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Environmental assessment of industrial aquaponics in arid zones using an integrated dynamic model

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ABSTRACT

Land desertification, water scarcity, and food security challenges in arid zones are intensifying, driving the need for sustainable agricultural solutions like aquaponics. This study investigated innovative water and energy-saving strategies using an integrated dynamic model for an on-demand industrial aquaponics system in Israel. The model evaluated the performance of a recirculating aquaculture system (RAS), hydroponics system (HPS), and desalination unit (DU) by adjusting physical and operational parameters to optimize water and nutrient use efficiency, energy consumption, and yield. Optimizing the system design resulted in an aquaponics system with approximately 420 m^3 RAS, 6.85 ha HPS and 40 m^3/d DU, achieving phosphorus use efficiency of 96 %, a water use efficiency of 97 %, freshwater input of 1.5 L/day/m^2, and energy consumption of 0.56 kWh/day/m^2. To mitigate the challenges of extreme arid climates, evaporative cooling combined with outdoor shading and mechanical cooling was found to be a feasible option to control temperature and humidity in the greenhouse. Dehumidification technologies further improved system performance by recovering 22 % freshwater from seawater and increasing nitrogen use efficiency by 18 %. Achieving daily energy self-sufficiency required 4500 m^2 photovoltaic panels and 5000 m^2 solar heating system. While the system model was initially devised with a specific focus on conditions in Israel, it has been designed with scalability, allowing it to be adapted and applied extensively across diverse peri-urban regions and arid zones globally.

1. Introduction

A constantly growing global population endangers food security by increasing the stress on limited resources such as phosphorus and fresh water, which are essential elements for food production [1,2]. Land desertification is increasing: arid zones cover about 41 % of the Earth's land surface and are home to over 40 % of the global population [3]. Addressing these challenges requires adequate and sustainable desert food systems for drylands to maximize the resources (water and nutrients) and minimize the negative impacts of the desert. Greenhouses with soilless production systems [4] and aquaculture in the Negev desert [5] are options for tackling these challenges in drylands. However, greenhouse agriculture generally relies heavily on synthetic fertilizers [6], and aquaculture is known to release nutrients into the surrounding water [7] along with N_2O emissions [8,9]. Hence, there is a need for more sustainable food production methods.

In this context, aquaponics, combining aquaculture with hydroponics, has been identified as a farming technology that, through nutrient and waste recycling, can aid in achieving sustainable development goals, particularly for desert and urban regions [10]. Thus, aquaponics fits well into an ecosystem approach to food production. In traditional aquaponics, in which fish and plants share one system, there is a trade-off between the optimal conditions in both subsystems in terms of pH, temperature, and nutrient concentrations [11,12]. On-demand

Abbreviation: RAS, Recirculating Aquaculture System; HP(S), Hydroponics System(s); AD, Anaerobic Digestion; DU, Desalination Unit; UASB, Upflow Anaerobic Sludge Blanket; CHP, Combined Heat-Power; NFT, Nutrient Film Technique; DWC, Deep Water Culture; FCR, Feed Conversion Ratio; COD, Chemical Oxygen Demand; AP(S), Aquaponics system(s); ET, Evapotranspiration; RH, Relative Humidity; WUE, Water Use Efficiency; NUE, Nutrient Use Efficiency; DO, Dissolved Oxygen; VPD, Vapor Pressure Deficit; PAR, Photosynthetically Active Radiation; NIR, Near Infrared Radiation; SHS, Solar Heating System; SEER, Seasonal Energy Efficiency Ratio; BTU, British Thermal Unit; FWI, Fresh Water Input.

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coupled aquaponics systems (APS) follow a different approach, creating separate ecosystems which have inherent advantages for both fish and plants [13]. However, these APS increase the amount of fresh water required [14]. Furthermore, 10–40 % of the fish sludge is discharged daily to maintain good water quality, which is considered to be an additional environmental and economic burden of APS [5]. The sustainability of APS can be increased by incorporating anaerobic digesters into the system to produce energy and bio-fertilizer from solid wastes [15]. To increase nutrient use efficiency (NUE) and water use efficiency (WUE), a desalination loop with a desalination unit (DU) was also proposed [14,16], in addition to an anaerobic digestion (AD) loop [17].

Several researchers [11,18–20] have designed multi-loop APS models with anaerobic digesters in order to analyze mass balances and examine system behavior under variable system designs and operation strategies. Consequently, these models can be used in optimal design studies of the system or in finding optimal management and operational strategies. However, none of these studies have examined APS in arid zones with respect to nutrient demand and water saving. The dynamic models studied by [14] and [21] showed that on-demand coupled systems typically require a significant amount of additional fertilizer or nutrient manipulation to meet the optimal growth conditions for plants.

Whilst several studies have developed numerical models for one- and multi- loop APS [11,18,22,23], only the study of [4] integrates a multi-loop APS model with a full-scale, spatially distributed, deterministic greenhouse climate model. Sizing the respective subsystems is fundamental to achieving a functioning balanced system [4,10]. However, the complexity of multi-loop systems means simple rules of thumb cannot be used, as they come with the inherent risk of making false assumptions for each subsystem [24]. The greenhouse climate model is particularly relevant for sizing the system as nutrient uptake by plants is location dependent, with crop transpiration as a significant driver [25].

The availability of APS with cooling to support fish and plant growth in extremely arid regions is limited. It is challenging to apply an APS in extremely arid climates with high temperatures and radiation, especially regarding the hydroponics subsystem [26]. Under such conditions, extra cooling facilities are required in the greenhouse as one of the strategies to mitigate the effect of high temperatures and radiation while also being less dependent on outdoor environmental conditions [27]. Besides temperature, humidity also has to be strictly regulated to maintain optimal growth and prevent plant diseases [28]. Taking into account the outdoor climate conditions and the required indoor climate conditions, and supported by expert advice, a suitable method needs to be chosen to regulate indoor humidity [29]. A suitable, low-cost method for agricultural applications to save water and prevent waste is to equip the greenhouse with a dehumidification unit [30].

Besides concerns regarding temperature and humidity, highly productive greenhouses are also known for their high energy consumption. For a standard greenhouse, [31] reported that cooling and heating could account for up to 50 % of the energy use and 20 % of the production costs. Reducing energy consumption is crucial for reducing greenhouse gas emissions and reducing dependency on fossil fuels [32]. Many innovation studies and research programs were explored, driven by environmental regulation and cost reduction to save energy in greenhouses [27]. For example, dehumidification and heat recovery can be used to control the indoor climate, decreasing the need for energy-inefficient ventilation [29]. It should be noted that the use of solar energy as an abundant and environmentally clean energy source, specifically in arid regions, may allow complete off-grid operation of the APS [5]. Thus, greenhouses in arid zones have much potential for energy use reduction.

In this study, we present an integrated aquaponics and greenhouse climate model, with anaerobic digestion, desalination, dehumidification, and cooling, that is based on existing aquaponics [4,24] and greenhouse models [10] and on available data from an APS in the Negev, Israel. This study aimed to investigate and explore the effect various operational strategies and design parameters have on the optimal design and operation of an industrial APS in an arid and varied climate. With this model, energy, water, and nutrient use can be predicted and optimized to give insight into the possibilities and constraints for the application of APS in arid zones. In addition, the carbon neutrality of the integrated APS in arid zones was investigated.

2. Materials and methods

2.1. System description

The APS, with 390 m^3 RAS and 2.5 ha HPS as a reference, can be divided into four different compartments: 1) recirculating aquaculture system (RAS), 2) hydroponics system (HPS), 3) anaerobic digestion unit (AD), and 4) desalination unit (DU) (Fig. 1). These four compartments are connected to each other by the flow of water, nutrients, and carbon.

In this section, only fish growth, which determines the amount of fish feed and thus nutrient intake, and evapotranspiration rate, which is directly related to plant growth and uptake of water and nutrients by the plant, are explicitly presented. Both strongly affect the flow of water and nutrients in the APS. All other relationships and equations are presented in Supplementary Materials SM.1. The water quality, such as DO, pH, temperature, EC, and oxidation–reduction potential (ORP), TAN, nitrite, nitrate, SRP and TSS, was monitored by water quality sensors of Smart Water Xtreme (Libelium, Spain).

In the RAS, Nile Tilapia (*Oreochromis niloticus*) is grown in consecutive staggered production. The RAS in the reference system consists of 13 cultivation tanks of 30 m^3 each, and thus a total volume of 390 m^3, a biofilter, a trickling filter, a sump, and a settling tank. Fish are harvested when a maximum stocking density of 80 kg/m^3 is reached, resulting in a final fish weight of 600 g per fish. Losses due to mortality are neglected. The dimensions and operational values are based on conventional commercial Tilapia cultivation obtained from research by [33]. The growth of the Nile Tilapia in the RAS is simulated based on the model described by [4], as follows:

$$W_f^{total}(t) = W_f^{total}(t-1) + \left(W_f(t_0)^{1-\beta_f} + (1-\beta_f)\alpha_f e^{\gamma_f T_w} t\right)^{\frac{1}{1-\beta_f}} \quad (1)$$

where, W_f^{total} is the total fish weight in all the tanks (g/m^3); $W_f(t_0)$ is the starting weight per fish (g); T_w is the water temperature (°C); and α_f, β_f and γ_f are the species-specific growth coefficients, which are obtained by fitting a curve to Nile Tilapia growth data [4]. The required amount of feed is calculated by multiplying the increase in fish weight with the feed conversion rate (FCR) for each tank and dividing it by the mass fraction of feed consumed. The FCR is calculated according to a study by [18], where the same fish species were cultivated under comparable conditions. The feed composition and destination of N, P, and C are shown in Table 1. For optimal fish growth and minimal loss of nutrients, the water in the RAS needs to meet certain requirements. Table 1 gives an overview of these parameters and their values. Standard analytical techniques and onsite experiments in previous studies were obtained for the analysis of water quality and nutrient data [5,15,17,34].

