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Climate-Dependent and Crop-Specific Operating Strategies for Greenhouse Evaporative Cooling in Hot-Arid and Coastal Environments

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Abstract

Greenhouse production in hot-arid and semi-arid regions faces a critical trade-off between achieving thermal suitability for crops and managing the high energy and water consumption of active cooling systems. This study evaluates the performance of fan-and-pad evaporative cooling across three contrasting Sudanese climates—Khartoum (hot-arid), El Obeid (semi-arid), and Port Sudan (hot-humid coastal)—by quantifying thermal suitability, Heating Stress Hours (HSH), and water-use efficiency for tomato and cucumber. Monthly simulations revealed distinct climatic responses: Khartoum and El Obeid maintained stable indoor temperatures but required substantial cooling water (peaking >800 kg m^{-2}), whereas Port Sudan exhibited lower cooling loads yet limited evaporative effectiveness due to high ambient humidity. Ventilation scenarios (20–200 m^3 m^{-2} h^{-1}) demonstrated diminishing thermal returns beyond threshold rates, with Marginal Water Cost (MWC) rising sharply. The practical operating ranges were identified as 100–140 m^3 m^{-2} h^{-1} for Khartoum and 100–120 m^3 m^{-2} h^{-1} for El Obeid; in Port Sudan, ventilation beyond 120 m^3 m^{-2} h^{-1} yielded minimal benefit. Pad efficiency (η) optimization was crop- and climate-dependent: tomato peaked at η = 90% (Khartoum) and η = 80% (El Obeid), while cucumber optima were lower (η = 70% and 60–70%, respectively), with overcooling reducing suitability at higher efficiencies. In Port Sudan, η ≈ 100% maximized suitability without overcooling due to thermodynamic humidity constraints. These findings demonstrate that maximizing cooling output does not ensure sustainable performance; instead, crop-specific, climate-calibrated operational strategies are essential for balancing thermal mitigation and resource conservation in protected agriculture.

Keywords: Crop-specific optimization; Thermal suitability; Water-use efficiency; Ventilation rate; Pad efficiency; Heating stress hours

Introduction

Greenhouse cultivation has become a cornerstone of sustainable agriculture by enhancing water-use efficiency, enabling year-round production, and improving crop productivity under controlled environmental conditions (Achour et al., 2021). However, maintaining optimal thermal conditions during hot seasons remains a major challenge, particularly in arid and semi-arid regions, where intensive cooling requirements can substantially increase both energy and water consumption (Allali et al., 2025). Greenhouse cooling technologies are generally classified as passive or active systems depending on climatic conditions and cooling requirements. Passive cooling strategies, such as natural ventilation and shading, reduce internal temperatures through air circulation and solar radiation attenuation without relying on energy-intensive mechanical devices (García et al., 2011). Although these approaches are environmentally favorable, they often prove insufficient during periods of extreme heat, limiting their applicability in hot climates (Brækken et al., 2023). In contrast, active cooling systems offer superior temperature-reduction capabilities but are associated with higher energy and water demands (Alshenaifi et al., 2023; Allali et al., 2025).

The increasing cooling demand in hot climates presents a significant sustainability challenge because active cooling systems may account for up to 50% of total greenhouse energy consumption during summer periods and can reach 70% in extremely hot regions, substantially increasing operational costs and environmental impacts (Mobsteker et al., 2016; Li et al., 2024). As global temperatures continue to rise, improving the efficiency of greenhouse cooling technologies has become a critical research priority for sustainable protected agriculture (Gooroochurn et al., 2022). Among active cooling technologies, evaporative cooling systems are widely adopted owing to their relatively low energy requirements and reduced environmental footprint (Allali et al., 2025). These systems utilize the latent heat of water evaporation to lower air temperature and are commonly classified into Direct Evaporative Cooling (DEC), Indirect Evaporative Cooling (IDEC), and hybrid cooling systems. Fan-and-pad evaporative cooling systems, a widely used form of DEC, have been extensively studied and optimized over the past two decades. Under peak summer conditions, these systems can reduce indoor air temperature by 15–25 °C compared with naturally ventilated greenhouses, achieving cooling efficiencies ranging from 57% to 77% (Saberian et al., 2020). Cooling performance and temperature uniformity are strongly influenced by ventilation rates. Higher ventilation rates (1 ACM) provide lower average temperatures and improved spatial temperature distribution compared with lower ventilation rates (0.5 ACM), although these improvements are accompanied by increased water and energy consumption (Al-Helal et al., 2007).

Despite their excellent cooling performance, fan-and-pad systems are associated with considerable resource consumption. Water usage typically ranges from 8.4 to 14 $L \cdot m^{-2}$ of greenhouse floor area depending on ventilation intensity, while energy consumption increases proportionally with

airflow requirements (Al-Helal et al., 2007). Comparative studies have demonstrated that fan-and-pad systems generally provide more stable thermohygrometric conditions than alternative evaporative cooling technologies such as misting systems, albeit at the expense of greater water demand (Hegazy et al., 2022). More recently, the integration of solar photovoltaic (PV) systems has emerged as a promising approach for reducing dependence on grid electricity and enhancing the sustainability of greenhouse cooling operations (Omar et al., 2021).

