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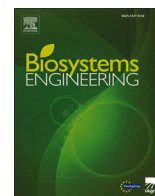
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Research Paper

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, CO₂ emissions (CO₂e) 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 CO₂e 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	
<i>Symbols</i>	
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_{cncls}	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_{cncls}	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
τ_{clad}	Transmissivity of cladding and dust (combined), %
τ_{esh}	Transmissivity of exterior shade screen, %
τ_{ish}	Transmissivity of interior shade screen, %
<i>Abbreviations</i>	
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 abundance 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

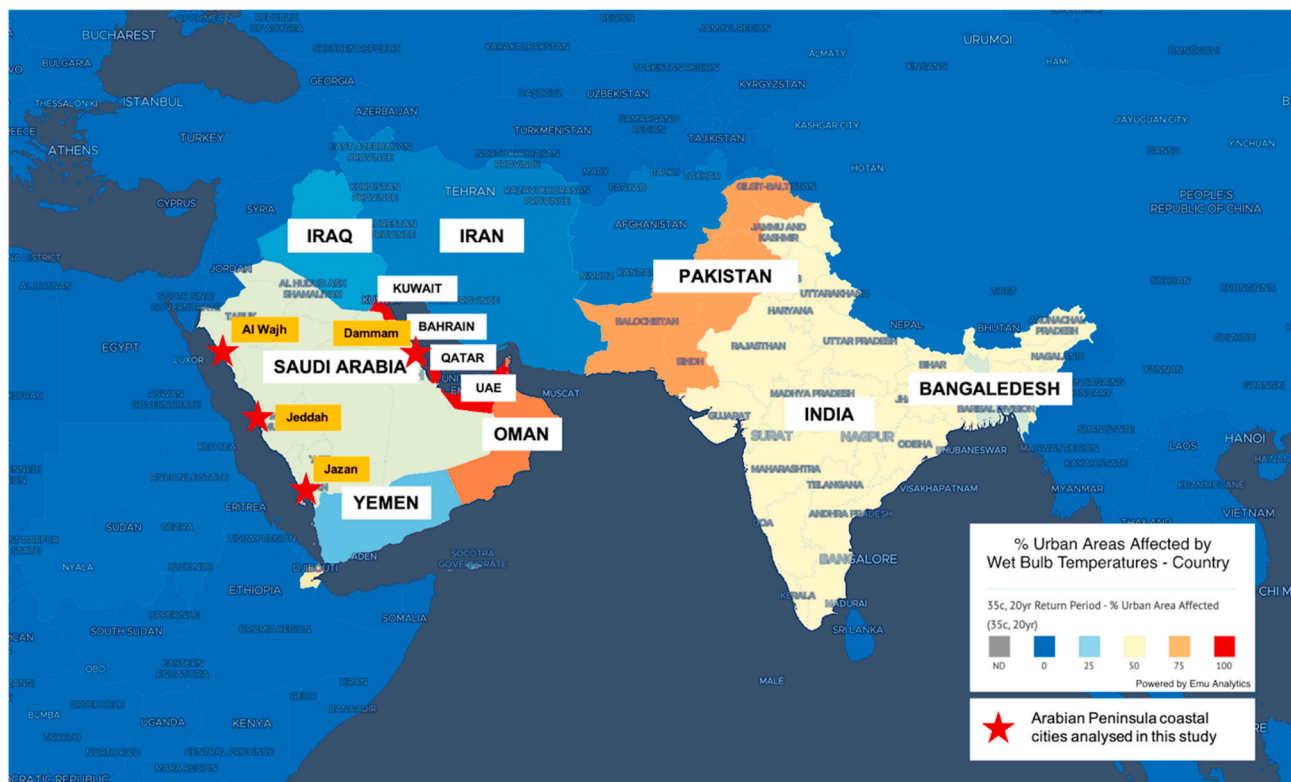


Fig. 1. Countries predicted to have a significant portion of urban areas at risk of peak wet bulb temperatures $>35^{\circ}\text{C}$ in the next 20 years (Emu Analytics, 2021). Red stars indicate the coastal locations in the Arabian Peninsula that were analysed in this study. (For interpretation of the 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 greenhouse 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	<ul style="list-style-type: none"> •Crop potential is limited by environmental conditions •High water demand for cooling •Highly susceptible to pests and diseases •Chemical products for pest control are needed •Environmental conditions can be non-homogenous due to design of evaporative cooling system •Year-round production is virtually impossible 	<ul style="list-style-type: none"> •Higher capital costs compared to low-tech •Evaporative cooling efficiency is limited by outdoor climate conditions •Year-round production is a major challenge •Skilled labour is required for operation and maintenance 	<ul style="list-style-type: none"> •High energy consumption required to operate closed cooling system •Capital costs are the highest of the tech levels •Highly skilled labour required for operation and maintenance, which can be difficult to source