For the HPS in the reference system, a Venlo-type greenhouse with a total area of 2.5 ha is used, of which 50 % is covered by plants. Crops are grown according to a deep-water culturing method in troughs with a water depth of 20 cm [40]. Tomato (*Solanum lycopersicum*) is grown in staggered production with a growth cycle duration of 125 days [41]. In the HPS, crops lose a significant amount of water due to evapotranspiration. The evapotranspiration rate depends on the internal greenhouse conditions and the growth stage of the crop. Previous studies showed that the FAO Penman-Monteith equation, which was initially developed for open-field agriculture, can also be used to calculate the reference evapotranspiration rate, ET_0, for indoor crop production [4,41,42]. In accordance with the study by [41], adaptations for application to indoor crop production were made by choosing a general K_c reduction factor λ of 21.4 % [28], see Eq. (2). By multiplying the reference

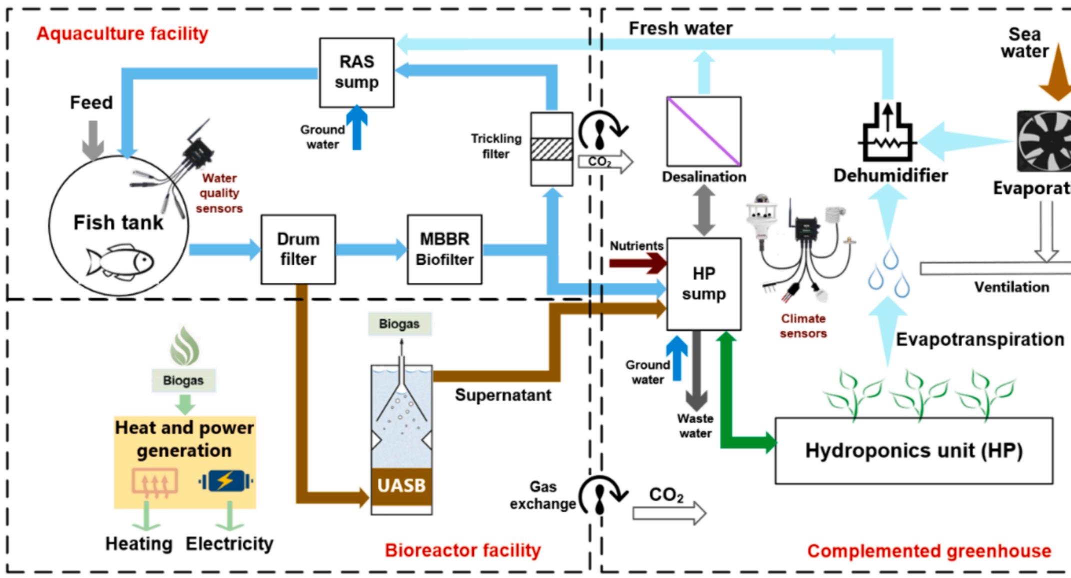

Fig. 1. Water flow scheme of the multi-loop APS with anaerobic digestors, desalination unit and an advanced greenhouse model. Water vapor in the greenhouse is recovered via dehumidification into the RAS. Water from HPS is concentrated via desalination into the RAS sump. Greenhouse and aquaculture facilities are separated from one another to provide optimal climatic conditions for fish and plants. However, waste CO_2 from the aquaculture facility is directed toward the greenhouse.

Table 1
Aquaculture, mineralization, nutrients, and desalination parameters are used in our multi-loop aquaponics model.

Function	Parameter	Value	Unit	Source
RAS	Fish species	Tilapia	–	–
	Temperature fish tank	29	°C	[33]
	TAN	<0.06	mg/L	[33]
	DO	>4	mg/L	[33]
	Harvest weight	600	g	[35]
	Max stocking density	80	kg/m^3	[35]
	Growth cycle	193	days	[35]
Fish feed	Dry matter content	95 %	of feed	[5]
	Protein content	45 %	of feed	[5]
	N content feed	7 %	of feed	[5]
	P content feed	1.3 %	of feed	[5]
	COD	1.4	g O_2 /g feed	[32]
Fish metabolism	Uneaten feed	18 %	of feed	[7,36]
	COD of solid excretion	20.2 %	of COD in feed	[37]
	N fish retention	35 %	of N in feed	[38]
	TAN excretion	33 %	of N in feed	[38]
	N feces	13 %	of N in feed	[38]
	P fish retention	28 %	of P in feed	[39]
	P feces	37 %	of P in feed	[39]
	P soluble excretion	17 %	of P in feed	[39]
Water and nutrients	Biofilter efficiency	98	% TAN nitrified	[36]
	Groundwater TAN	0.5	mg/L	[35]
	Groundwater NO_3–N	5	mg/L	[35]
	Groundwater P	0	mg/L	[35]
Anaerobic digestion	P mineralization	90 %	of incoming flow	[5,17,34]
	N mineralization	86 %	of incoming flow	[5,17,34]
	Water in effluent	98 %	of incoming flow	[5]
Desalination	Desalination flow to RAS (filtered)	62 %	of incoming flow	[14,16]
	Desalination flow to HPS (brine)	38 %	of incoming flow	[14,16]
Crop nutrients	N in HPS	177	mg/L	[6]
	P in HPS	49	mg/L	[6]

evapotranspiration with a crop-specific and growth stage-dependent constant (K_c), the crop-specific evapotranspiration rate (ET_{cg}) in the greenhouse can be determined as follows:

$$ET_{cg} = \lambda K_c \times (0.408\Delta R_{net} + 37\gamma u_2(e_s - e_a)/(T + 273))/(\Delta + \gamma(1 + 0.34u_2) \quad (2)$$

All parameters are described in Table A1 in Appendix A. Four different growth stages are considered, and their K_c values and plant heights are shown in Table A2 in Appendix A. All nutrients present in the evapotranspiration-driven flow to the plants are considered to be consumed by the plants [4]. The most important nutrients for optimal tomato growth are nitrate and phosphate. In the HPS, the concentration of these nutrients is constant, see Table 1. To maintain these concentrations in the HPS, fertilizer supplementation or dilution was applied.

The greenhouse climate highly affects the evapotranspiration rate of the plants, and thus the flow of water and nutrients. The HPS is separated into five different sub-compartments, which are considered homogenous in terms of mass and energy distribution. These compartments are: 1) corridor, 2) air ducts, 3) air under plants, 4) plants, and 5) air above plants (Fig. B1). The climate-smart greenhouse model can be found in Supplementary Materials SM.1. The environmental microclimate data, such as temperature, RH, solar radiation and air pressure, were monitored by multifunction climate sensors of Smart Agriculture Xtreme (Libelium, Spain).

For optimal plant growth, it is important to precisely regulate temperature and humidity, especially in the extremely arid climate in Midreshet Ben-Gurion, Israel. In combination with literature research into greenhouse cooling methods, companies and experts in this field were consulted in order to give insight into current operational cooling systems and the required greenhouse conditions (Table B1, Appendix B). A standard method for cooling greenhouses in regions with high temperatures is evaporative cooling [42,43]. It should be mentioned that the cooling pad can be operated with salt water. On the opposite side, where the air leaves the greenhouse, the air is dehumidified, and fresh water is collected [30,44]. When evaporative cooling is activated, fans are used to regulate the airflow through the pads and to the plants by a 4-way switch system at: 1) 100 % capacity, 2) 75 % capacity, 3) 50 % capacity, or 4) 25 % capacity. In general, the 100 % capacity is implemented; 75 %, 50 %, and 25 % capacity are only used when cooling is needed, but ambient radiation is below 600, 500, and 400 W/m^2, and the ambient temperature is below T_{plants}^{max}-2 °C, T_{plants}^{max}-5 °C, and T_{plants}^{max}-8 °C, respectively, in order to prevent temperatures falling below the minimum acceptable temperature. In the case that evaporative cooling is not sufficient, 20, 40 or 60 % of outdoor shading is deployed to reduce the amount of radiation admitted. If the combination of these techniques is still not sufficient, mechanical coolers are used for the residual requirement. Heating is carried out by a solar heating system. Since heating is mostly required during the night, a heat storage tank was installed to store the heat produced during the day.

An anaerobic digester is used to remobilize nutrients from the fish sludge to make them available for the plants and thus increase the NUE. In the anaerobic digester, phosphorus is remobilized as phosphates, and nitrates are remobilized as TAN [45], with a remobilization rate of, respectively, 90 % [39] and 86 % [38]. In order to process the sludge, the required reactor volume is 48 m^3, and the produced methane is used as fuel for a combined heat and power (CHP) generator. The CHP generator can convert the energy of combustion from methane combustion energy (40 MJ/m^3 methane) to electrical energy (35 %) and thermal energy (50 %) [5]. In addition to biogas production, the anaerobic digester has two more outflows: 1) liquid effluent or supernatant with remobilized nutrients going to the HPS, lowering the need for additional fertilizers, and 2) waste sludge containing undigested organic matter, which can be used as fertilizer for open-field agriculture [5].

A desalination unit is incorporated into the system to help maintain low nutrient concentrations in the RAS while maintaining high concentrations in the HPS [14]. The nutrient solution from the HPS storage tank is pumped to a generator-/solar-combined desalination system, from which the concentrated nutrient solution (62 vol%) is transported back to the HPS storage tank. Thus, the nutrient concentration in the HPS increases, while the distilled water (38 vol%) is transported to the RAS, diluting it. This results in lower dilution requirements of the RAS water and lower additional fertilizer requirements in the HPS, thus increasing water and nutrient use efficiency.

The dynamic aquaponics system (APS) model is fundamentally premised on water, nutrient, and energy balances, all of which are primarily expressed through differential equations. Subsequent numerical solutions to these differential equations are achieved via the application of the trapezoid method [24]. The recirculating aquaculture system (RAS), anaerobic digestion (AD), and desalination unit (DU) are treated as homogeneous entities in relation to mass and energy distribution. The development of a dynamic carbon model, supporting the balances related to the carbon cycle and footprint of aquaponics in Israel, was undertaken in a prior study [5]. Further specifics pertaining to the modeling process can be accessed in Supplementary Materials SM.1.

Table 2
Parameter description and values for the greenhouse and aquaponics system. Data reported by [4,24,28,33,43].

System	Parameter		Reference	Range	Unit
Greenhouse system	d_{duct}	Diameter of airduct. The airduct is set up at the bottom of the greenhouse, drawing air through the greenhouse.	0.8	0–1	m
	H_{pad}	Height of evaporative pad system on one side wall of the greenhouse	1.5	1.0–2.0	m
	r_{cover}	Thickness of cover glass on the roof of the greenhouse.	0.004	0.002–0.01	m
	$V_{ductairmax}$	Maximum working airspeed inside airducts	9	5.0–15.0	m/s
	$V_{panairmax}$	Airspeed of the maximum working capacity (100 % work load) of the adiabatic pad.	1.27	1.0–2.0	m/s
	U	Heat transfer coefficient of the cover	4.2	1.2–5	W/m^2/K
	RH_{max}	Maximum allowed humidity in the greenhouse	80 %	50 %–90 %	–
	T_{max}	The temperature at which cooling is enabled	28	25.0–32.0	°C
Desalination	r_{desa}	Input flow for desalination relative to HPS area.	10	0–200	m^3/day
HPS	A_{HPS}	Area of the greenhouse planted with crops.	2.5	10–18	Ha
RAS	V_{tank}	Volume of each fish tank	30	20–50	m^3
	n_{tank}	Number of fish tanks	13	10–20	–

2.2. Performance and sensitivity analysis

In this study, eight greenhouse parameters were varied to observe their effect on water use, energy consumption, and crop transpiration (Table 2). Additionally, four aquaponics parameters were varied to investigate their influence on nutrient dynamics and system performance. For the greenhouse parameters, three combination scenarios were also tested. In scenario 1, a system with and without dehumidification under different RH values was evaluated. In scenario 2, an extremely warm (~40 °C) and wet (RH 70 %) day in an extreme climate, resulting in the low cooling efficiency of the pad system, was analyzed. Finally, in scenario 3, an extremely cold (5–15 °C) day, resulting in high thermal energy requirements, was simulated and analyzed.

