled greenhouse systems in this study (the low- and mid-tech) was validated against experimental values reported by Xu et al. (2015) for a commercial greenhouse facility in Shanghai, China during the summer, which has a hot humid climate similar to the locations studied in this analysis. Although Xu et al. (2015) reported limited data over three days of measurement, a variety of conditions were measured such as varied levels of solar radiation and internal/external shading combinations.

Figure A1 compares the measured greenhouse temperature in Xu et al. (2015) with predicted values generated by the energy balance model described above. The short time period (9:48–11:24) was the only dataset reported that included all of the input parameters required for the energy balance model; these parameters included outdoor air temperature, humidity, and solar radiation, in addition to the facility design specifications. The plant transpiration rate used in the current study was also applied to the experimental dataset, since the crop conditions were not clearly described in the study. The external shade screen was deployed from the beginning of the measurement period, and then the internal shade screen was also deployed starting around 11:00. It is clear from Fig. A1 that the predicted values closely follow the trend of the measured values and are responsive to changes in ambient conditions as well as the deployment of the internal shade screen; the measured results indicate higher sensitivity to environmental changes. The average relative error for the predicted values was very small, only 1.7%, indicating strong predictive performance of the energy balance model used in the current study for hot humid conditions.

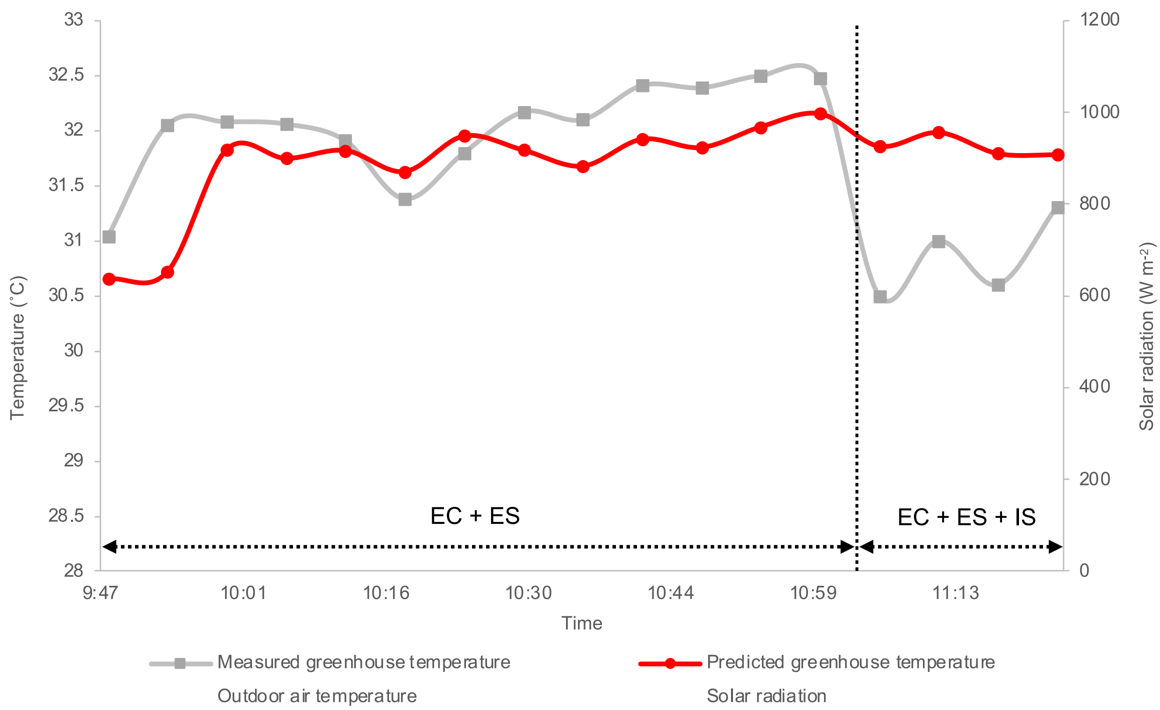


**Fig. A1.** Comparison of measured to predicted values for internal air temperature for evaporatively cooled commercial greenhouse facility in Shanghai, China on August 5, 2012; EC = evaporative cooling, ES = exterior shade screen, and IS = interior shade screen. Measured ambient relative humidity was between 63 and 68% during the measurement period; calculated ambient wet bulb temperature was 26–27 °C.