Advantages	<ul style="list-style-type: none"> •Low energy consumption •Low capital costs •Less skilled labour required for operation and maintenance 	<ul style="list-style-type: none"> •Trade-off between cost and productivity •Positive pressure environment provides more protection from pests and diseases •More homogenous indoor environment compared to low-tech •More efficient use of water for evaporative cooling than low-tech 	<ul style="list-style-type: none"> •Plant growth, yield, and fruit quality are optimised •High water-use efficiency •Crops are well-protected from pests and disease •Less use of chemical products for pest control •Year-round production is feasible •Not limited by weather conditions •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 CO₂ emissions) and financial performance of a given greenhouse design, which are key to ascertain its economic and environmental sustainability (Bathaei & Streimikienė, 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 m² crop production area plus a 375 m² 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:

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

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):

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

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_{evap} , 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

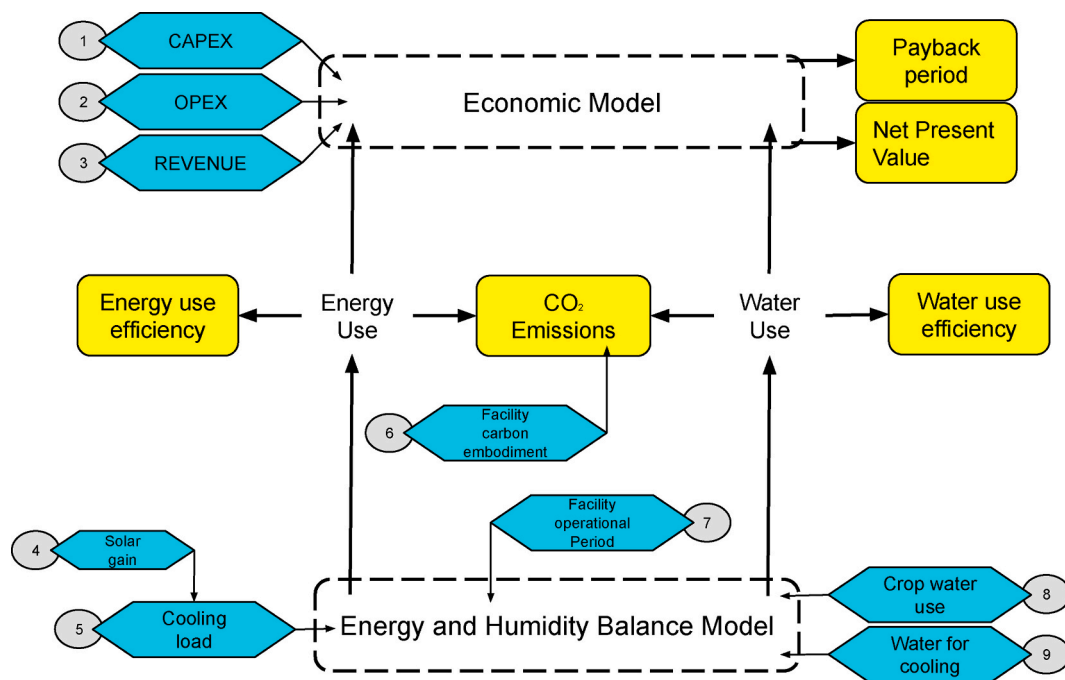


Fig. 2. Overview of the model-based assessment method for evaluating various greenhouse designs in hot climates. The key outputs are the performance measures (yellow boxes), which are derived from the greenhouse energy and humidity balance and economic models. The primary input parameters (blue hexagons) 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
CO₂ 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 (τ_{clad} , τ_{ish} , τ_{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 kgCO 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 kgCO 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 kgCO 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	Calculated. 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