Optimizing evaporative cooling systems is essential for improving both environmental sustainability and economic performance. Operational optimization strategies include variable-speed fan control based on real-time environmental conditions and water recycling technologies, both of which can significantly reduce energy and water consumption (Allali et al., 2025; Kim et al., 2007). In addition, system design parameters—including evaporative pad dimensions, fan placement, fan spacing, and air velocity—play critical roles in determining cooling efficiency and indoor climate uniformity. For example, elevated fan placement preferentially cools the upper canopy while increasing ceiling humidity, whereas lower fan placement improves temperature uniformity but may necessitate supplemental humidification (Saberian et al., 2020).

Although evaporative cooling systems have been extensively investigated, most previous studies have focused primarily on maximizing cooling efficiency and temperature reduction. Comparatively little attention has been given to crop-specific optimization that simultaneously considers thermal suitability, heat stress mitigation, and resource consumption across different climatic conditions. Furthermore, the optimal cooling efficiency may vary substantially among crops and locations, indicating that maximizing cooling performance does not necessarily correspond to the most sustainable or economically viable operating strategy. Consequently, determining crop-specific cooling requirements and identifying optimal evaporative cooling efficiencies remain critical challenges for sustainable greenhouse production in hot-arid and semi-arid environments. This study aims to evaluate the performance of fan-and-pad evaporative cooling systems across three contrasting climatic regions in Sudan—Khartoum (hot-arid), El Obeid (semi-arid), and Port Sudan (hot-humid coastal)—to determine crop-specific and climate-dependent optimal operating strategies. Specifically, the study seeks to: (i) quantify the effects of ventilation rate and pad efficiency on indoor thermal conditions, cooling water consumption, and crop thermal suitability; (ii) identify practical operating thresholds that maximize the reduction of Heating Stress Hours (HSH) while minimizing the Specific Cooling Water Requirement (SCWR) and Marginal Water Cost (MWC); and (iii) establish location-specific and crop-specific recommendations for sustainable greenhouse management that balance thermal performance with water-use efficiency, moving beyond the conventional approach of maximizing cooling output toward optimized, resource-efficient climate control.

Model description

A dynamic energy-balance model was developed to simulate the thermal behavior of a fan-and-pad evaporatively cooled greenhouse under the contrasting climatic conditions of Khartoum, El Obeid, and Port Sudan. The greenhouse was configured as a single-span gable-roof structure, oriented east–west, and covered with a polyethylene film (U-value ≈ 6.5 W m^{-2} K^{-1}). The structural dimensions and thermophysical properties were kept constant across all locations to isolate the climatic effects on system performance.

Hourly typical meteorological year (TMY) data—including dry-bulb temperature, relative humidity, wind speed, and global solar radiation—were used as boundary conditions. The indoor air temperature was computed from a quasi-steady-state energy balance that accounts for convective heat gains from solar radiation transmitted through the cover, conductive heat exchange with the ambient air, and latent heat removal via evaporative cooling and crop transpiration. The greenhouse air was treated as a well-mixed single zone, and infiltration was assumed negligible relative to the forced ventilation rate.

The evaporative cooling system was modelled as a counter-flow fan-and-pad unit; the inside air temperature was determined using the pad efficiency equation:

$$T_{gh} = \frac{h_{gh} - W_{pad} * r_0}{c_{pa} + W_{pad} * c_{pv}} \quad (1)$$

Where:

T_{gh} : Greenhouse air temperature(°C),

h_{gh}: Greenhouse moist-air enthalpy (kJ kg^{-1} dry air)

W_{pad}: Humidity ratio after pad (kg kg^{-1} dry air)

r_0 :Latent heat of vaporization (kJ kg^{-1})

c_{pa}: Specific heat of dry air (kJ kg^{-1} °C^{-1})

c_{pv} : Specific heat of water vapor (kJ kg^{-1} °C^{-1})

Crop thermal suitability was assessed against species-specific optimum temperature ranges: tomato (18–26 °C) and cucumber (22–30 °C). For each simulated hour, the indoor temperature was classified as optimal, sub-optimal, or heat-stressed. From these classifications, three key performance indicators were derived: (i) Heating Stress Hours (HSH)—the annual count of hours exceeding the upper optimum threshold; (ii) Climate Suitability Ratio (CSR)—the percentage of operating hours within the optimum range; and (iii) Specific Cooling Water Requirement (SCWR)—the ratio of total annual cooling water consumption to the number of optimal thermal hours (kg m^{-2} h^{-1}). Additionally, the Marginal Water Cost (MWC) (kg h) was calculated between consecutive ventilation increments to quantify the trade-off between additional water use and heat-stress reduction.