Likewise, the modelling approach used to calculate the energy balance of the high-tech closed greenhouse design in the current study was validated against measured values reported by Mao et al. (2024). The authors reported on the experimental performance of a fan coil cooling system in a commercial glasshouse producing tomato in Wuhan, China during the summer, which also has a hot humid climate; two days of data were reported, the first day was rainy (July 25, 2023) and the next day was sunny (July 27, 2023).

Figure A2 shows the predicted values of the internal greenhouse temperature compared to the measured values over the course of the sunny day. The cooling system was off in the morning for several hours after sunrise until 10:00 and then again after 18:00; the significant difference in predicted versus measured values during the beginning period (peaking at 46.3 °C and 34.1 °C, respectively) may be attributable to natural ventilation occurring but which was not reported in the study. It is unlikely that the grower allowed the temperature to climb into this range, which would cause the crop severe heat stress. Regardless, the model assumes that no ventilation was occurring during these periods when the cooling system was turned off, which resulted in the highest predicted internal temperatures of the day. The predicted values followed the trend of the measured values with temperature peaks just before and just after the cooling system was turned off. The average relative error over the 12-h period was 10%, which indicates strong predictive performance.

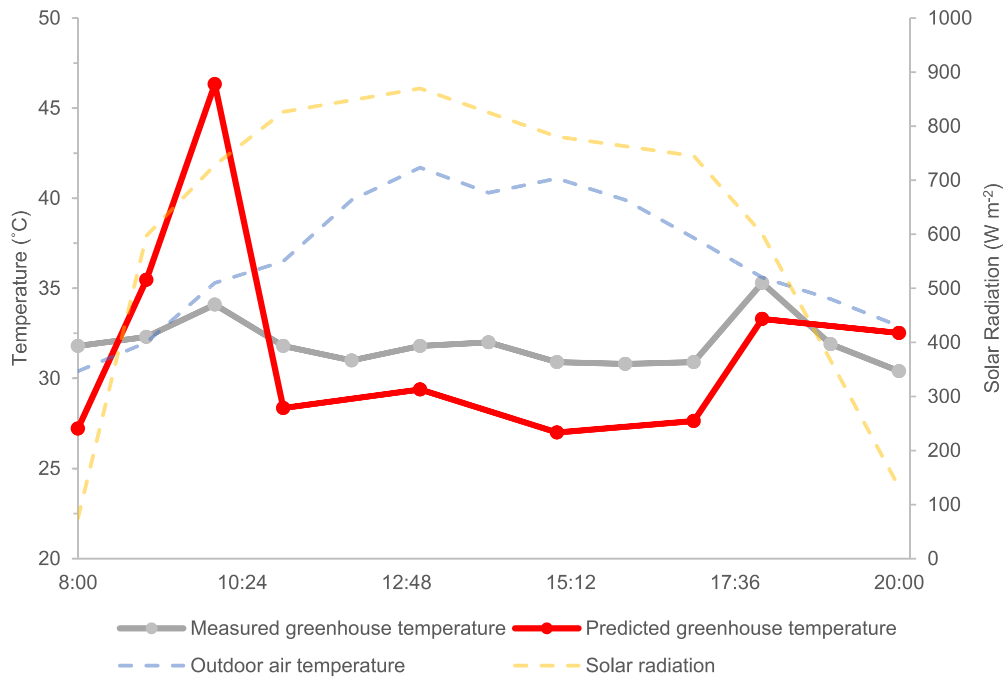


**Fig. A2.** Comparison of measured to predicted values for internal air temperature for mechanically cooled commercial greenhouse facility in Wuhan, China on July 27, 2023 (Mao et al., 2024); Note that the cooling system was turned off before 10:00 and after 18:00.