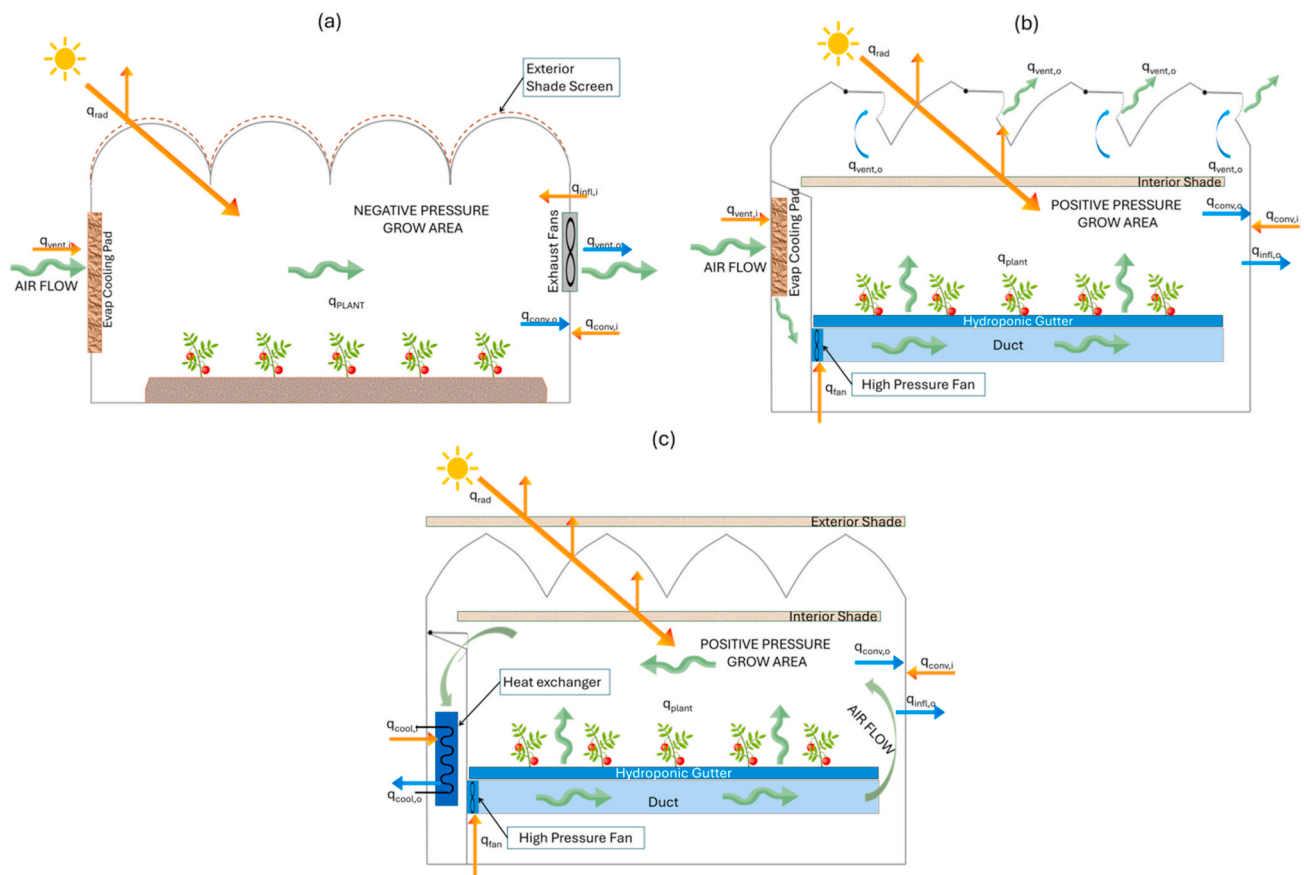


Fig. 3. Schematic designs for (a) low-tech (b) mid-tech and (c) high-tech greenhouse designs modelled in this study. Green arrows show air flow, blue arrows show outgoing energy transfer, and orange arrows show incoming energy transfer. (For interpretation of the references to colour in this figure legend, 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; Martínez-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 (m²)	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 ⁻¹) Sidewalls: Double polycarbonate (U = 3.6 W m ⁻² C ⁻¹)	Roof: Double polyethylene film (U = 4.0 W m ⁻² C ⁻¹) Sidewalls: Double polycarbonate (U = 3.6 W m ⁻² C ⁻¹)	Roof: Double polyethylene film (U = 4.0 W m ⁻² C ⁻¹) Sidewalls: Double polycarbonate (U = 3.6 W m ⁻² C ⁻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)
CO₂ 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. CO₂ enrichment strategy