Operating Hours:

$$HOp = \sum_{t=1}^{8760} I(T_{OUT} > 27) \quad (2)$$

Thermal Suitability Assessment (Cumulative), which happens in the range of Operating Hours:

- **Optimal Hours (OHop)** :

$$\text{OHop_tomato} = \sum I(18 \leq T_{gh} \leq 27) \text{ , OHop_cucumber} = \sum I(22 \leq T_{gh} \leq 30) \quad (3)$$

- **Crop Suitability Ratio:**

$$\text{CSR\%} = \frac{\text{OHop_tomato}}{\text{HOp}}, \frac{\text{OHop_cucumber}}{\text{HOp}} \quad (4)$$

- **Heat Stress Hours (HSHop):**

$$\text{HSHop_tomato} = \sum I(T_{gh} > 27) \text{ , HSHop_cucumber} = \sum I(T_{gh} > 30) \quad (5)$$

- **Marginal Water Cost**

$$\text{MWC} = \frac{W2-W1}{HSH1-HSH2} \text{ (kg h)} \quad (6)$$

- **Specific Cooling Water Requirement**

$$\text{SCWR} = \frac{W}{\text{OHop}} \text{ (kg m}^{-2}\text{h}^{-1}\text{)} \quad (7)$$

Two parametric scenario sets were executed: (1) variable ventilation rate at a fixed pad efficiency of 80%, and (2) variable pad efficiency (60–100%) at a fixed ventilation rate of 180 $m^3\ m^{-2}\ h^{-1}$. All simulations were run on an annual basis (8,760 h), and the outputs were aggregated to monthly and annual totals for comparative analysis across the three climatic zones.

Results and discussion

Climatic variation in cooling demand and water consumption

Figure 1 compares the monthly indoor and outdoor air temperatures for Khartoum, El Obeid, and Port Sudan under the simulated evaporative cooling system. Clear differences were observed among the three climatic regions. Khartoum and El Obeid maintained relatively stable indoor temperatures throughout the year despite experiencing high outdoor temperatures, whereas Port Sudan exhibited higher indoor temperatures during the summer months even though its outdoor temperatures were generally lower. These findings align with Achour et al. (2021), who emphasized that greenhouse cultivation enhances water-use efficiency and enables year-round production under controlled environmental conditions. However, Allali et al. (2024) noted that maintaining optimal thermal conditions during hot seasons remains a major challenge in arid and semi-arid regions, where intensive cooling requirements substantially increase both energy and water consumption. García et al. (2011) demonstrated that passive cooling strategies, such as natural ventilation and shading, reduce internal temperatures through air circulation and solar radiation attenuation without relying on energy-intensive mechanical devices, although Brækken et al. (2023) cautioned that these approaches often prove insufficient during periods of extreme heat, limiting their applicability in hot climates. Seasonal variations also differed among locations, with the highest indoor

temperatures occurring during the hot season and lower temperatures during winter. Overall, the results indicate that the cooling system responded differently under the three climatic conditions, producing distinct annual temperature profiles that formed the basis for the subsequent evaluation of thermal suitability, cooling water consumption, and system performance.

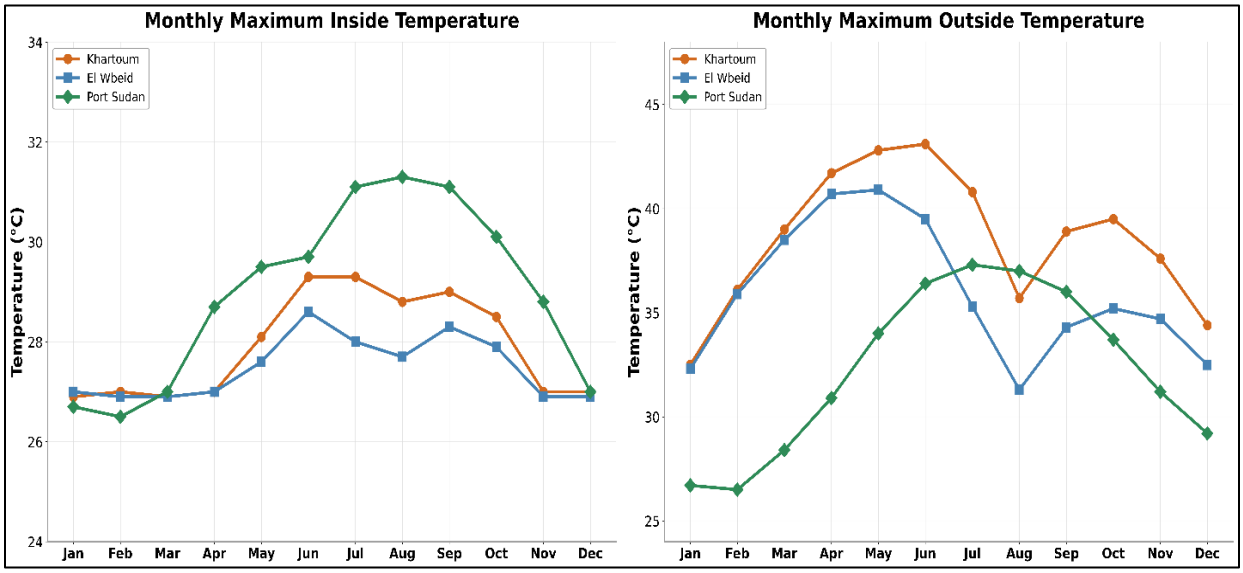

Figure 1. Monthly indoor and outdoor air temperatures for Khartoum, El Obeid, and Port Sudan under simulated evaporative cooling.