Table A1 - Parameters used in greenhouse energy and humidity balance modelling.

| Parameter | Description | Units | Value | Source |
|---|---|---|---|---|
| $A_r$ | Area (horizontal) of roof | $m^2$ | See Table 4 | Assumed |
| $A_s$ | Area of sidewalls | $m^2$ | See Table 4 | Assumed |
| $B$ | energy absorbed by structure/ground | % | 20% | Aldrich et al. (1994) |
| $C_4$ | Empirically derived constant | W s $m^{-3}$ $Pa^{-1}$ | 0.9 | ASHRAE (1996) |
| $e_{fan}$ | Fan efficiency | % | 75% | Assumed |
| $e_{mtr}$ | Motor efficiency | % | 80% | Assumed |
| $G_E$ | Transpiration conductance | m $s^{-1}$ | Varies | Calculated |
| $h$ | Air headloss | Pa | Low-tech: 15 Pa<br>Mid- and high-tech: 100 Pa | Based on experience* |
| $I_{plant}$ | Solar energy available in plant zone | W | Varies | Calculated |
| $k$ | Crop-specific transpiration parameter | dimensionless | 0.4 for cherry tomato | Salazar-Moreno et al. (2019) |
| $LAI$ | Leaf area index, ratio of leaf area to ground area | $cm^2$ leaf area $cm^2$ floor area covered by $canopy^{-1}$ | 4 for mature cherry tomato crop; assuming 66% of ground area covered with plant canopy | Kuijpers et al. (2021) |
| $m_{vent}$ | Moisture moved by ventilation; low and mid-tech only | kg $hr^{-1}$ | Varies | Calculated |
| $m_{infl}$ | Moisture moved by infiltration of air through cladding | kg $hr^{-1}$ | Varies | Calculated |
| $m_{evapc}$ | Moisture contributed by evaporative cooling | kg $hr^{-1}$ | Varies | Calculated |
| $m_{trsp}$ | Moisture contributed by transpiration from crop | kg $hr^{-1}$ | Varies | Calculated. Mahmood et al. (2022) |
| $m_{cnds}$ | Moisture removed by condensation on heat exchangers; high-tech only | kg $hr^{-1}$ | Varies | Calculated |
| $q_{cool}$ | Heat exchange through mechanical cooling | W | Varies | Calculated |
| $q_{conv}$ | Heat exchange through convection/ conduction through cladding | W | Varies | Calculated |
| $q_{fan}$ | Heat contributed by fan motor | W | Varies | Calculated; ASHRAE (1996) |
| $q_{infl}$ | Heat exchange due to conduction by air leakage through cladding | W | Varies | Calculated |
| $q_{plant}$ | Heat exchange absorbed by plants | W | Varies | Calculated |
| $q_{rad}$ | Heat exchange due to solar radiation | W | Varies | Calculated |
| $q_{vent}$ | Heat exchange due to ventilation | W | Varies | Calculated |
| $r_b$ | Aerodynamic resistance | s $m^{-1}$ | 200–300 | Salazar-Moreno et al. (2019) |
| $r_s$ | Stomatal resistance | s $m^{-1}$ | Varies | Calculated |
| $R_g$ | Outside global irradiance | W $m^{-2}$ | Varies | European Commission (2022) |
| $R_n$ | Net radiation at crop level | W $m^{-2}$ | Varies | Calculated |
| $T_a$ | Temperature ambient | °C | Varies | KAPSARC (2022) |

(continued on next page)

(*continued*)

| Parameter | Description | Units | Value | Source |
|---|---|---|---|---|
| $T_i$ | Temperature at greenhouse entrance following cooling | °C | High-tech: 26 °C daytime, 18 °C nighttime<br>Low- and mid-tech: Varies | Calculated |
| $T_o$ | Temperature of greenhouse interior temperature at discharge or air return | °C | Varies | Calculated |
| $U_r$ | Thermal transmittance of roof | $W\ m^{-2}\ °C^{-1}$ | Mid- and high-tech: 3.5 low-tech: 4.0 | Aldrich et al. (1994) |
| $U_s$ | Thermal transmittance of sidewalls | $W\ m^{-2}\ °C^{-1}$ | Mid- and high-tech: 3.5 low-tech: 4.0 | Aldrich et al. (1994) |
| $V$ | ventilation rate | $m^3\ s^{-1}$ | Varies | Calculated (to meet climate setpoints) |
| $X$ | Water vapor concentration in the greenhouse | $kg\ m^{-3}$ | Varies | Calculated (based on psychrometric chart) |
| $X_{plant}$ | *Water vapor concentration within crop canopy* | $kg\ m^{-3}$ | Varies | Calculated |
| $X_{sat}$ | *Saturated water vapor concentration* | $kg\ m^{-3}$ | Calculated; = 5.563xEXP(0.0572xT) | Salazar-Moreno et al. (2019) |
| $Y$ | Percentage of reflected irradiance that must be removed as heat | % | 55% | Assumed |
| $\mathcal{E}$ | Ratio of latent to sensible heat | Dimensionless | Varies | Calculated |
| $\tau_{clad}$ | Transmissivity of cladding and dust (combined) | % | 85% double wall polycarbonate<br>80% double wall polyfilm | Aldrich et al. (1994) |
| $\tau_{esh}$ | Transmissivity of exterior shade screen | % | high-tech: 40% | Assumed |
| $\tau_{ish}$ | Transmissivity of interior shade screen | % | mid-tech: <50%<br>high-tech: 15% diffusion screen | Example: Svensson PARperfect variable system |
| $\lambda$ | Latent heat of water vaporisation | $J\ g^{-1}$ | 2260 | Known |
| **Subscripts** | | | | |
| *i* | subscript denoting flow of energy into greenhouse | | | |
| *o* | subscript denoting flow of energy out of greenhouse | | | |