CO₂ 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 CO₂ may be inefficient and prohibitively expensive. Since the utilisation of CO₂ 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 CO₂

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-Gómez 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 CO₂ 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 CO₂ enrichment because it is impractical to enrich the air at the required ventilation rates.

2.10. CO₂ emissions

This analysis quantified both the energy and water footprints, as well as the climate change impact from CO₂ emissions (CO₂e) 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 CO₂e 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 CO₂e 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 CO₂e equivalent based on 1.11 kgCO₂e kWh⁻¹ (U.S. Energy Information Administration, 2022) for petroleum-based electricity generation. The CO₂ 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 CO₂ 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 CO₂ 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.

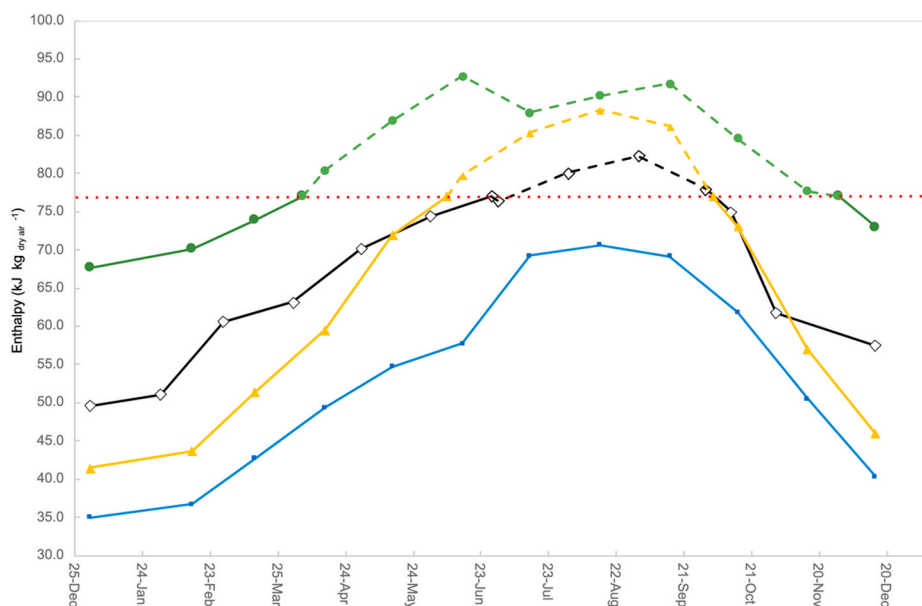


Fig. 4. Comparison of average monthly daytime ambient enthalpy for coastal sites in Saudi Arabia. Solid lines (●—Jazan, ▲—Al Wajh, ◆—Jeddah, ■—Dammam) are periods when climate was suitable for evaporative cooling; dashed lines (—●—Jazan, —▲—Al Wajh, —◆—Jeddah) are periods of the year when climate was not suitable for evaporative cooling, defined in this study as 5-day average enthalpy exceeding 77 kJ kg⁻¹ dry air⁻¹ (■—■).