Figure 2 presents the monthly cooling load, expressed as the difference between outdoor and indoor air temperatures, for the three study locations. Khartoum exhibited the highest cooling loads throughout the year, with peak values of approximately 14.7**°C** during April and May, followed by a gradual decline toward late summer. El Obeid showed a similar seasonal pattern but with lower peak cooling loads, reaching approximately 13.3°C in May before decreasing rapidly during the following months. In contrast, Port Sudan consistently recorded the lowest cooling loads, with a maximum of approximately 6.2°C in June and comparatively small seasonal variation. These substantial differences in annual cooling demand reflect the increasing cooling demand in hot climates reported by Mobsteker et al. (2016) and Li et al. (2024), who found that active cooling systems may account for up to 50% of total greenhouse energy consumption during summer periods and can reach 70% in extremely hot regions, substantially increasing operational costs and environmental impacts. As global temperatures continue to rise, Gooroochurn et al. (2022) emphasized that improving the efficiency of greenhouse cooling technologies has become a critical research priority for sustainable protected agriculture. The present results provide the basis for evaluating the corresponding variations in thermal suitability, cooling water consumption, and pad efficiency presented in the following sections.

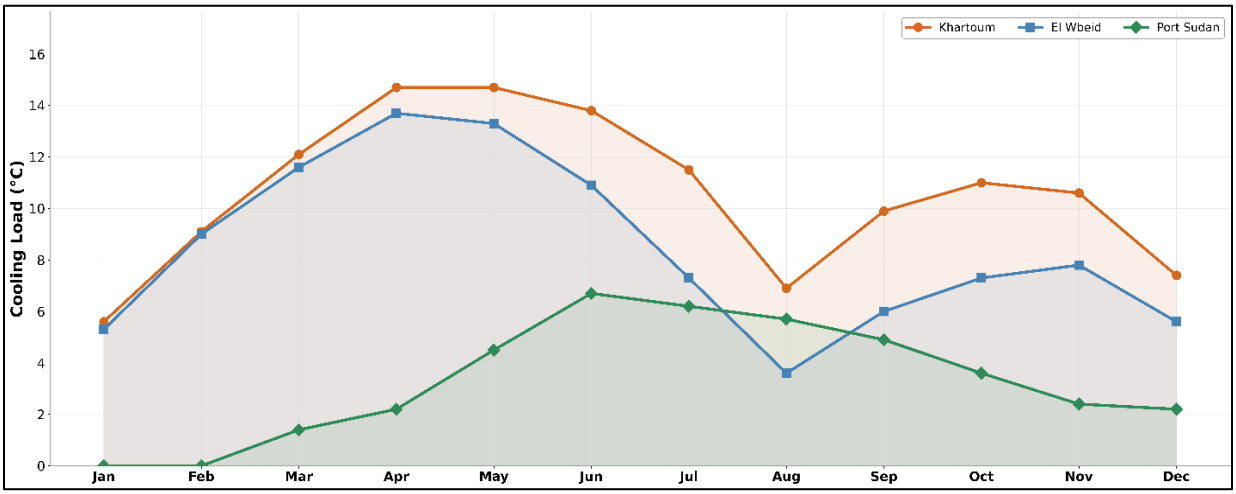

Figure 2. Monthly cooling load (outdoor–indoor air temperature difference) for Khartoum, El Obeid, and Port Sudan.

Figure 3 illustrates the monthly evaporative cooling water consumption for the three climatic regions. Clear differences were observed among the study locations. Khartoum and El Obeid exhibited the highest monthly water consumption, with peak values exceeding 800 kg m^{-2} during the hottest months, whereas Port Sudan recorded a substantially lower maximum of 418.5 kg m^{-2} in July. Seasonal variations also differed among locations. Peak water consumption occurred during April–May in Khartoum, March–April in El Obeid, and June–July in Port Sudan, reflecting differences in seasonal climatic conditions. Khartoum and El Obeid showed larger seasonal fluctuations in water demand, while Port Sudan exhibited a lower and more uniform annual pattern. These findings are consistent with Al-Helal et al. (2007), who reported that water usage for fan-and-pad systems typically ranges from 8.4 to 14 L m^{-2} of greenhouse floor area depending on ventilation intensity, while energy consumption increases proportionally with airflow requirements. Comparative studies by Hegazy et al. (2022) have demonstrated that fan-and-pad systems generally provide more stable thermohydrometric conditions than alternative evaporative cooling technologies such as misting systems, albeit at the expense of greater water demand. Overall, the results demonstrate distinct monthly water consumption profiles among the three climatic regions and provide the basis for evaluating the corresponding differences in annual thermal suitability (CSR), Specific Cooling Water Requirement (SCWR), and evaporative cooling performance presented in the following sections.