## References


Abdel-Ghany, A., Picuno, P., Al-Helal, I., Alsadon, A., Ibrahim, A., & Shady, M. (2015). Radiometric characterization, solar and thermal radiation in a greenhouse as affected by shading configuration in an arid climate. *Energies, 8*(12), 13928–13937. https://doi.org/10.3390/en81212404

Abdel-wahab, S. K. (1994). Energy and water management in evaporative cooling systems in Saudi Arabia. *Resources, Conservation and Recycling, 12*(3–4), 135–146. https://doi.org/10.1016/0921-3449(94)90002-7

Ahmed, H. A., Al-Faraj, A. A., & Abdel-Ghany, A. M. (2016). Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. *Scientia Horticulturae, 201*, 36–45. https://doi.org/10.1016/j.scienta.2016.01.030

Al-Ibrahim, A., Al-Abbadi, N., & Al-Helal, I. (2006). PV greenhouse system – system description, performance and lesson learned. *Acta Horticulturae, 710*, 251–264. https://doi.org/10.17660/ActaHortic.2006.710.26

Aldrich, R. A., & Bartok, J. W. (1994). In *Northeast regional agricultural engineering service*. Ithaca: Greenhouse engineering. https://ecommons.cornell.edu/handle/1813/69429.

ASHRAE. (1996). 1996 ASHRAE handbook: Heating, ventilating, and air-conditioning systems and equipment. *American Society of heating, R. And A.C. Engineers* (ASHRAE) https://iifiir.org/en/fridoc/1996-ashrae-handbook-hvac-systems-and-equipment-si-edition-1630.

Baeza, E., Hemming, S., & Stanghellini, C. (2020). Materials with switchable radiometric properties: Could they become the perfect greenhouse cover? *Biosystems Engineering, 193*, 157–173. https://doi.org/10.1016/j.biosystemseng.2020.02.012

Bao, J., Lu, W. H., Zhao, J., & Bi, X. T. (2018). Greenhouses for $CO_2$ sequestration from atmosphere. *Carbon Resources Conversion, 1*(2), 183–190. https://doi.org/10.1016/j.crcon.2018.08.002

Barbosa, G. L., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health, 12*(6), 6879–6891. https://doi.org/10.3390/IJERPH120606879

Bathaei, A., & Štreimikienė, D. (2023). A systematic review of agricultural sustainability indicators. *Agriculture, 13*(2), 241. https://doi.org/10.3390/AGRICULTURE13020241

Buchholz, M. (2021). The new generation of greenhouses. In *Unlocking the potential of protected agriculture in the countries of the gulf cooperation council—saving water and improving nutrition* (pp. 97–132). Cairo: FAO. https://doi.org/10.4060/cb4070en.

Campen, J. B., Al Assaf, K., Al Harbi, A., Sharaf, M. Y., de Zwart, F., Voogt, W., Scheffers, K., Tsafaras, I., Babiker, O. M., & Qaryouti, M. (2020). Evaluation of water saving technologies at Estidamah research center in Saudi Arabia. *Acta Horticulturae, 1296*, 73–78. https://doi.org/10.17660/ACTAHORTIC.2020.1296.10

Campen, J., de Zwart, F., Voogt, W., Tsafaras, I., & Qaryouti, M. (2023). Evaluation of three levels of greenhouse technology. *Estidamah* [Poster] https://www.estidamah.gov.sa/en/publications/posters/evaluation-three-levels-greenhouse-technology.

Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability, 3*(4), 262–268. https://doi.org/10.1038/s41893-020-0507-8

Cruz, S., & Gómez, C. (2022). Effects of daily light integral on compact tomato plants grown for indoor gardening. *Agronomy, 12*(7), 1704. https://doi.org/10.3390/agronomy12071704

Czyzyk, K. A., Bement, S. T., Dawson, W. F., & Mehta, K. (2014). Quantifying water savings with greenhouse farming. *Proceedings of the 4th IEEE global humanitarian technology conference, GHTC 2014*. https://doi.org/10.1109/GHTC.2014.6970300

Dimitropoulou, A-MN, Maroulis, VZ, & Giannini, EN (2023). A Simple and Effective Model for Predicting the Thermal Energy Requirements of Greenhouses in Europe. *Energies, 16*(19), 6788. https://doi.org/10.3390/en16196788.

Elvanidi, A., Benitez Reascos, C. M., Gourzoulidou, E., Kunze, A., Max, J. F., & Katsoulas, N. (2020). Implementation of the circular economy concept in greenhouse hydroponics for ultimate use of water and nutrients. *Horticulturae, 6*(4), 83. https://doi.org/10.3390/horticulturae6040083

Emu Analytics. (2021). Location insights explorer (version release-2.2.32.8096797): Overall global wet bulb temperatures % urban areas affected 35c 20yr return period. https://glowb.emu-analytics.net/b/53.

Estidamah. (2021). Effect of greenhouse technology, nutrient solution salinity, and root cooling on yield and water use efficiency of different cherry tomato cultivars. *Estidamah* [Poster] https://estidamah.gov.sa/en/publications/posters/double-production-tomatoes-greenhouses.

European Commission. (2022). Photovoltaic geographical information system (PVGIS) version 5.2. https://re.jrc.ec.europa.eu/pvg_tools/en/#MR.

FAO & UN Water. (2021). *Progress on the level of water stress: Global status and acceleration needs for SDG indicator 6.4.2*. Rome: FAO. https://doi.org/10.4060/cb6241en

FAOSTAT. (2020). *Land use. License*. CC BY-NC-SA 3.0 IGO. https://www.fao.org/faostat/en/#data/RL.

Fitz-Rodríguez, E., Kubota, C., Giacomelli, G. A., Tignor, M. E., Wilson, S. B., & McMahon, M. (2010). Dynamic modeling and simulation of greenhouse environments under several scenarios: A web-based application. *Computers and Electronics in Agriculture, 70*(1), 105–116. https://doi.org/10.1016/j.compag.2009.09.010

Ghalavand, Y., Hatamipour, M. S., & Rahimi, A. (2014). A review on energy consumption of desalination processes. *Desalination and Water Treatment, 54*(6), 1526–1541. https://doi.org/10.1080/19443994.2014.892837

Ghani, S., El-Bialy, E. M. A. A., Bakochristou, F., Mohamed Rashwan, M., Mohamed Abdelhalim, A., Mohammad Ismail, S., & Ben, P. (2020). Experimental and numerical investigation of the thermal performance of evaporative cooled greenhouses in hot and arid climates. *Science and Technology for the Built Environment, 26*(2), 141–160. https://doi.org/10.1080/23744731.2019.1634421

Goddek, S., Körner, O., Keesman, K. J., Tester, M. A., Lefers, R., Fleskens, L., Joyce, A., van Os, E., Gross, A., & Leemans, R. (2023). How greenhouse horticulture in arid regions can contribute to climate-resilient and sustainable food security. *Global Food Security, 38*, Article 100701. https://doi.org/10.1016/j.gfs.2023.100701

Gorjian, S., Calise, F., Kant, K., Ahamed, M. D., Copertaro, B., Najafi, G., Zhang, X., Aghaei, M., & Shamshiri, R. R. (2021). A review on opportunities for implementation of solar energy technologies in agricultural greenhouses. *Journal of Cleaner Production, 285*, Article 124807. https://doi.org/10.1016/j.jclepro.2020.124807

Hahn, R. H., & Rosentreter, E. E. (1995). American society of agricultural engineers. In *ASAE standards 1995: Standards, engineering practices and data* (Vol. 826). ASAE.