From the large amount of data generated by the model, the most important outcomes are summarized in a set of key performance indicators (KPIs), which include fresh water input (FWI), water use efficiency (WUE), nutrient (N and P) use efficiency (NUE), energy consumption (E), and carbon neutrality. Together, the KPIs cover the relevant factors for determining the performance of the system. Because of the explorative character of the study, we used parameter sensitivity and scenario analyses to give an indication of the influence of individual design and control parameters (Table 2) on the KPIs. The sensitivity analysis of the system parameters is compared with the normalized (non-dimensional) sensitivity coefficients, as presented by [46].

2.3. Case study

Midreshet Ben-Gurion, Israel, has been chosen as a benchmark location due to its key role globally in dryland technologies and agriculture, and its geographical location as an appropriate arid climate zone to build the APS. The environmental conditions demand complicated agricultural practices, but the system can bring fresh food to the local population at low transport costs. The numerical-experimental platform utilized in this study is based on a dynamic aquaponics model previously developed and validated in our prior research [35]. Experimental data for fish growth, plant transpiration, water quality, and nutrient balances were collected through continuous monitoring using sensors and analytical techniques [47]. Data collection and analysis methods, including sensor calibration, nutrient dynamics, and energy use measurements, are described in detail in our earlier studies [48].

Representative three-year reference climate data sets were used for simulations to evaluate the yearly dynamics of the greenhouse climate and energy consumption. The reference data set consisted of typical Israeli climate data with hourly values for air temperature, RH, direct and diffuse global radiation, and wind speed and direction. Simulations were run for three full years with a time step of 1 min, integrated hourly for the graphical outputs. In this study, we tailored the operational strategies and technical equipment simulations to accommodate the unique requirements of arid zones and desert climates. These regions, which include parts of the US, Australia, China, the Middle East, and Africa, exhibit pronounced seasonal variations, significantly influencing our design considerations. Furthermore, the model's adaptability and scalability make it equally applicable for *peri*-urban regions, where efficient, sustainable food production is often a crucial concern. Thus, a simulation study was carried out to size the components of an industrial multi-loop APS in such a climate (Fig. 1) while keeping the fish water environment low in nutrients and providing an optimal nutrient supply for the plants.

3. Results

3.1. Aquaponics system design in the arid climate

3.1.1. System sizing

Modifications to the greenhouse dimensions, and consequently the cultivated area, significantly influence the overall uptake of water and nutrients by plants. Consequently, the precise calibration of the HPS dimensions becomes a critical factor, ensuring that the APS maintains nutrient concentrations within acceptable thresholds in the RAS whilst concurrently upholding recommended nutrient levels within the HPS. The DU affects the balance by lowering the nutrient concentrations in the RAS with distilled water from the HPS and concentrating the RAS effluent going into the HPS. To optimize the system with regard to water (FWI), nutrients (NUE-N and NUE-P), and total energy use (E), different HPS dimensions, desalination rates and RAS volumes were considered. In this analysis, the reference settings are shown in Table 2.

NUE-N and NUE-P, nutrient (N and P) supplementation, and WUE are affected by both HPS size and desalination rate (Fig. 2a-h). Nutrient supplementation has a positive effect on the NUE as dilution of the HPS water will be set to a minimum. However, for a balanced system, minimal supplementation is preferable. Since the WUE is dominated by the influence of salt water, which is used for the cooling pad system, the most important KPI is the fresh water input per m^2 HPS area. Fresh water input decreases with an increase in both HPS size and desalination rate, while crop evapotranspiration only changes with the HPS size. Energy consumption becomes more efficient with increasing HPS size, where the desalination rate only affects thermal energy consumption since it operates fully on thermal energy. Besides NUE, due to its limited availability in arid zones, water input and the supplementation percentage are used to select an appropriate HPS size and desalination rate. Fig. 2 shows that both NUE and use of fresh water and energy, at an HPS size of 68,450 m^2, almost stabilize. Furthermore, supplementation is only 5 % N and 34 % P of the total nutrient input at this size, whereas supplementation increases rapidly at larger HPS sizes. Therefore 68,450 m^2 (approx. 6.85 ha) has been selected as the most appropriate HPS size. A desalination rate of 40 m^3/day has been chosen because it enhances both the freshwater input and the NUE. This rate operates on thermal heat, a sustainable energy source that is particularly apt for deployment in arid climates.

Considering the HPS area (6.85 ha) and desalination rate (40 m^3/d) as determined above, the sensitivity of the RAS size has been studied to give insight into its effect on the KPIs (Fig. 2i-l). Increasing RAS size lowers NUE and supplementation requirements and increases the fresh water requirement. Lowering the RAS size makes the system more efficient regarding NUE and FWI. However, more supplementation is required to lower the self-regulating capacity of the system. A RAS with 14 tanks of 30 m^3 each seems to be appropriate. These values are considered for further calculations.

Since RAS size in APS can be adjusted according to the required production capacity, a rule of thumb regarding HPS to RAS scaling is desirable to make the Israel system applicable for different locations in arid regions with varying production capacity needs. Scaling the HPS to the RAS depends on the climate conditions and water loss in the HPS. In addition, the scaling ratio depends on the considered KPI. Three different KPIs are used to scale the HPS to the RAS: 1) setting the fresh water input to 1.524 $Ld^{-1}m^{-2}$ HPS area, 2) setting NUE-P to 95.9 %, and 3) setting the N supplementation to 5.5 %. A linear relation between RAS and HPS size was found for each of the three KPIs (Fig. 2m).

3.1.2. Design parameter analysis

The evaporative system, with outdoor shading, mechanical cooling, and heating, keeps the greenhouse temperature and humidity in the desert APS between set limits at all times. To quantify the effect of different greenhouse settings (Table 2), the KPIs, i.e., FWI, E, and NUE, were investigated throughout three years, and are summarized in Fig. 3.

The settings (size and airspeed) of the airduct (Fig. 3a&d) and evaporative pad (Fig. 3b&e) slightly affect the water and energy consumption and NUE, while the glass thickness of the cover of the greenhouse, and its heat transfer coefficient, does not cause significant differences (Fig. 3c&f). Airducts are typically found in Venlo greenhouses. Their design affects both nutrient use efficiency and energy consumption. The FWI increases linearly with the setting of the evaporative pad, which also affects the NUE. As energy-saving covers have become common in new greenhouses, one is deployed after sunset, lowering the heat transfer coefficient of the greenhouse to a minimum [43]. An increase in the insulation of the greenhouse (decrease of transfer coefficient or increase in thickness) results in a minor decrease in variation, as the average temperature in the desert is higher, paired with large energy savings.

Decreasing the maximum RH is a common water-saving strategy, which leads to a higher NUE and a lower risk of crop disease, despite a higher energy consumption (Fig. 3g) and dehumidification requirement. As this mainly occurs in summer, the seasonal temperature and radiation differences are increased. In contrast to the close to optimal RH of 85 % in northern latitudes, as reported by Jansen and Keesman (2022), the optimal maximum RH in arid zones with respect to FWI and NUE is lower, as higher FWI is needed for higher RH. Changing the maximum temperature has an important effect on fresh water use and NUE (Fig. 3h). Increasing the permitted maximum temperature will lead to an increase in evapotranspiration (ET), especially in summer. Raising the maximum temperature by two degrees improves the NUE and lowers the energy demand, with little effect on fresh water demand. A higher temperature with an increased transpiration rate increases the risk of burn and drought stress due to water loss and accumulated nutrients in the leaves [6]. Consequently, the optimal maximum RH is around 80 % and the maximum temperature is around 28 °C (Fig. 3g-h).

3.1.3. Optimal system design

Combining all optimal settings from Figs. 2 and 3, as described above, the greenhouse climate model was set up for arid zones. During the summer full evaporative pad capacity is required all day, whereas during the winter, full pad capacity is only required in the afternoon. In winter, evaporative cooling is generally sufficient to keep the temperature at the plants below 28 °C, whereas in summer, additional shading is required, and there is even a need for supplemental mechanical cooling under certain conditions (Fig. 4a&b). Outdoor shading limits the radiation entering the greenhouse, which highly affects the