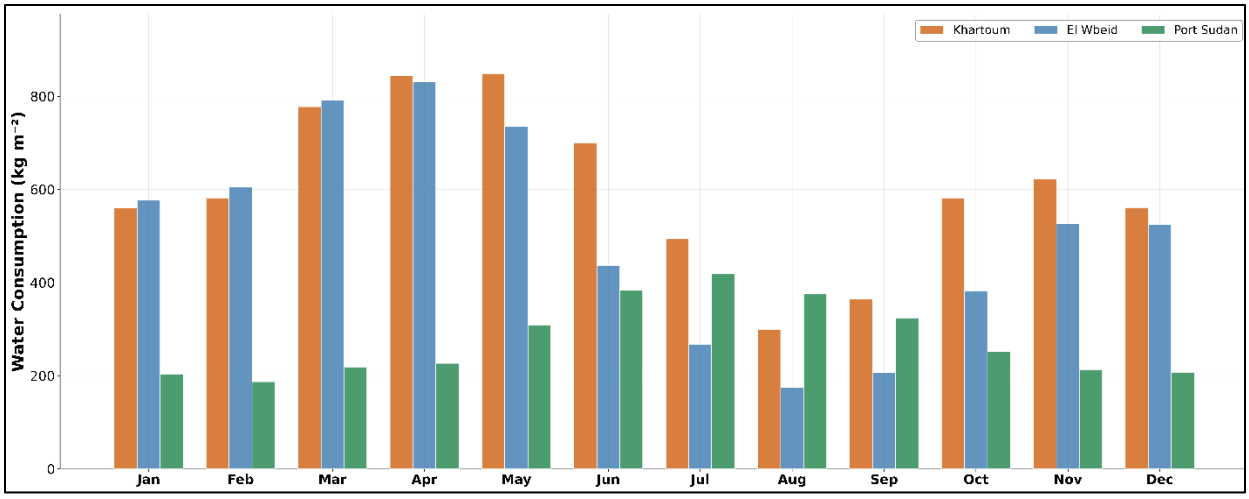

Figure 3. Monthly evaporative cooling water consumption for Khartoum, El Obeid, and Port Sudan.

Figure 4 compares the monthly cooling water consumption and cooling load for the three study locations. In Khartoum, both variables followed similar seasonal patterns, with maximum values occurring during April–May before declining toward late summer. El Obeid exhibited a comparable trend, although peak water consumption preceded the maximum cooling load by approximately one month. In contrast, Port Sudan showed lower values for both variables throughout the year, with peak water consumption and cooling load occurring during June–July**.** The seasonal agreement between cooling water consumption and cooling load indicates that water demand generally followed the greenhouse cooling requirement, although the magnitude and timing of both variables differed among the three climatic regions. These differences provide the basis for the subsequent evaluation of annual thermal suitability (CSR), Specific Cooling Water Requirement (SCWR), and the overall performance of the evaporative cooling system.