https://books.google.com/books/about/ASAE_Standards.html?id=to0dAQAAMAAJ.
Hochmuth, G. J. (2001). Production of greenhouse tomatoes–Florida greenhouse vegetable production handbook, Vol. 3. *Horticultural Sciences Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, 1–18*. https://edis.ifas.ufl.edu/publication/CV266.
Jemai, N., Soussi, M., & Chaibi, M. T. (2022). Opportunities for implementing closed greenhouse systems in arid climate conditions. *Horticulturae, 8*(12), 1102. https://doi.org/10.3390/HORTICULTURAE8121102
Jin, C., Du, S., Wang, Y., Condon, J., Lin, X., & Zhang, Y. (2009). Carbon dioxide enrichment by composting in greenhouses and its effect on vegetable production. *Journal of Plant Nutrition and Soil Science, 172*(3), 418–424. https://doi.org/10.1002/JPLN.200700220
Karim, M. F., Hao, P., Nordin, N. H. B., Qiu, C., Zeeshan, M., Khan, A. A., & Shamsi, I. H. (2020). $CO_2$ enrichment using CRAM fermentation improves growth, physiological traits and yield of cherry tomato (*Solanum lycopersicum* L.). *Saudi Journal of Biological Sciences, 27*(4), 1041–1048. https://doi.org/10.1016/J.SJBS.2020.02.020
Kimball, B. A., Mitchell, S. T., Jones, S., & Dorman, B. D. (1979). Tomato Yields from $CO_2$-enrichment in unventilated and conventionally ventilated greenhouses. *Journal of the American Society for Horticultural Science, 104*(4), 515–520. https://doi.org/10.21273/JASHS.104.4.515
Kittas, C., Bartzanas, T., & Jaffrin, A. (2003). Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. *Biosystems Engineering, 85*(1), 87–94. https://doi.org/10.1016/S1537-5110(03)00018-7
Kuijpers, W. J., Katzin, D., van Mourik, S., Antunes, D. J., Hemming, S., & van de Molengraft, M. J. (2021). Lighting systems and strategies compared in an optimally controlled greenhouse. *Biosystems Engineering, 202*, 195–216. https://doi.org/10.1016/j.biosystemseng.2020.12.006
Kurklu, A. (2022). A feasibility study for different crops in a high-tech greenhouse in Turkey. *World Journal of Agriculture and Soil Science, 8*(3), 1–10. https://doi.org/10.33552/WJASS.2022.08.000688
Lamnatou, C., & Chemisana, D. (2013). Solar radiation manipulations and their role in greenhouse claddings: Fresnel lenses, NIR- and UV-blocking materials. *Renewable and Sustainable Energy Reviews, 18*, 271–287. https://doi.org/10.1016/j.rser.2012.09.041
Lefers, R., Bettahalli, N. M. S., Nunes, S. P., Fedoroff, N., Davies, P. A., & Leiknes, T. (2016). Liquid desiccant dehumidification and regeneration process to meet cooling and freshwater needs of desert greenhouses. *Desalination and Water Treatment, 57*(48–49), 23430–23442. https://doi.org/10.1080/19443994.2016.1173383
Lefers, R. M., Tester, M., & Lauersen, K. J. (2020). Emerging technologies to enable sustainable controlled environment agriculture in the extreme environments of Middle East-North Africa coastal regions. *Frontiers in Plant Science, 11*, 801. https://doi.org/10.3389/fpls.2020.00801
Li, Y., Ding, Y., Li, D., & Miao, Z. (2018). Automatic carbon dioxide enrichment strategies in the greenhouse: A review. *Biosystems Engineering, 171*, 101–119. https://doi.org/10.1016/J.BIOSYSTEMSENG.2018.04.018
Mahmood, F., Govindan, R., Yang, D., Bermak, A., & Al-Ansari, T. (2022). Forecasting cooling load and water demand of a semi-closed greenhouse using a hybrid modelling approach. *International Journal of Ambient Energy, 43*(1), 8046–8066. https://doi.org/10.1080/01430750.2022.2088617
Manor, G., Geva, A., Jacobs, D., Secker, I., Tabak, S., & Singer, L. (2005). Cleaning machine for dusty greenhouse soft roofs. *Acta Horticulturae, 691*, 641–648. https://doi.org/10.17660/ActaHortic.2005.691.78
Mao, Q., Ji, C., Li, H., Peng, Y., & Li, T. (2024). Dynamic temperature distribution characteristics of a large glasshouse with cooling system during the start-stop stage. *Computers and Electronics in Agriculture, 220*, Article 108913. https://doi.org/10.1016/j.compag.2024.108913