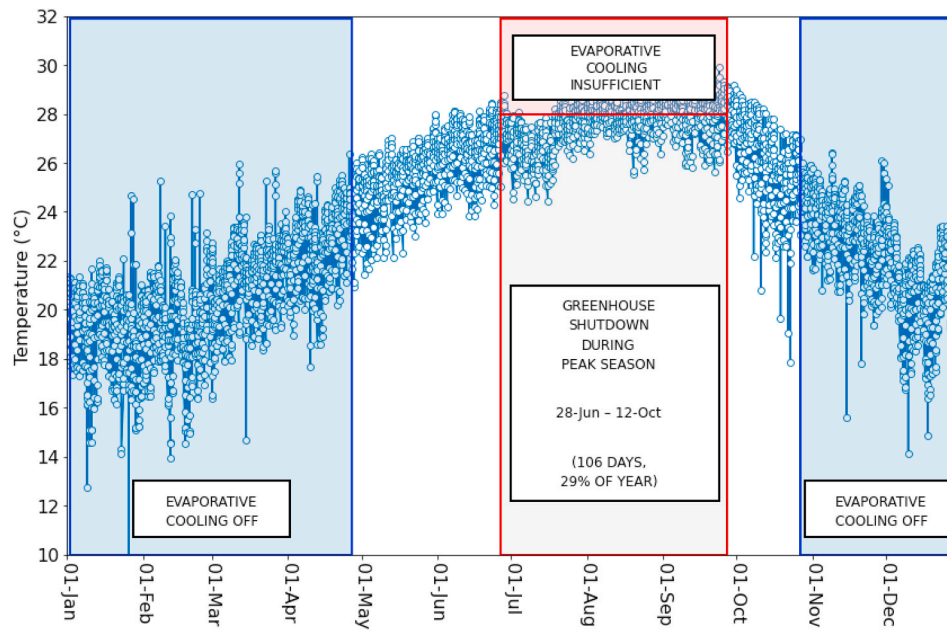


Fig. 5. Simulated greenhouse internal conditions (inside next to the cooling pad). Analysis is based on 5-year historical meteorological data for Jeddah, Saudi Arabia (Saudi General Authority for Statistics, 2023); shutdown period is based on enthalpy during daytime hours (6:00–18:00).

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

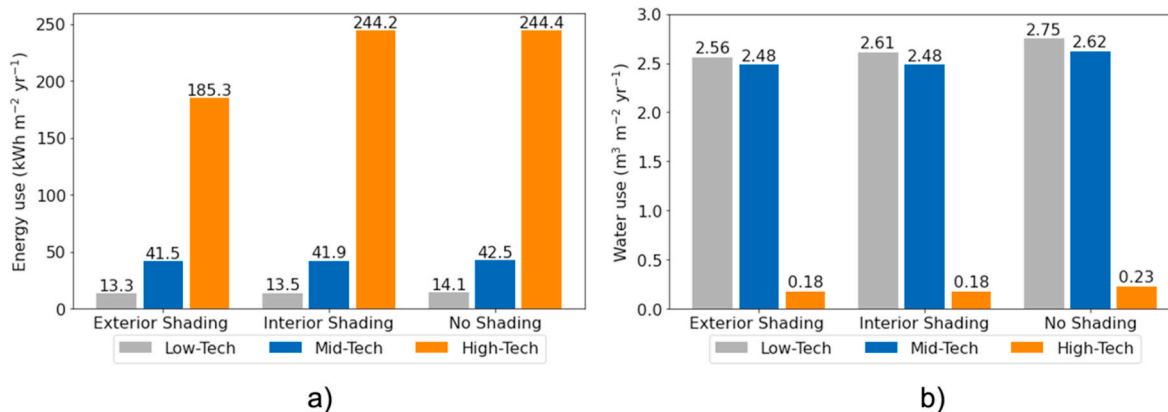


Fig. 6. Impact of exterior shading, interior shading, and no shading on the (a) energy usage and (b) water usage for each greenhouse technology level.

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. CO₂ emissions

The CO₂e related to energy and water usage and structural carbon embodiment of each greenhouse design are shown in Table 13. The majority of CO₂e 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 CO₂e 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 CO₂e 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 CO₂e 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

Table 13

CO₂ emissions (CO₂e) 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 ₂ e m ⁻² yr ⁻¹)	14.8	43.5	206
CO ₂ emissions per unit tomato yield (kgCO ₂ e kg _{yield} ⁻¹)	1.34	2.90	6.64

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 CO₂e during operations.

Most studies report CO₂e impact in terms of yield (kgCO₂e kg_{yield}⁻¹), directly linking the environmental impact to productivity. The overall CO₂e for the low- and mid-tech designs were very close to values reported by Ntinis 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 kgCO₂e kg_{yield}⁻¹, compared to an average of 2.12 kgCO₂e kg_{yield}⁻¹ for the low- and mid-tech greenhouses in this study. Page et al. (2012) reported 1.86 kgCO₂e 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 CO₂e.