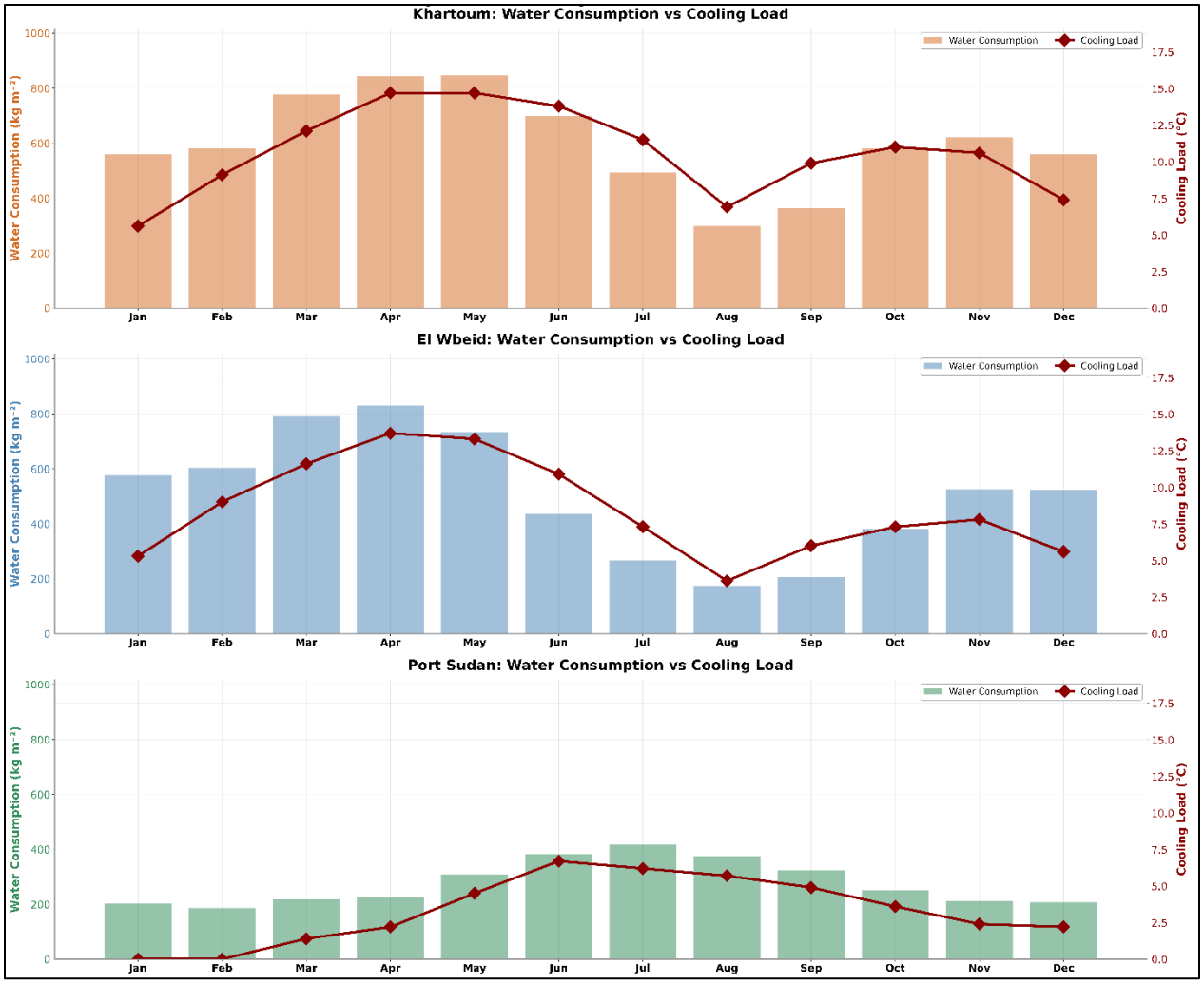

Figure 4. Comparison of monthly cooling water consumption and cooling load for Khartoum, El Obeid, and Port Sudan.

The effect of ventilation rate

Increasing ventilation substantially reduced Heating Stress Hours (HSH), but the associated increase in cooling water consumption was not proportional, resulting in diminishing thermal returns at higher ventilation rates. In Khartoum, Annual cooling water consumption increased linearly with ventilation rate, indicating that greater airflow continuously enhanced evaporation through the wetted cooling pads. This response agrees with Sabeh et al. (2006), who reported that cooling water use in pad-and-fan systems increases proportionally with the ventilation (air exchange) rate under semi-arid greenhouse conditions. However, the thermal response was not proportional. While increasing ventilation from 20 to 100 $m^3 m^{-2} h^{-1}$ markedly reduced Heating Stress Hours (HSH) for both tomato and cucumber, further increases produced progressively smaller reductions despite continued water consumption. Recent reviews of greenhouse cooling systems highlight similar diminishing-return behavior, where operating beyond the optimum airflow mainly increases resource consumption

without equivalent thermal gains (Allali et al., 2025). The present study extends these findings by quantifying the ventilation threshold at which additional water provides only marginal reductions in crop heating stress under Sudanese climatic conditions. The design-related influences on this threshold are consistent with Saberian et al. (2020), who emphasized that pad dimensions, fan placement, and air velocity critically determine cooling efficiency and indoor climate uniformity.

Crop response differed considerably between the two crops. Cucumber was more responsive to increased ventilation, with HSH declining to zero at 160 $m^3\ m^{-2}\ h^{-1}$, whereas tomato still experienced 945 h of heating stress at the same ventilation rate. Consequently, the Marginal Water Cost (MWC) increased markedly at higher ventilation rates, indicating that progressively larger amounts of cooling water were required to eliminate each additional hour of heating stress. For example, increasing ventilation from 160 to 180 $m^3\ m^{-2}\ h^{-1}$ required an additional 803.7 $kg\ m^{-2}\ yr^{-1}$ of cooling water while reducing tomato HSH by only 118 h, with no further improvement for cucumber. This sharp increase in marginal water requirement demonstrates that additional airflow beyond 140 $m^3\ m^{-2}\ h^{-1}$ yields limited thermal benefit relative to the extra water consumed. Therefore, the practical operating range for the evaporative cooling system in Khartoum is 100–140 $m^3\ m^{-2}\ h^{-1}$**,** where most of the reduction in heating stress is achieved while maintaining efficient cooling water use. This operating range supports the optimization approach advocated by Kim et al. (2007), who demonstrated that variable-speed fan control and water recycling technologies can significantly reduce energy and water consumption without compromising cooling effectiveness.