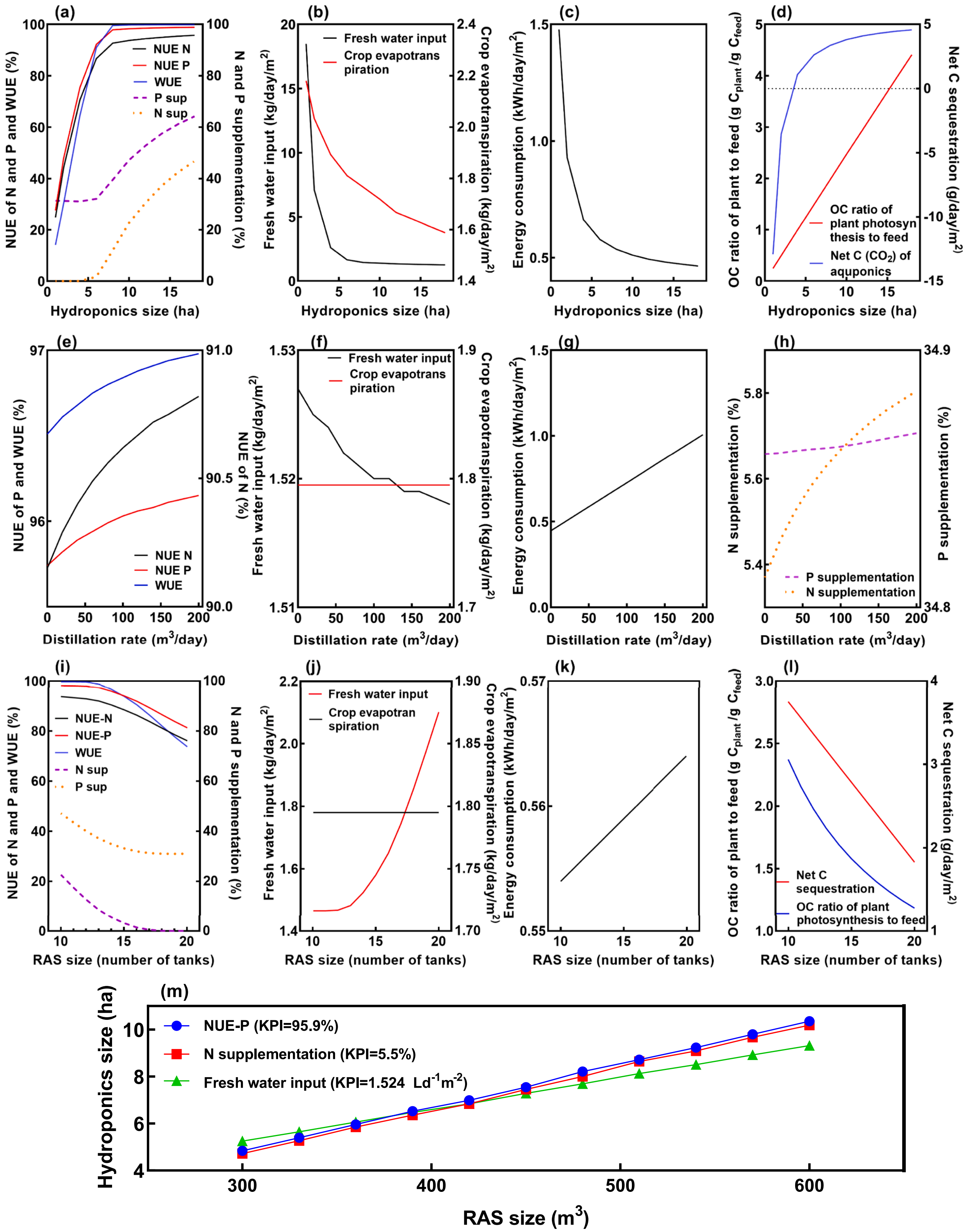

Fig. 2. (a-h) The effect of HPS size and desalination rate on NUE, supplementation requirements, FWI, energy use and carbon dynamics regarding constant reference parameters shown in Table 2. (i-l) The effect of RAS size on NUE, supplementation requirements, FWI, energy use and carbon dynamics regarding a constant HPS volume (6.85 ha) and a desalination rate (40 m^3/d). (m) Rule of thumb for sizing HPS to RAS regarding setting 1) NUE-P to 95.9 %, 2) N supplementation to 5.5 % or 3) fresh water input (FWI) to 1.524 $Ld^{-1}m^{-2}$ HPS area, based on RAS size in m^3.

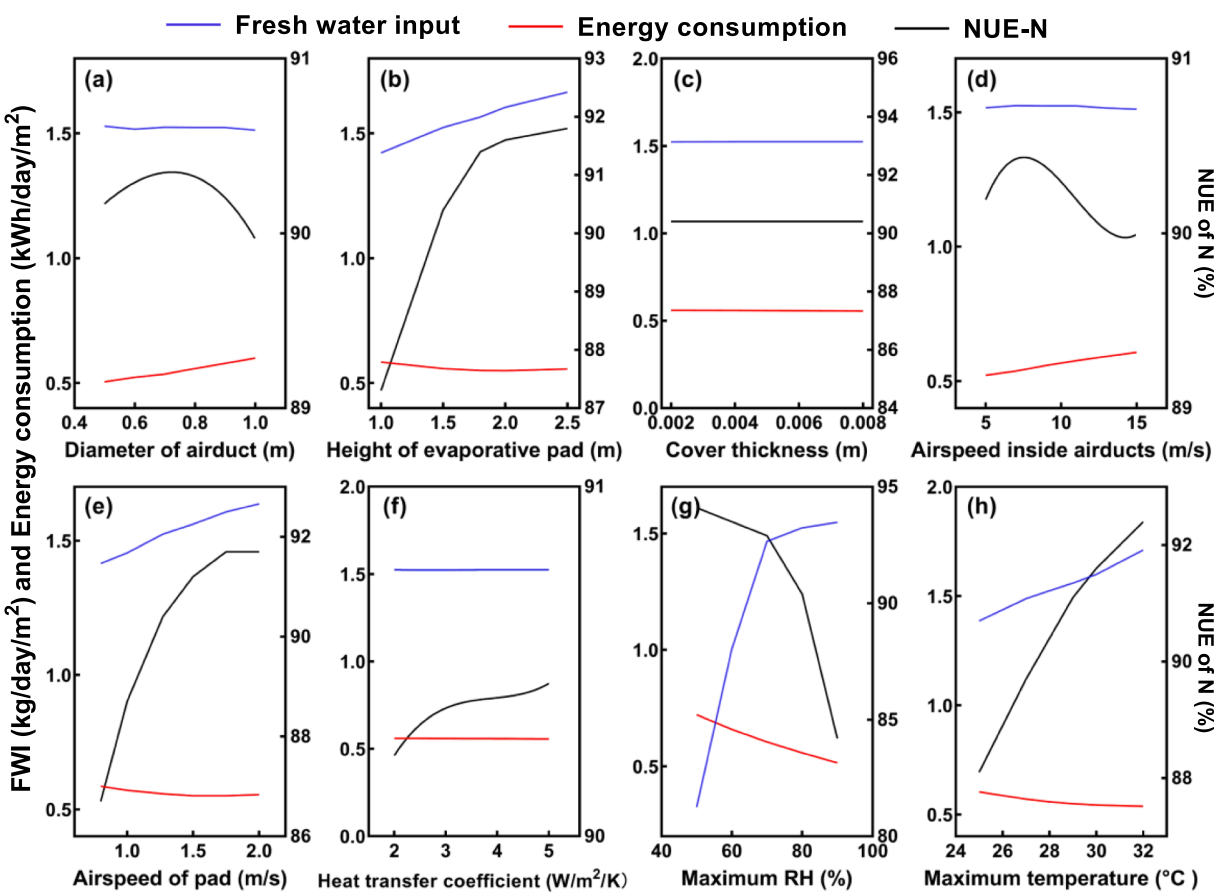

Fig. 3. Fresh water input and total energy consumption (left axis), and nitrogen use efficiency (right axis) of the APS against variation of greenhouse design scenarios. Each of the settings' parameters is varied along the range shown in Table 2.

evapotranspiration rate of the plants. This explains the limited evapotranspiration rate during the summer and the increase in spring (Fig. 4) when radiation is moderate and low shading is required.

To validate the model for the Israel system, as used in this study, KPIs have been compared with output values from greenhouse climate models in Namibia [4] and the Netherlands [24]. Regarding fresh water input as the most important KPI for arid zones, evapotranspiration is considered the most important output of the greenhouse model. Comparing the three models shown in Table 3, a total ET increase of around 56 % is observed in the reference models due to their lack of evaporative cooling. Thus, the reference systems in the Netherlands and Namibia require more fresh water and result in a higher nutrient consumption by plants, which increases the supplementation requirements from the RAS and thus results in an increase of the nutrient use efficiencies (1.8 % NUE-N and 0.5 % NUE-P). However, the self-regulatory effect of the system is reduced. In the Israel system, a high evaporative pad capacity is required to keep the RH at 80 %, resulting in a higher fresh water loss via ventilation, and thus overall higher fresh water input (63 %) as compared to the reference systems. Furthermore, the reference models show higher ET rates during the night in summer compared to winter, whereas the ET rate during the night for the Israel system was constant all year.

In relation to the energy consumption of the system implemented in Israel, the thermal energy demand experiences a slight decrease as a result of the Evapotranspiration (ET) process, owing to a reduced cooling necessity for the plants via the evaporative pad. This dynamic also lessens the cooling requirements instigated by shading strategies, thereby reducing the demand for electrical energy. Concurrently, a reduction in the necessity for dehumidification, resulting from a decrease in ET, leads to an overall decline in electrical energy expenditures.

3.2. *Aquaponics system performance*

3.2.1. *Yield and nutrients*

Considering 14 fish tanks, a production cycle of 193 days, and with every 13.8 days a new batch being started, total fish weight and feeding rate are subject to fluctuation. After a startup time of one production cycle lasting 193 days, the total fish weight in the RAS stabilizes at around 12,250 kg, while the feed rate stabilizes at around 185 kg per day. Interestingly, Bar-Yosef et al. (2009) claim that a mass fraction of 25 % of N being TAN optimizes plant growth . In the Israel system, a mass fraction of around 28 % of N being TAN is found in the HPS, which is close to the recommended ratio.

The fluctuations for NO_3-N and P concentrations in the RAS are mainly caused by the flow of water from the RAS to the HPS. A yearly pattern for nutrient concentrations in the RAS can be explained by the effect of the climate on water consumption in the HPS, as shown in Fig. 5. HPS water is taken up by plants, after which it should be replenished with RAS water to keep the HPS volume constant. However, evapotranspiration has a low season dependency due to the highly controlled greenhouse climate regarding shading, cooling, and RH regulation. Strong season dependency is mostly caused by dehumidification. Part of the water loss from the HPS is compensated by the dehumidification of both air above the plant and vaporized salt water from the evaporative pad system to keep the relative humidity in range. During the summer, much dehumidification is required, causing higher water recovery and thus lower water transport from RAS to the HPS, resulting in higher RAS concentrations. When the inflow of water to the HPS is higher than the outflow of water, surplus (HPS wastewater) is