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 CO₂e contribution. Note that the energy and CO₂e 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

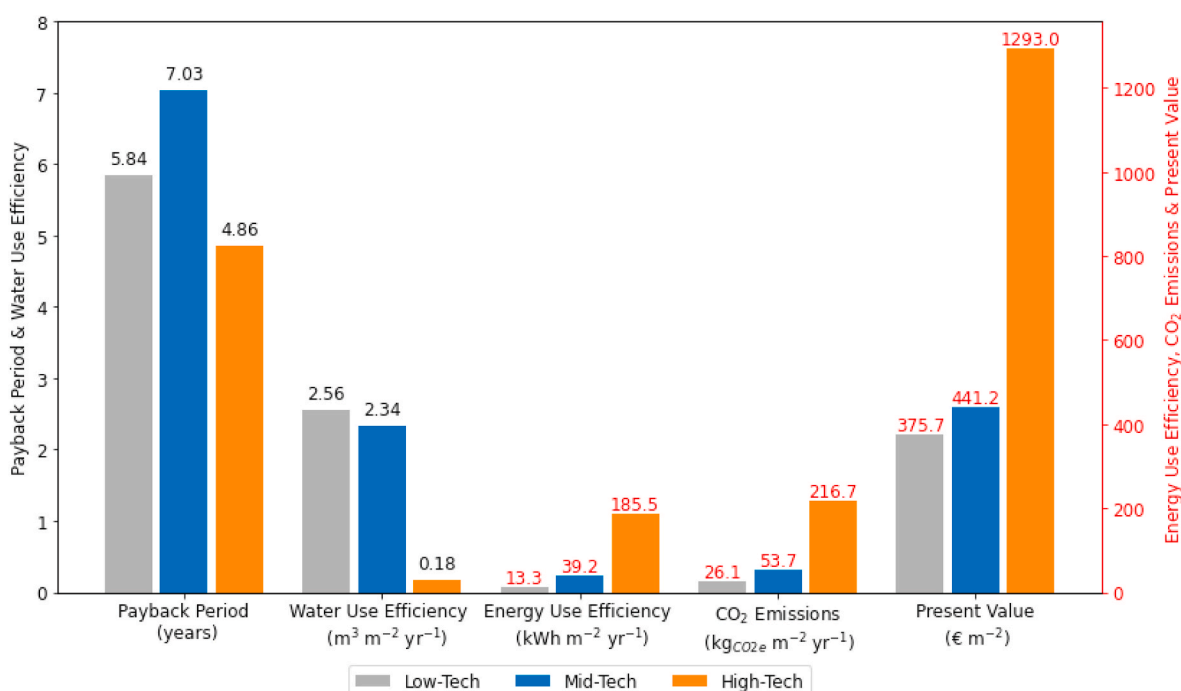


Fig. 7. Comparison of low-, mid-, and high-tech greenhouse systems according to performance measures.