Table 1. Ventilation rate effects on water consumption, HSH, and MWC for tomato and cucumber in Khartoum**.**

Ventilation ($m^3\ m^{-2}\ h^{-1}$)	Water consumption ($kg \cdot m^{-2}\ yr^{-1}$)	HSH-Tomato (h)	HSH-Cucumber (h)	ΔHSH-Tomato (h)	MWC-Tomato ($kg\ h^{-1}$)	ΔHSH-Cucumber (h)	MWC-Cucumber ($kg\ h^{-1}$)	Tomato % Baseline	Cucumber % Baseline
20	803.7	3145	2928	–	–	–	–	59.4	77.5
40	1607.5	2734	2064	411	1.96	864	0.93	51.6	54.6
60	2411.2	2069	1260	665	1.21	804	1.00	39.1	33.4
80	3214.9	1672	818	397	2.02	442	1.82	31.6	21.7
100	4018.7	1382	467	290	2.77	351	2.29	26.1	12.4
120	4822.4	1176	123	206	3.90	344	2.34	22.2	3.3
140	5626.1	1054	6	122	6.59	117	6.87	19.9	0.2
160	6429.9	945	0	109	7.37	6	133.97	17.8	0
180	7233.6	827	0	118	6.81	0	–	15.6	0
200	8037.3	728	0	99	8.12	0	–	13.7	0
Outside-HSH		5295	3778	–	–	–	–	100	100

El Obeid exhibited the same linear relationship between ventilation rate and annual cooling water consumption observed in Khartoum, with water demand increasing from 673.0 to 6,729.6 kg m^{-2} yr^{-1} as ventilation increased from 20 to 200 m^3 m^{-2} h^{-1} (Table 2). However, annual water consumption remained consistently 16–19% lower than in Khartoum, reflecting the lower evaporative demand under the relatively milder climatic conditions. The climatic modulation of water demand is consistent with Al-Helal et al. (2007), who found that evaporative demand and ventilation intensity directly govern resource consumption in pad-and-fan systems. Similar to Khartoum, increasing ventilation substantially reduced Heating Stress Hours (HSH), although the reduction became progressively smaller at higher ventilation rates, indicating diminishing thermal returns. Increasing ventilation from 20 to 100 m^3 m^{-2} h^{-1} resulted in the largest decrease in HSH for both crops, whereas further increases produced only modest additional improvements despite continued increases in water consumption.

Crop response differed considerably between tomato and cucumber. Cucumber responded rapidly to increased ventilation, with HSH declining to zero at 120 m^3 m^{-2} h^{-1}, whereas tomato still experienced 921 h of heating stress at the same ventilation rate. Consequently, the Marginal Water Cost (MWC) increased as ventilation rate increased, indicating that progressively larger quantities of cooling water were required to eliminate each additional hour of heating stress. For example, increasing ventilation from 160 to 180 m^3 m^{-2} h^{-1} required an additional 672.9 kg m^{-2} yr^{-1} of cooling water while reducing tomato HSH by only 173 h, with no further improvement for cucumber. Compared with Khartoum, the lower MWC values in El Obeid indicate more efficient utilization of cooling water, particularly at moderate ventilation rates. Nevertheless, the increasing marginal water requirement at higher ventilation rates confirms the onset of diminishing returns. Therefore, the practical operating range for the evaporative cooling system in El Obeid is 100–120 m^3 m^{-2} h^{-1}, where most of the reduction in heating stress is achieved while maintaining efficient cooling water use. As Kim et al. (2007) demonstrated, such location-specific operating ranges can be maintained through operational optimization strategies that adjust airflow in response to real-time environmental conditions rather than fixed maximum rates.

Table 2. Ventilation rate effects on water consumption, HSH, and MWC for tomato and cucumber in El Obeid.

Ventilation (m^3 m^{-2} h^{-1})	Water ($kg \cdot m^{-2}$ yr^{-1})	HSH-Tomato (h)	HSH-Cucumber (h)	ΔHSH-Tomato	MWC-Tomato (kg h^{-1})	ΔHSH-Cucumber	MWC-Cucumber (kg h^{-1})	Tomato % Baseline	Cucumber % Baseline
20	673	2859	2691	-	-	-	-	72.5	101.7
40	1345.9	2488	1870	371	1.81	821	0.82	63.1	70.6
60	2018.9	1806	1048	682	0.99	822	0.82	45.8	39.6
80	2691.8	1421	514	385	1.75	534	1.26	36	19.4
100	3364.8	1126	104	295	2.28	410	1.64	28.5	3.9
120	4037.7	921	0	205	3.28	104	6.47	23.3	0
140	4710.7	757	0	164	4.1	0	-	19.2	0
160	5383.7	611	0	146	4.61	0	-	15.5	0
180	6056.6	438	0	173	3.89	0	-	11.1	0
200	6729.6	312	0	126	5.34	0	-	7.9	0
Outside-HSH		3946	2647	-	-	-	-	100	100