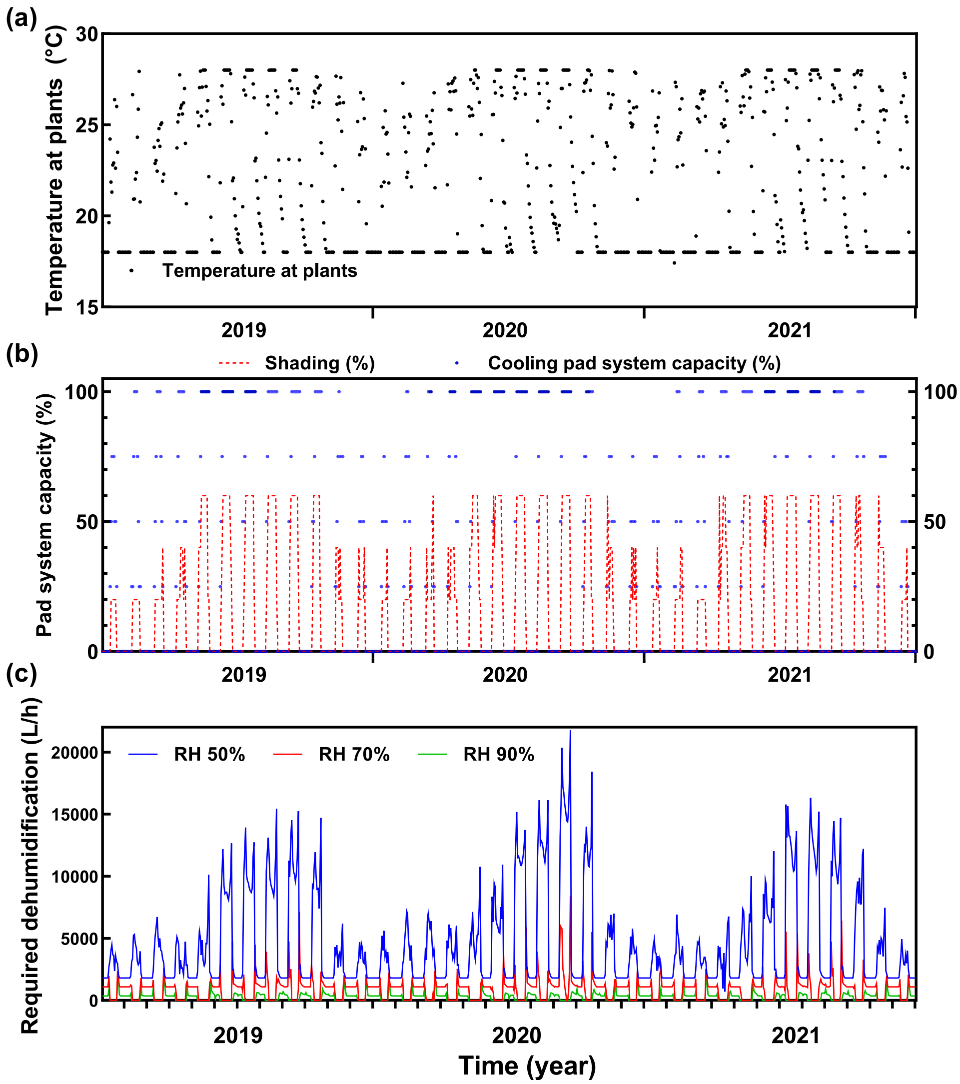

Fig. 4. (a & b) Monthly average values for each hour of the day for pad system operating capacity (0, 25, 50, 75, or 100 %) and required shading (0, 20, 40 or 60 %) to keep the greenhouse temperature at the plants between 18 and 28 °C. (c) Monthly average values for each hour of the day for required dehumidification are based on a constant RH value at the plants of 50, 70, or 90 %. Hence, the data shows monthly average values per hour, and thus the x-axis shows 12 days for each year, from 0 to 24 h, for each month from January to December in the period from 2019 to 2021, and thus 864 data points in total for each variable.

Table 3
Key performance indicator values and other system parameters for tomatoes grown in the Israel greenhouse model under desert climate conditions compared with reference models in the Netherlands [24] and Namibia [4].

KPIs	Unit	Israel model	Netherlands model	Namibia model
Fresh water input	kg/day/m^{2a}	1.524	2.478	2.397
Crop ET	kg/day/m^{2a}	1.795	2.806	2.754
Water recovery from salt water	kg/day/m^{2a}	1.773	1.729	2.050
NUE-N	%	90.4 %	92.2 %	92.1 %
NUE-P	%	95.9 %	96.4 %	96.3 %
N supplementation	%	5.5 %	28.3 %	27.4 %
P supplementation	%	34.9 %	51.2 %	50.5 %
WUE	%	96.7 %	99.8 %	99.7 %
Energy consumption	kWh/day/m^{2a}	0.558	0.796	0.742
Electric energy consumption	kWh/day/m^{2a}	0.156	0.384	0.330

[a] Calculations based on the area of the greenhouse (m^2).

removed to maintain constant volumes.

3.2.2. Energy

A yearly pattern regarding energy consumption is presented in Fig. 6. Electrical energy consumption is dictated by fans, pumps, air blowers, and mechanical coolers, which are all mainly required during the summer, resulting in a summer- /winter- based fluctuation. Both the energy consumption for the dehumidifier and the energy production from methane are negligible compared to the total consumption.

In the context of sustainability, it is desirable to achieve self-sufficiency within the system, a feat that can be realized through the installation of photovoltaic (PV) panels. The area of PV panels required is contingent on factors such as the ambient radiation and the energy efficiency of the PV panels themselves. Given an efficiency rate of 21.1 %, a figure drawn from currently available commercial systems, it is estimated that a PV panel surface area of approximately 4500 m^2 would be necessary to meet the system's daily electricity demands.

The thermal energy consumption within the system is primarily determined by the requirements of the desalination unit (DU) and the greenhouse heating needs. DU is considered to be constantly operating, whereas the supplemented thermal energy for heating the greenhouse is

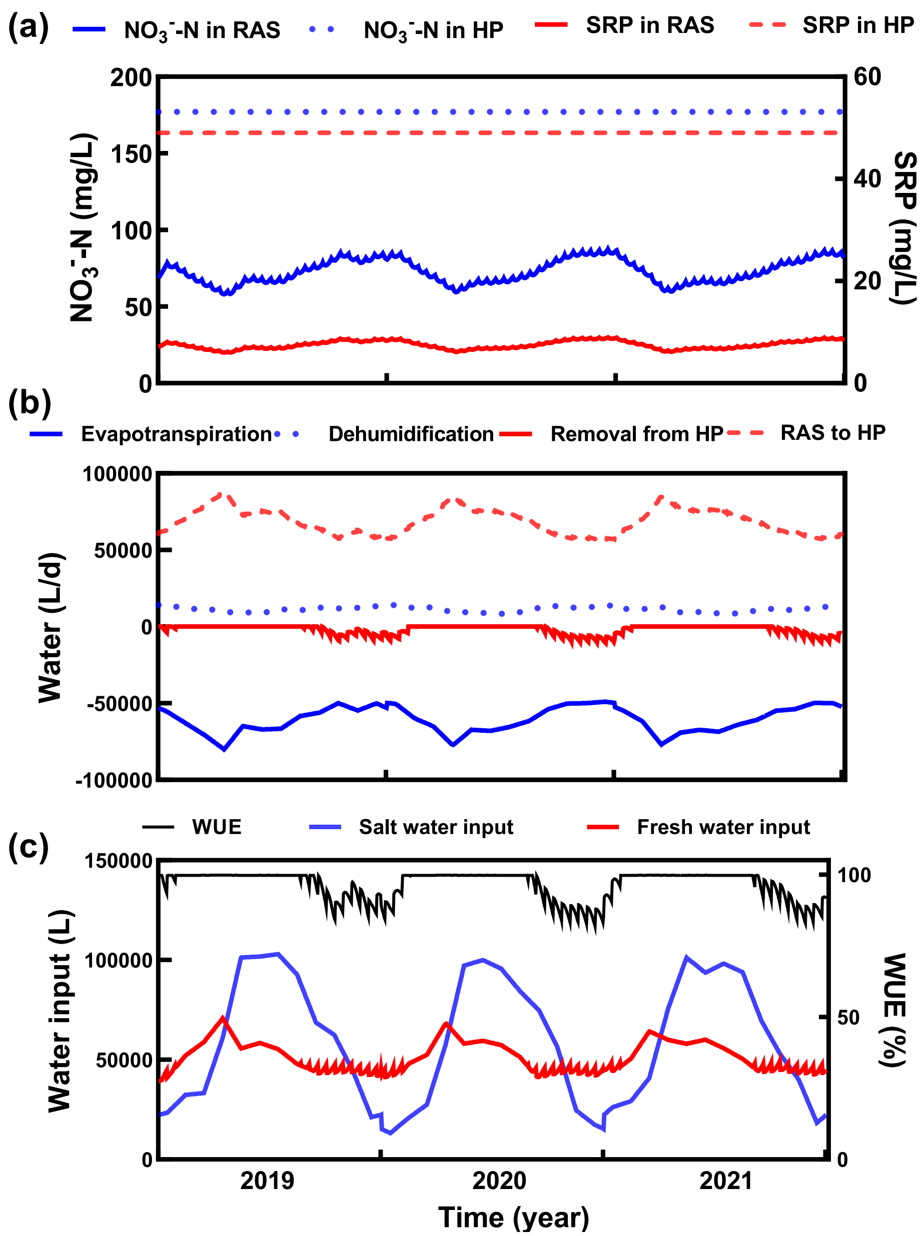

Fig. 5. (a & b) Nitrate (NO_3-N) and phosphorus (P) concentration in the RAS and the HPS, with the corresponding water transport from the RAS to the HPS, which is given by water loss due to evapotranspiration and surplus removal (HPS wastewater) due to RAS dilution requirements, minus the recovery by dehumidification and the transport of distilled water from the HPS to the RAS (15,200 L/d). (c) Salt water and fresh water requirements (L/d) of the Israel APS.

only required during the winter. Heating the groundwater before it enters the RAS requires low energy use compared to the total consumption. Heating the AD and heat production from methane are negligible. In practice, groundwater is commonly stored outdoors in black tanks to preheat the water before entering the RAS, limiting the need for an external heat supply. However, this practice is neglected in the model resulting in a worst-case scenario that overestimates the energy costs for groundwater heating. A solar heating system (SHS) can be used to supply the required heat energy. Considering an efficiency of 51 % [49], an SHS area of approximately 5000 m^2 is required to cover the thermal energy needs on a daily basis.

3.2.3. Carbon

In a staggered production cycle of 193 days, a new batch is started every 13.8 days resulting in a fluctuating total carbon input (114 kg/day) from fish feed and biogas produced from the fish sludge (Fig. 7a). However, due to seasonal temperature and radiation differences, crop growth and net plant photosynthesis show a strong seasonal dependence. The minimal net plant photosynthesis with corresponding carbon uptake is in winter, which is 1.8 times lower than in summer (Fig. 7a).

Carbon flows and CO_2 emission for each part of APS are shown in Fig. 7b. The CO_2 emission of the system is 15.6 kg/day, which is mainly driven by respiration. The application of recoverable gas exchange technology would contribute hugely to carbon neutrality as it recovers CO_2 from RAS (42.2 kg/day) and biogas (32.8 kg/day), and exchanges gas with the greenhouse system. The gas exchange technology reduces 83.4 % of CO_2 emissions. During operation, electricity consumption and water use lead to a significant amount of CO_2 emission. However, as these emissions are calculated indirectly, they are not shown in Fig. 7b. Nevertheless, these emissions are assessed as follows. Assuming electric power is generated by a thermal power plant, CO_2 emission per unit of power generation is 0.01 $kgCO_2$/kWh [50]. In arid zones, the emission of water is 0.42 $kgCO_2$/ton [51]. Overall, the direct and indirect CO_2 emission in this system is expected to be 90.1 $kgCO_2$/day in total.