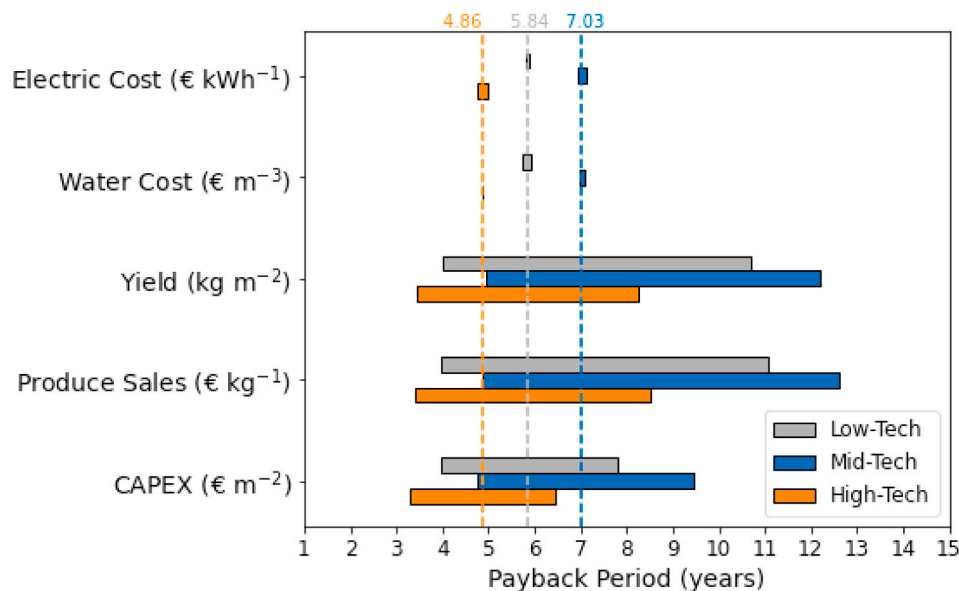


Fig. 8. Results of sensitivity analysis for (a) low-tech, (b) mid-tech, and (c) high-tech greenhouses. Each parameter was varied by $\pm 30\%$ of base scenario value to show the impact on the payback period.

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 $\sim 9\%$ energy savings and lower embodied CO₂ 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.** CO₂ emissions contributions from greenhouses mostly come from energy usage related to cooling, rather than embodied CO₂ 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 ($1.01 \text{ kWh m}^{-2} \text{ day}^{-1}$ 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 $7.5 \text{ kWh m}^{-2} \text{ day}^{-1}$ (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 $1 \text{ kWh m}^{-2} \text{ day}^{-1}$. 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% ($0.28 \text{ kWh m}^{-2} \text{ day}^{-1}$) but would increase water consumption by 360% ($1.78 \text{ L m}^{-2} \text{ day}^{-1}$). 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 $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$. 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_{mr}) will contribute heat (q_{fan} , W) to a system as per EQ-A2 ([ASHRAE, 1996](#)):

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

q_{fan} increases as the back-pressure on the fan (h , Pa) and ventilation (V , $\text{m}^3 \text{ s}^{-1}$) increases. C_4 is a constant equal to $0.9 \text{ W s m}^{-3} \text{ Pa}^{-1}$. 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:

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

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 (τ_{esh}), the cladding with or without dust (τ_{clad}), and the internal shade screen (τ_{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:

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

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

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

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 (ϵ), stomatal resistance (r_s , in m s^{-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 m s^{-1}) is a constant ranging from 200 to 300 m s^{-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.

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

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

$$r_s = \left(82 + 570e^{\frac{-kR_n}{LAI}} \right) \sqrt[3]{1 + 0.023(T_a - 20)^2} \quad \text{EQ-A8}$$

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

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

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

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 , $2260 \text{ kJ kg}_{\text{water}}^{-1}$) 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.