Maraveas, C. (2019). Environmental sustainability of greenhouse covering materials. *Sustainability, 11*(21), 6129. https://doi.org/10.3390/su11216129
Martínez-Ruiz, A., López-Cruz, I. L., Ruiz-García, A., Pineda-Pineda, J., & Prado-Hernández, J. V. (2019). HortSyst: A dynamic model to predict growth, nitrogen uptake, and transpiration of greenhouse tomatoes. *Chilean Journal of Agricultural Research, 79*(1), 89–102. https://doi.org/10.4067/S0718-58392019000100089
Martinez-Granados, D., Marín-Membrive, P., & Calatrava, J. (2022). Economic assessment of irrigation with desalinated seawater in greenhouse tomato production in SE Spain. *Agronomy, 12*, 1471. https://doi.org/10.3390/AGRONOMY12061471
Mishra, K., Stanghellini, C., & Hemming, S. (2023). Technology and materials for passive manipulation of the solar spectrum in greenhouses. *Advanced Sustainable Systems, 7*, Article 2200503. https://doi.org/10.1002/adsu.202200503
Moustafa, A., Mohammadi, A. Al, Abou-Hadid, A., Peacock, J. M., & Manners, G. R. (1998). *Protected agriculture in the arabian Peninsula: Summary proceedings of an international workshop: Doha, Qatar, february 15-18*. International Center for Agriculture Research in the Dry Areas (ICARDA). https://books.google.com/books/about/Protected_Agriculture_in_the_Arabian_Pen.html?hl=fr&id=VmXDgNvzpQsC.
Ntinas, G. K., Neumair, M., Tsadilas, C. D., & Meyer, J. (2017). Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. *Journal of Cleaner Production, 142*, 3617–3626. https://doi.org/10.1016/j.jclepro.2016.10.106
Orr, J., Gibbons, O., & Arnold, W. (2020). A brief guide to calculating embodied carbon. *Structural Engineer, 98*(7), 22–27. https://doi.org/10.56330/JZNX5709
Ortiz, G. A., Chamorro, A. N., Acuña-Caita, J. F., López-Cruz, I. L., & Villagran, E. (2023). Calibration and implementation of a dynamic energy balance model to estimate the temperature in a plastic-covered Colombian greenhouse. *AgriEngineering, 5*(4), 2284–2302. https://doi.org/10.3390/agriengineering5040140
Page, G., Ridoutt, B., & Bellotti, B. (2012). Carbon and water footprint tradeoffs in fresh tomato production. *Journal of Cleaner Production, 32*, 219–226. https://doi.org/10.1016/J.JCLEPRO.2012.03.036
Palmitessa, OD, Paciello, P, & Santamaria, P (2020). Supplemental LED increases tomato yield in mediterranean semi-closed greenhouse. *Agronomy, 10*(9), 1353. https://doi.org/10.3390/agronomy10091353
Rorabaugh, P. (2015). Chapter 14 – greenhouse energy and resource alternatives: "Greening" the greenhouse. pp. 14–1–14-8. In *Introduction to hydroponics and controlled environment agriculture*. Tucson: University of Arizona Controlled Environment Agriculture Center https://ceac.arizona.edu/sites/default/files/Ch14.pdf.
Sabeh, N. C., Giacomelli, G. A., & Kubota, C. (2006). Water use in a greenhouse in a semi-arid climate. *Transactions of the ASABE, 54*(3), 1069–1077. https://doi.org/10.13031/2013.37098
Salazar-Moreno, R., López-Cruz, I. L., & Sánchez Cruz, A. C. (2019). Dynamic energy balance model in a greenhouse with tomato cultivation: Simulation, calibration and evaluation. *Revista Chapingo Serie Horticultura, 25*(1), 45–60. https://doi.org/10.5154/r.rchsh.2018.07.014
Saudi General Authority for Statistics. (2023). *Saudi Arabia hourly climate integrated surface data*. King Abdullah Petroleum Studies and Research Center (KAPSARC) Dataportal. https://datasource.kapsarc.org/explore/dataset/saudi-hourly-weather-data/information/. (Accessed 8 June 2024).
Shi, W., Yang, H., Ma, X., & Liu, X. (2023). Techno-economic evaluation and environmental benefit of hybrid evaporative cooling system in hot-humid regions. *Sustainable Cities and Society, 97*, Article 104735. https://doi.org/10.1016/j.scs.2023.104735