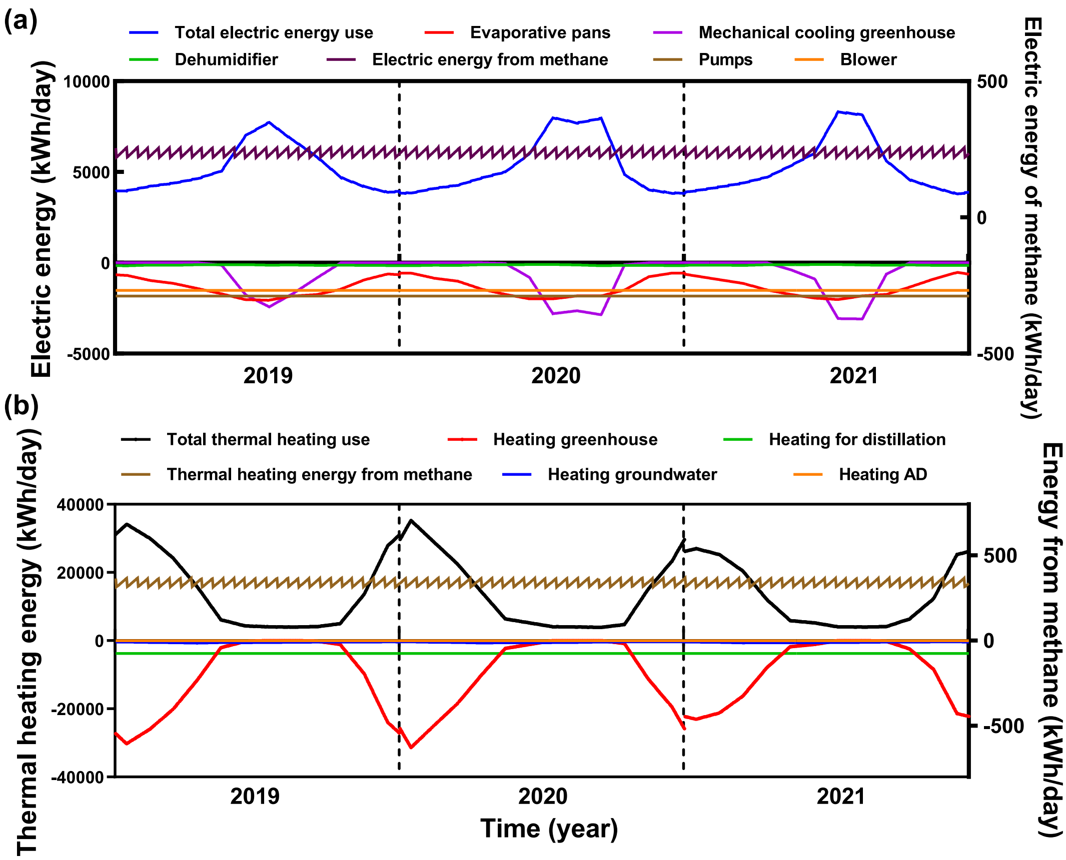

Fig. 6. Electric and thermal energy consumption, production and total requirement for the complete APS for three years from 2019 to 2021.

The carbon fixation ability of the Israel APS is 192.3 $kgCO_2$/day via net plant photosynthesis, of which 41.4 % of the CO_2 (79.6 kg/day) is recovered and fixed in the APS (Fig. 7b). It was observed that the Israel APS could fix a net 112.7 $kgCO_2$/day from the air, which is higher than the overall emission of the system.

4. Discussion

4.1. System performance in arid regions

Arid regions, particularly those with high population densities, are potentially ideal settings for APS, notwithstanding previous research that has highlighted certain challenges pertaining to overall feasibility and financial viability. However, the feasibility of an APS strongly depends on the operational location [4]. Arid climates provide a high potential for solar energy, which can be collected as thermal energy via an SHS or as electric energy via PV panels. High ambient radiation provides the cheap and sustainable energy required to operate fully self-sufficiently [5]. Considering the flow of recovered water from salt water and dehumidification, the system can even operate fully self-sufficiently regarding fresh water requirements, further decreasing operational costs. The food prices in most arid regions are much higher than in other regions, as crop production is challenged by harsh climate conditions and a lack of fresh water [52].

Fresh water requirement for tomato greenhouse production is, in general, between 2.1 and 2.9 L/day/m^2 greenhouse area [53]. The low fresh water requirements for the Israel APS can be explained by the incorporation of the dehumidification unit, which recovers the evapotranspiration water and the evaporated salt water through the cooling pad system. While lowering the FWI, the dehumidification unit significantly increases electrical energy costs. However, energy consumption is considered less important because of the abundance of potential solar energy in comparison to the scarcity of fresh water. In addition to a dehumidification unit, the incorporation of a DU also improves the FWI, but also the NUE (for both P and N) in exchange for thermal energy. An NUE-P of 95.6 % is considered high since, for RAS alone, the fish retention of P is 28 % [37,39], and thus in RAS 72 % of P is unused.

To cover the average electrical and thermal energy requirements on a daily basis, 0.45 ha PV and 0.5 ha SHS are required. However, an hourly base requirement cannot always be met due to the absence of radiation during the night and due to possible extreme conditions flattened out by an hourly interval of an average day, as considered in the Israel APS model. Thus, for the system to be self-sufficient, thermal and electrical energy storage is required. Since the greenhouse is heated by a water pipe-based system, a water-based thermal energy storage system is the most convenient. For electrical energy, a battery-based storage system can be used. The energy supplied by the CHP generator, both thermal and electrical, is negligible compared to the total thermal and electrical energy requirement of the overall system. Nevertheless, the implementation of a CHP generator is still considered because of its role in treating the methane produced by the anaerobic digester. The anaerobic digester is an important component in the remobilization of nutrients in the fish sludge, improving the NUE and especially the NUE-P.

A DU is implemented in the APS to increase the system performances (FWI, NUE, and WUE) albeit at the cost of increased thermal energy consumption. Considering arid conditions, thermal energy is sufficiently available, making the DU most certainly a feasible addition to the system. The desalination rate can be used as a tool to compensate for scaling insufficiencies by modifying concentrations in the RAS and the HPS. Increasing the desalination rate can solve overestimated HPS size and prevent excessive nutrient supplementation by increasing HPS nutrient concentrations. Decreasing the desalination rate can solve underestimated HPS size and prevent excessive dilution by lowering HPS nutrient concentrations.

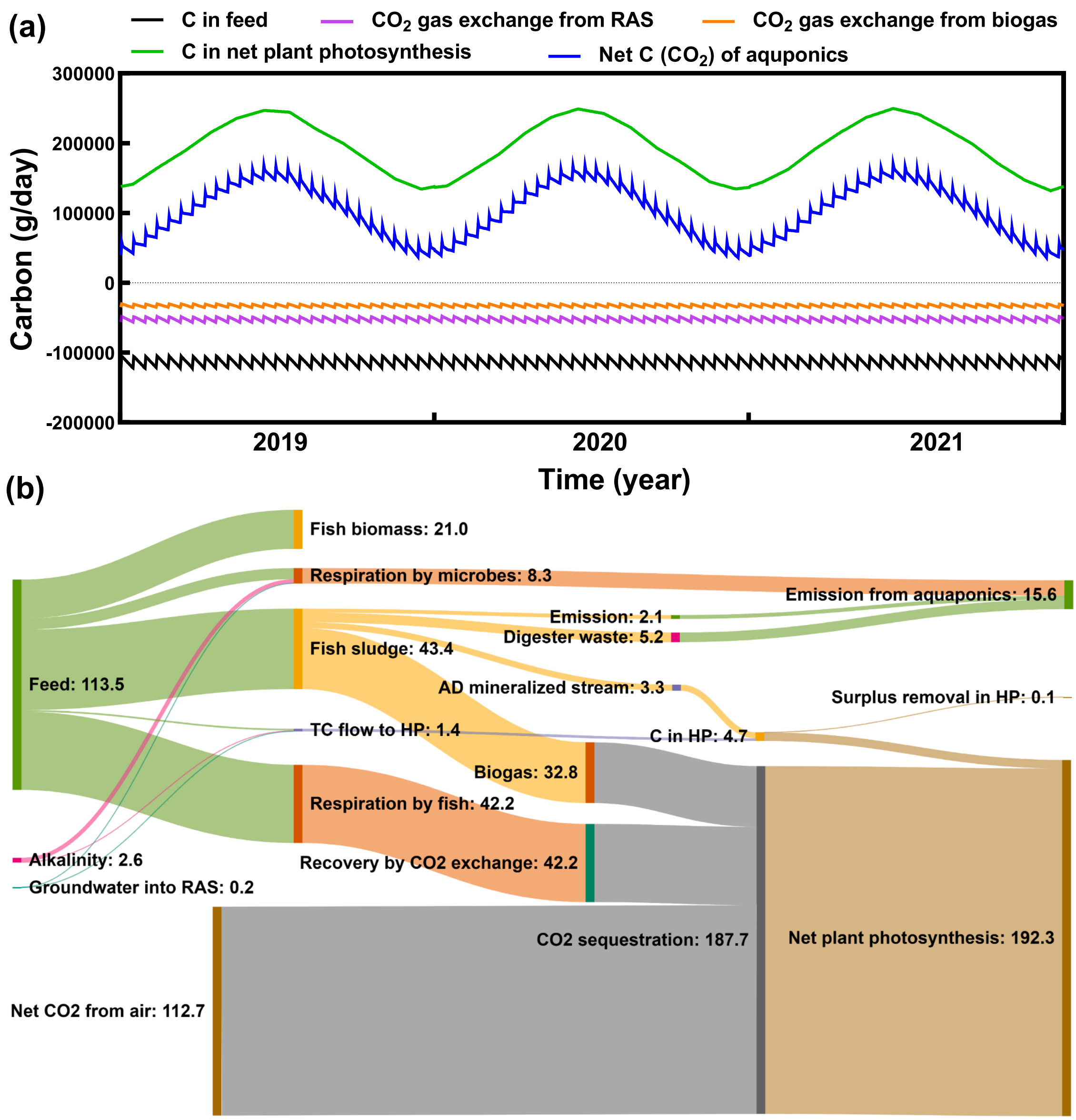

Fig. 7. (a) Carbon flows of the Israel APS with the optimal settings for three years from 2019 to 2021. (b) Sankey diagrams for the carbon neutral analysis of the APS under desert conditions. Primary carbon supplies are on the left, conversion processes are in the middle, and final carbon types are on the right. Line widths are proportional to the magnitude of carbon flows. Unit: kg/day.

4.2. Integrated aquaponics model

The model was designed and optimized based on potential application in Israel, with a given RAS size and extended with a desalination and biodigester unit. The model can be readily adapted for other locations within arid zones by adjusting the climate and environmental conditions, as well as accounting for variations in technological capabilities. The chosen strategies for regulating the greenhouse environment were specifically tailored for arid regions, encompassing not only the Middle East but also similar climatic conditions found in regions like Australia, Arizona, North Africa, and western China. This extensive geographical applicability endows the system with broad adaptability. Additionally, the desalination rate can be adjusted, and in certain cases even set to zero, allowing for the removal of the DU from the system design. Moreover, the size of the RAS can be easily modified to meet desired food production capacities or accommodate specific HPS areas. Similarly, the HPS area can be scaled to suit different fish species with varying stocking densities, assuming equivalent metabolic rates.