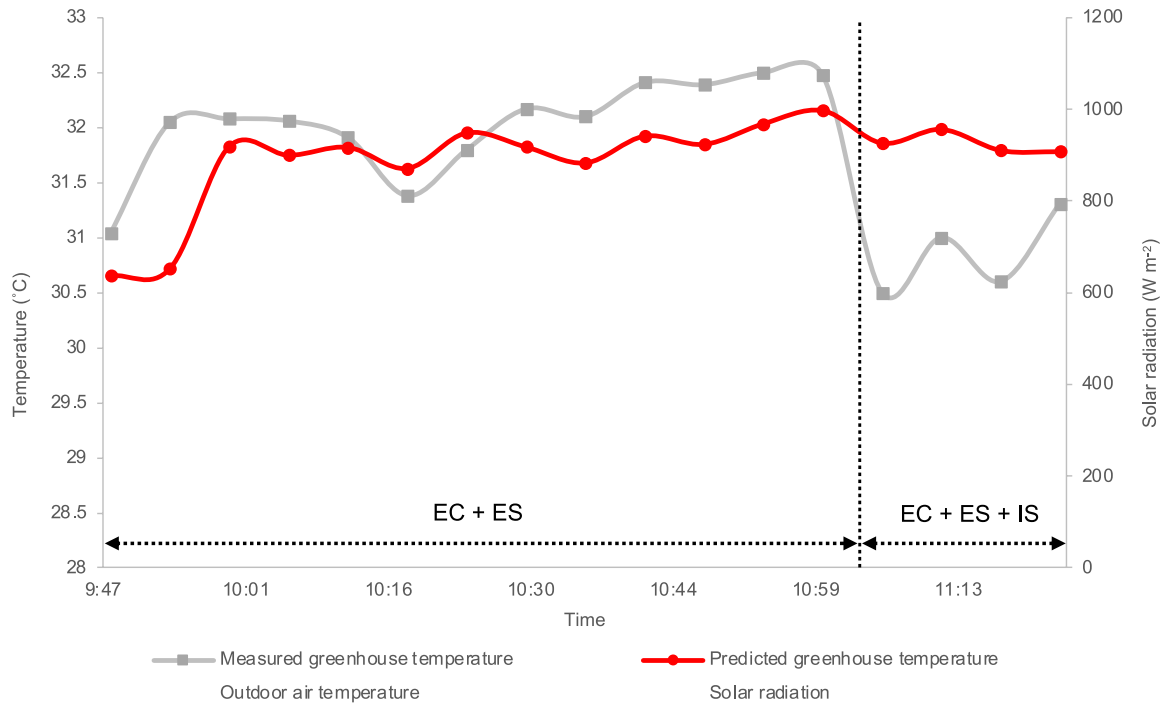


Fig. A1. Comparison of measured to predicted values for internal air temperature for evaporatively cooled commercial greenhouse facility in Shanghai, China on August 5, 2012; EC = evaporative cooling, ES = exterior shade screen, and IS = interior shade screen. Measured ambient relative humidity was between 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.

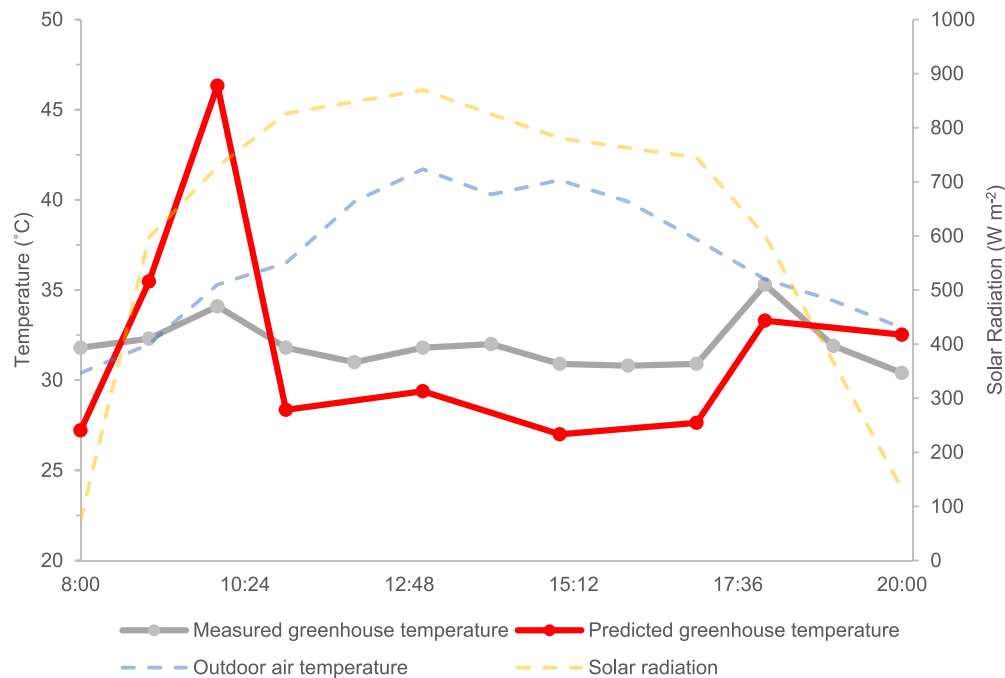


Fig. A2. Comparison of measured to predicted values for internal air temperature for mechanically cooled commercial greenhouse facility in Wuhan, China on July 27, 2023 (Mao et al., 2024); Note that the cooling system was turned off before 10:00 and after 18:00.

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_A	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 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 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
τ_{clad}	Transmissivity of cladding and dust (combined)	%	85% double wall polycarbonate 80% double wall polyfilm	Aldrich et al. (1994)
τ_{esh}	Transmissivity of exterior shade screen	%	high-tech: 40%	Assumed
τ_{ish}	Transmissivity of interior shade screen	%	mid-tech: <50% high-tech: 15% diffusion screen	Example: Svensson PARperfect variable system
λ	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			

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