Singh, H., Dunn, B., Maness, N., Brandenberger, L., Carrier, L., & Hu, B. (2021). Evaluating performance of cherry and slicer tomato cultivars in greenhouse and open field conditions: Yield and fruit quality. *HortScience, 56*(8), 946–953. https://doi.org/10.21273/HORTSCI16003-21
Soussi, M., Chaibi, M. T., Buchholz, M., & Saghrouni, Z. (2022). Comprehensive review on climate control and cooling systems in greenhouses under hot and arid conditions. *Agronomy, 12*(3), 626. https://doi.org/10.3390/AGRONOMY12030626
Teitel, M., Levi, A., Zhao, Y., Barak, M., Bar-lev, E., & Shmuel, D. (2008). Energy saving in agricultural buildings through fan motor control by variable frequency drives. *Energy and Buildings, 40*(6), 953–960. https://doi.org/10.1016/j.enbuild.2007.07.010
The University of Arizona Controlled Environment Agriculture Center. (2000). *Environmental control systems* [Web page] https://ag.arizona.edu/hydroponictomatoes/system.htm.
Torrellas, M., Antón, A., López, J. C., Baeza, E. J., Parra, J. P., Muñoz, P., & Montero, J. I. (2012). LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. *International Journal of Life Cycle Assessment, 17*, 863–875. https://doi.org/10.1007/s11367-012-0409-8
Trigui, M., Barrington, S. F., & Gauthier, L. (1999). Effects of humidity on tomato (Lycopersicon esculentum cv. Truss) water uptake, yield, and dehumidification cost. *Canadian Agricultural Engineering, 41*(3), 135–140. https://library.csbe-scgab.ca/docs/journal/41/41_3_135_ocr.pdf.
Tsafaras, I., Campen, J. B., Stanghellini, C., de Zwart, H. F., Voogt, W., Scheffers, K., Al Harbi, A., & Al Assaf, K. (2021). Intelligent greenhouse design decreases water use for evaporative cooling in arid regions. *Agricultural Water Management, 250*, Article 106807. https://doi.org/10.1016/j.agwat.2021.106807
United Nations, Department of Economic and Social Affairs, Population Division. (2022). World population prospects 2022, data sources. UN DESA/POP/2022/DC/NO. 9 https://population.un.org/wpp/Publications/Files/WPP2022_Data_Sources.pdf.
U.S. Energy Information Administration. (2022). Frequently asked questions (FAQs). https://www.eia.gov/tools/faqs/faq.php?id=74&t=11.
Vanthoor, B. H. E., Gázquez, J. C., Magán, J. J., Ruijs, M. N. A., Baeza, E., Stanghellini, C., van Henten, E. J., & de Visser, P. H. B. (2012). A methodology for model-based greenhouse design: Part 4, economic evaluation of different greenhouse designs: A Spanish case. *Biosystems Engineering, 111*(4), 336–349. https://doi.org/10.1016/J.BIOSYSTEMSENG.2011.12.008
Willits, D. H., & Peet, M. M. (1998). The effect of night temperature on greenhouse grown tomato yields in warm climates. *Agricultural and Forest Meteorology, 92*(3), 191–202. https://doi.org/10.1016/S0168-1923(98)00089-6
World Economic Forum. (2023). How entrepreneurs can strengthen food security in arid climates. https://www.weforum.org/agenda/2023/01/how-entrepreneurs-can-help-strengthen-food-security-in-arid-climates/.
Xu, J., Li, Y., Wang, R. Z., Liu, W., & Zhou, P. (2015). Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates. *Applied Energy, 138*, 291–301. https://doi.org/10.1016/j.apenergy.2014.10.061
Zhang, D., Du, Q., Zhang, Z., Jiao, X., Song, X., & Li, J. (2017). Vapour pressure deficit control in relation to water transport and water productivity in greenhouse tomato production during summer. *Scientific Reports, 7*(1), Article 43461. https://doi.org/10.1038/srep43461
Zhou, D., Meinke, H., Wilson, M., Marcelis, L. F. M., & Heuvelink, E. (2021). Towards delivering on the sustainable development goals in greenhouse production systems. *Resources, Conservation and Recycling, 169*, Article 105379. https://doi.org/10.1016/J.RESCONREC.2020.105379