APS performance is expressed in terms of key performance indicators (KPIs). For the Israel APS, freshwater input (FWI) requirements and NUE for N and P are considered the most important KPIs since fresh water is scarce in arid zones, N has an important role in fish toxicity, and P is globally a limited resource. Carbon flows and energy consumption are also monitored. When constructing a model, it is crucial to determine the key factors that hold the utmost significance and exert the highest impact on system performance. The Israel APS model specifically directs its attention toward investigating the influence of the arid climate on APS performance. Consequently, the greenhouse climate model, which accounts for temperature and vapor dynamics, assumes a position of paramount importance. This particular aspect of the APS experiences the most pronounced effects stemming from the arid climate, necessitating meticulous control of indoor conditions to facilitate optimal crop growth. Consequently, the energy consumption of the system is largely governed by the greenhouse, as it plays a pivotal role in maintaining the desired environmental parameters. The RAS focuses mainly on water and nutrient flows, which are considered to undergo only a minor influence from climate conditions. Factors neglected in the model are, for example, heat loss and evapotranspiration from the fish tanks, fish mortality, plant disease, and variable fish and crop yield. The influence of these parameters on the KPIs was considered of low importance and was neglected to keep the complexity of the model relatively low.

4.3. Greenhouse cooling and dehumidification strategy

Based on previous studies and expert advice, evaporative cooling was selected as the most appropriate cooling strategy for arid zones. Due to the dry ambient air, high cooling efficiencies can be gained under low operational costs. Besides, seawater can be used for vaporization, which can subsequently be recovered by dehumidification, thus lowering the fresh water requirements. A corridor-based system is used in which the air is conditioned in the corridor and supplied to the plant via air ducts for a homogenous temperature and vapor distribution. In addition, outdoor shading and mechanical cooling are supplemented. During the summer, almost 60 % shading is applied, and the solar radiation is reduced to a maximum of around 400 W/m^2, strongly reducing the incoming radiation. Graamans et al. (2017) considered a minimal solar radiation requirement to be 500 W/m^2 during the day, ensuring optimal growth [54]. Therefore, this shading might cause insufficiencies regarding PAR levels for the plants, reducing photosynthesis and affecting their growth, so it might be preferable to lower the shading percentage to optimize crop growth at the price of higher energy costs for mechanical cooling.

Dehumidification in the greenhouse is achieved by mechanical dehumidification, requiring a high amount of energy [29]. In practice, dehumidification is often carried out by ventilation or by a cool water (seawater) piping system. However, the resulting ambient air is too dry and warm for plant production, making the sole use of ventilation unsuitable. Regarding the water piping system, water recovery is difficult. Because fresh water scarcity is a common problem in arid zones and energy is sufficiently available from solar radiation, mechanical dehumidification with water recovery is selected as the most appropriate option. However, when air enters the corridor via the pad system during cooling, humid air above the plants leaves the greenhouse by ventilation. Thus, when vapor content in the air after going through the pad system is lower than in the air above the plants, dehumidification is technically also induced by ventilation.

Temperature and RH are considered the most important regarding optimal greenhouse conditions for tomato growth. In the literature, many different findings regarding optimal conditions for tomato production can be found, with temperatures ranging between 12 and 30 °C and RH values between 35 % and 90 % [28,55]. Therefore, the findings from the literature study were supplemented by advice from greenhouse operating experts and researchers in the field of greenhouse crop production (Table B1 in Appendix). Based on these findings, the temperature is kept between 18 and 28 °C, with a constant RH of 80 % for the Israel APS model. CO_2 was not considered since its connection with the overall system is relatively low and would further complicate the model. Nevertheless, a minimal airflow through the air ducts was considered at 25 % of the maximal airflow, which is equal to 222.6 m^3/s, to secure sufficient CO_2 supply to the plants via the corridor.

The relative humidity at the plant compartment is considered at a constant value of 80 % throughout the whole simulation study. However, RH is expected to drop 80 % below in practice when dry ambient air enters the greenhouse via the cooling pad system. A sensitivity analysis shows that overestimated RH values highly underestimate the evapotranspiration and dehumidification requirements, which subsequently influence the required FWI, NUE, and energy costs. In practice, a naturally lowered RH will not increase dehumidification requirements as much as given by the sensitivity analysis. On the contrary, it might even reduce dehumidification requirements since a drop in RH provides a buffer for vapor before reaching the RH limit. However, a drop in RH increases ET, which subsequently increases dehumidification requirements. To calculate the dehumidification requirements with more accuracy, RH must be changed from constant to variable. Due to the strong interconnections between ET, RH, and temperature, for a deeper understanding of the evapotranspiration and dehumidification requirements, it is advisable to use a more sophisticated model.

4.4. Carbon neutrality and economic outlook

The carbon fixation ability of the Israel model is 28.1 kg/day/ha via the net plant photosynthesis, of which 59 % of the net CO_2 (16.5 kg/day/ha) is fixed from the air; this is much higher than the overall emission of the APS. Interestingly, overall, net CO_2 sequestration is observed (normalizing 1 kg feed-C input, about 1.69 kg plants-C fixation via aquaponics), which dramatically reduces aquaponics' environmental footprint and improves its sustainability. Therefore, the high energy and water efficiency of the greenhouse system make the gas exchange-assisted Israel APS a promising technology to achieve a "carbon neutral" strategy in arid zones.

As stated above, arid and warm zones require innovative agricultural technologies to bolster local food security. This work appears to be the first study to assess the effect of desert climatic conditions on sizing high-tech APS. Abundant external solar energy (for photosynthesis, heating during the night, and electricity generation), as well as the availability of brackish/salt water (for cooling), make temperate deserts ideal places for growing food in arid zones. However, it should be noted that this only applies to large-scale, high-tech and climate-controlled greenhouse systems. In principle, it is possible to implement such systems in most regions worldwide. However, the current study has only examined the technical feasibility. Further research is required to examine the economic meaningfulness of such systems in different arid zones. The most important points for economic success are (1) the size of the system and construction cost; (2) crop, fish, and sales opportunities; (3) food prices in the local market; (4) energy resources and their prices; and (5) labor costs. Based on these criteria, the operation's ROI can be determined, which is an indicator of business profitability. However, it is not only the crop selection and sales opportunities that would make it a profitable business model. Also, regional cooking habits, norms, and values play important roles in food choices in each cultural setting. Thus, an understanding of local contexts is necessary to ensure the adoption of the innovation.

5. Conclusions

We successfully combined a greenhouse climate model and a multi-loop aquaponics model of two cultivation systems to attain an innovative, integrated dynamic simulator applicable to various scenarios. This study showed, through an elaborate sensitivity and scenario analysis concerning the efficient use of resources (water and nutrients), energy, and carbon neutrality, that the novel use of evaporative cooling through a pad-fan system accompanied by outdoor shading and mechanical cooling makes accomplishing optimal tomato crop growth feasible for arid regions. Mechanical dehumidification is considered most appropriate for RH regulation due to its ability to recover water vapor, lowering the freshwater requirements of the overall system. A key discovery was the inclusion of a DU in the APS which enhanced its performance in terms of FWI and NUE. However, this improvement in system performance came at the expense of increased energy consumption. Fortunately, these energy demands can be adequately met by solar energy systems, including photovoltaic panels and solar heating, ensuring energy self-sufficiency in arid zones. The proposed system demonstrates broad applicability across arid zones, including urban regions. To accommodate varying production demands, a general guideline is provided for scaling the HPS to the RAS size, enabling adjustment of the production capacity. It is suggested that the anaerobic digestion of plant wastes should also be incorporated in future research to improve the NUE and energy production further.

CRediT authorship contribution statement

Ze Zhu: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Uri Yogev:** Writing – review & editing, Supervision. **Amit Gross:** Writing – review & editing, Supervision, Funding acquisition. **Karel J. Keesman:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis.

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.

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Appendix A. Model parameters

Table A1
Initial model parameter settings.

Constant	Definition	Value	Unit	Source
η_{bf}	Efficiency biofilter	98	%	[36]
η_{DU}^{th}	Thermal efficiency desalination unit	250	kWh/m^3 distilled water	[14]
η_{dehum}^{e}	Electrical efficiency dehumidifiers	11.3	kWh/m^3 water recovered	[29]
η_{CHP}^{e}	Efficiency electrical energy production with CHP	35	%	[15]
η_{CHP}^{th}	Efficiency thermal energy production with CHP	50	%	[15]
η_{SHS}	Efficiency SHS	51	%	[49]
η_{PV}	Efficiency PV	21.1	%	[49]
ρ_{air}	Air density	1.16	kg/m^3	[14]
$C_{\rho,air}$	Specific heat of air	1000	J/kg/°C	[14]
ρ_{water}	Water density	1000	kg/m^3	[14]
$C_{\rho,water}$	Specific heat of water	4187	J/kg/°C	[14]
$r_{denit}^{passive}$	Efficiency passive denitrification	10	%	[36]
μ	Conversion factor of dry matter feed to solids in the RAS	25	%	[33]
$\alpha_f \beta_f \gamma_f$	Fish growth variables are determined by a fitting tool	0.0277; 0.4071; 0.0897	–	[4]
u	Airspeed at plant leaves	0.5	m/s	[18]
γ	Psychometric constant	0.0673	kPa/°C	[27]
τ	Transmittance greenhouse cover	0.8	–	[27]
α	Absorption ratio of incoming radiation by the greenhouse	0.7	–	[42]
λ	Latent heat of vaporization	2,260	kJ/kg	[42]
U_{AD}	Overall heat exchange coefficient for the anaerobic digester	0.75	W/m^2/°C	[5]
κ	Thermal conductivity of glass	0.96	W/m/°C	[29]
d	Cover thickness greenhouse	0.004	m	determined
H	Heat transfer coefficient	240	W/m^2/°C	[29]
$\overline{R}_{gas}$	Gas constant	8.314	J/K/mol	[29]
M	Molar weight of water	0.018	kg/mol	[29]
ζ	Biogas yield per mass unit of COD	0.150	m^3/kg COD	[5]
ε	Energy density of methane	35	MJ/m^3	[5]

Table A2
Growth stage duration with corresponding crop coefficient and plant height for indoor production of tomato in arid zones.

	Unit	Initial	Crop development	Midseason	Late season	Total/average
Duration	day	7	38	60	15	120
Kc	–	0.4	0.4–0.78*	0.78	0.78–0.46*	0.678
Plant height	m	0.1–2.5*		2.5		2.050

*Transitions are considered to be linear.

Appendix B. Greenhouse systems design in arid zones

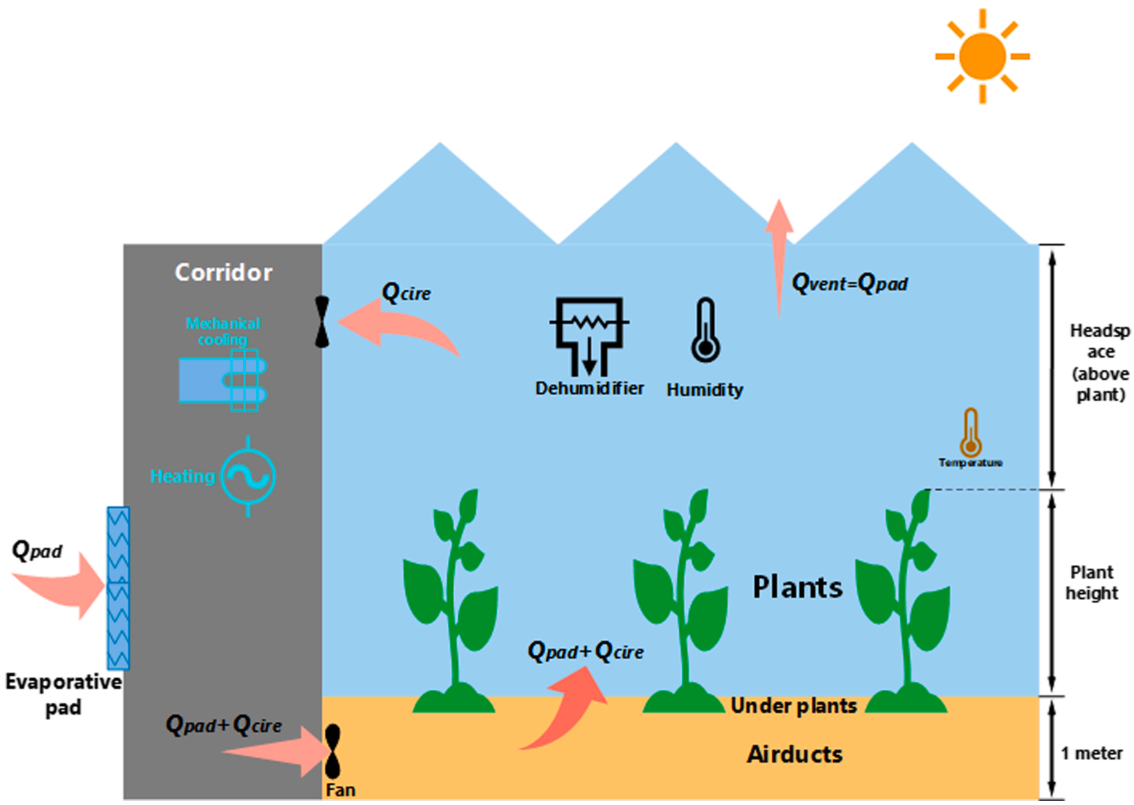

Fig. B1. The front view of the Venlo-type greenhouse used in the study with five different compartments: 1) Corridor, 2) Air ducts, 3) Air under plants, 4) Plants and 5) Air above plants. Each compartment in itself is considered homogenous in terms of mass and energy distribution. Possible air flows are indicated by arrows.

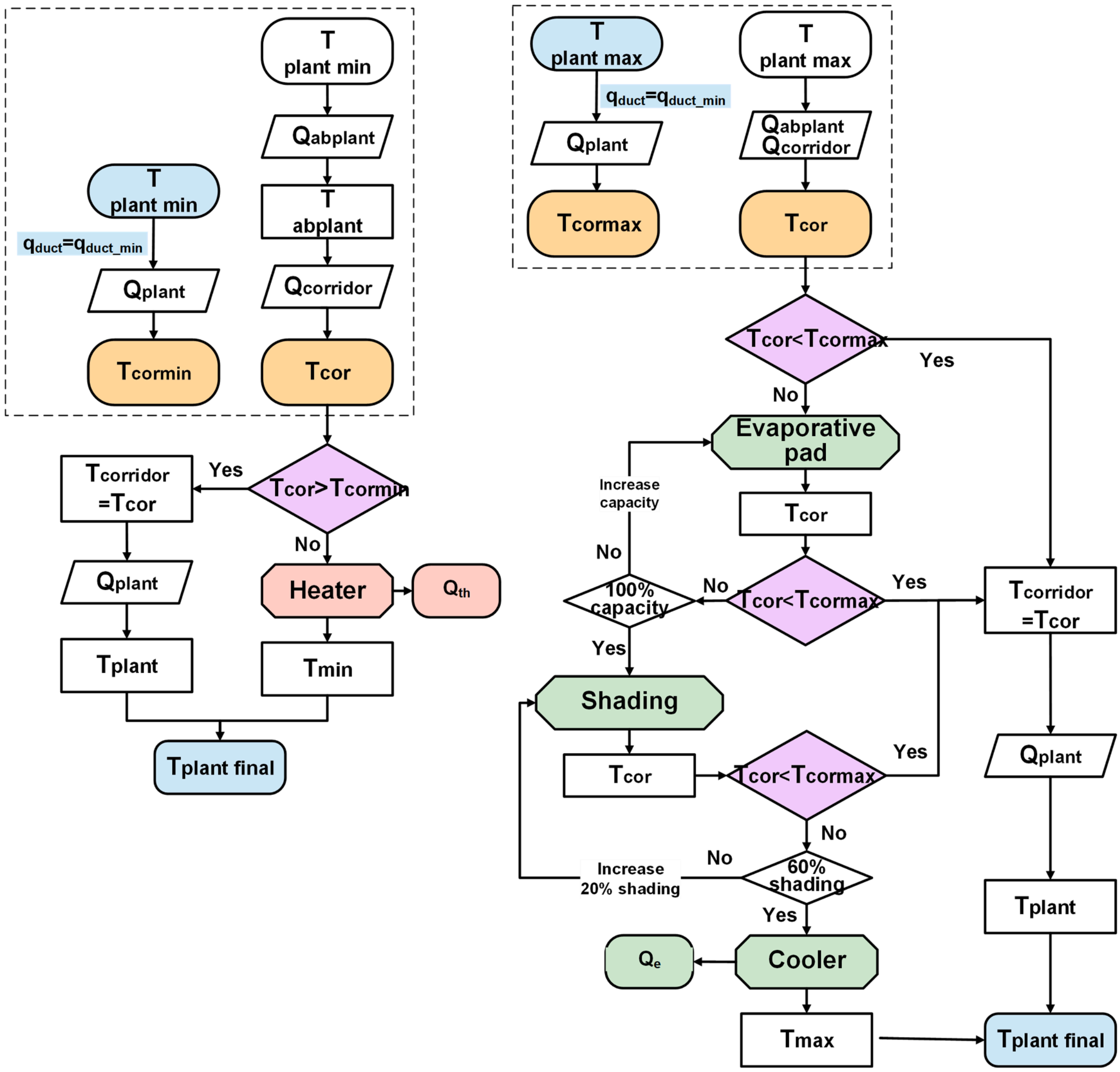

Fig B2. The intermittent control strategy of the greenhouse concerns temperature (*T*) and absolute humidity (*X*).

Table B1
Expert advice regarding required greenhouse conditions and optimal regulation systems.

Expert advisor	Optimal cooling method	Use of corridor and air duct	Corridor width (m)	Use of shading	T indoor for tomato (°C)	RH (%)	Humidity regulation	Wind speed at plant leaves (m/s)	Horizontal T gradient in greenhouse	Vertical T gradient at plants
#1	Evaporative cooling supported by mechanical cooling	yes	1.5–2	yes	>18	–	–	0.5	negligible	~1°C
#2	Evaporative cooling with pre desiccant treatment	yes	2.5	yes (indoor)	18–28	85 = max	Ventilation + active mechanical dehumidification	–	negligible	negligible
#3	Evaporative cooling supported by mechanical cooling	yes	2	no	18–28	80 = max	Ventilation + active mechanical dehumidification	–	negligible	<3°C (Depending on shading)
#4	Evaporative cooling supported by outdoor shading	yes	–	yes (outdoor)		–	–	–	–	–
#5	Evaporative cooling	yes	–	–	<28	–	Only by ventilation	–	–	–
Conclusion	Evaporative cooling supported by outdoor shading and mechanical cooling	yes	2	yes (outdoor)	18–28	80 = max	Ventilation + active mechanical dehumidification	0.5	negligible	~1°C

Table B2
Greenhouse dimensions as considered for the Israel APS, based on conventional large-scale corridor-based tomato greenhouses.

Section	Dimension	Value (m)
Overall greenhouse	Length	248
	Width	100
	Height	7
	Gutter height	5.5
Corridor	Width	2
	Height	5.5
Air ducts	Distance between duct cores	1.5
Plant ditches	Width	0.4
	Depth	0.2
Center path	Width	4

Table B3
Calculation strategy for the greenhouse temperature in the plant compartments.

Step number	Calculation steps for temperature in the plant compartment and required cooling in the corridor.
Heating	
1	Assume $T_{plants} = T_{plants}^{min}$, $q_{ducts} = q_{ducts}^{min}$, Based on the energy balance for the plant compartment alone, what is the required $T_{corridor}$ to keep the plants at T_{plants}^{min}?
2	Based on $T_{plants} = T_{plants}^{min}$, $q_{ducts} = q_{ducts}^{min}$, calculate $T_{aboveplants}$ and consecutively $T_{corridor}$. Compare $T_{corridor}$ with the calculated minimal required value in step 1. If q_{ducts}^{min} is sufficient to keep T_{plants} in range, step 3 is executed as last step, if not continue to step 4.
3	No mechanical heating is required. If also no cooling is required q_{ducts}^{min} is considered and T_{plants} can be calculated according to these settings.
4	Mechanical heating is required. The amount of heating required is calculated considering T_{plants}^{min} and q_{ducts}^{min}.
Cooling	
1	Assume $T_{plants} = T_{plants}^{max}$, $q_{ducts} = q_{ducts}^{min}$. Based on the energy balance for the plant compartment alone, what is the required $T_{corridor}$ to keep the plants at T_{plants}^{max}?
2	Based on $T_{plants} = T_{plants}^{max}$, $q_{ducts} = q_{ducts}^{min}$, calculate $T_{aboveplants}$ and consecutively $T_{corridor}$. Compare $T_{corridor}$ with the calculated maximal required value in step 1. If q_{ducts}^{min} is sufficient to keep T_{plants} in range, step 3 is executed as last step, if not continue to step 4.
3	No cooling is required. If also no heating is required q_{ducts}^{min} is considered and T_{plants} can be calculated according to these settings.
4	If cooling is needed, the evaporative pad system is activated, at 100 % or 50 % capacity according to the outdoor climate conditions. When the pad system is activated q_{ducts} is constant. If the Pad system is sufficient to keep T_{plants} in range, step 5 is executed as the last step. If not continue to step 6.
5	T_{plants} is calculated according to the settings in step 4.
6	Since evaporative cooling is not sufficient, shading is applied alongside. At first 20 % is applied. If this is not sufficient, 40 % is applied. If this is still not sufficient, 60 % is applied.
7	If the shading alongside the evaporative cooling system is sufficient to keep T_{plants} in range, the exact value for T_{plants} can be calculated according to the settings in step 4 and 6. If not, the required amount of mechanical cooling can be calculated considering T_{plants}^{max} and the settings in step 4 and 6.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inpa.2024.09.005.

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