Port Sudan exhibited the lowest annual cooling water consumption among the three locations, increasing linearly from 368.6 to 3,686.3 kg m^{-2} yr^{-1} as ventilation increased from 20 to 200 m^3 m^{-2} h^{-1} (Table 3). Despite the substantially lower water consumption, the reduction in Heating Stress Hours (HSH) was considerably smaller than that observed in Khartoum and El Obeid, indicating that increasing ventilation alone was less effective under the humid coastal climate. Similar to the other locations, increasing ventilation from 20 to 100 m^3 m^{-2} h^{-1} produced the largest reduction in HSH, whereas additional increases resulted in progressively smaller improvements despite continued increases in water consumption, demonstrating diminishing thermal returns.

Crop response also differed from the inland locations. Although cucumber showed greater sensitivity to ventilation than tomato, HSH remained at 281 h even at the maximum ventilation rate of 200 m^3 m^{-2} h^{-1}, while tomato still experienced 2,963 h of heating stress. Consequently, the Marginal Water Cost (MWC) increased with ventilation rate, indicating that progressively larger quantities of cooling water were required to eliminate each additional hour of heating stress. For example, increasing ventilation from 160 to 180 m^3 m^{-2} h^{-1} required an additional 368.6 kg m^{-2} yr^{-1} of cooling water while reducing tomato HSH by only 64 h and cucumber HSH by 131 h. Compared with Khartoum and El Obeid, the smaller reduction in HSH despite increased ventilation suggests that the humid coastal climate limits the effectiveness of evaporative cooling. Therefore, increasing ventilation beyond 100–120 m^3 m^{-2} h^{-1} provides only limited additional thermal benefit, indicating that further improvements in greenhouse climate control would likely require complementary cooling or environmental control strategies rather than increased ventilation alone. This need for complementary strategies rather than single-approach solutions supports the conclusions of Brækken et al. (2023) regarding the inadequacy of standalone passive cooling during extreme heat events, and aligns with García et al. (2011), who found that natural ventilation and shading often prove insufficient without complementary active measures.

Table 3. Ventilation rate effects on water consumption, HSH, and MWC for tomato and cucumber in Port Sudan.

Ventilation (m^3 m^{-2} h^{-1})	Water ($kg \cdot m^{-2}$ yr^{-1})	HSH-Tomato (h)	HSH-Cucumber (h)	ΔHSH-Tomato	MWC-Tomato (kg h^{-1})	ΔHSH-Cucumber	MWC-Cucumber (kg h^{-1})	Tomato % Baseline	Cucumber % Baseline
20	368.6	3993	2809	-	-	-	-	67.1	70.7
40	737.3	3886	2382	107	3.45	427	0.86	65.3	60
60	1105.9	3769	1967	117	3.15	415	0.89	63.4	49.5
80	1474.5	3631	1528	138	2.67	439	0.84	61.1	38.5
100	1843.2	3466	1234	165	2.23	294	1.25	58.3	31.1
120	2211.8	3305	957	161	2.29	277	1.33	55.6	24.1
140	2580.4	3171	721	134	2.75	236	1.56	53.3	18.1
160	2949.1	3087	503	84	4.39	218	1.69	51.9	12.7
180	3317.7	3023	372	64	5.76	131	2.81	50.8	9.4
200	3686.3	2963	281	60	6.14	91	4.05	49.8	7.1
Outside-HSH		5947	3973	-	-	-	-	100	100

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The 160–180 $m^3\ m^{-2}\ h^{-1}$ ventilation interval provides a useful benchmark for evaluating the efficiency of increasing ventilation under contrasting climatic conditions. In Khartoum, this interval marks the onset of pronounced diminishing returns, with the Marginal Water Cost (MWC) increasing to 6.81 kg h^{-1}, indicating that additional water consumption produced only limited reductions in Heating Stress Hours (HSH). In El Obeid, MWC also increased to 3.89 kg h^{-1}, confirming that even under more favorable climatic conditions, the thermal benefit of increasing ventilation declined at higher airflow rates. In Port Sudan, the increase in ventilation from 160 to 180 $m^3\ m^{-2}\ h^{-1}$ required additional cooling water while producing only modest reductions in HSH, with tomato MWC reaching 5.76 kg h^{-1}. These results demonstrate that increasing ventilation does not necessarily result in proportional improvements in greenhouse thermal performance. Instead, the relationship between ventilation, cooling water consumption, and HSH is strongly influenced by local climatic conditions. Consequently, the optimum ventilation rate should be selected according to the location-specific balance between thermal improvement and cooling water demand. These location-specific thresholds reflect the systematic findings of Allali et al. (2025), who emphasized that operating beyond optimum airflow increases resource consumption without equivalent thermal gains, and align with Omar et al. (2021), who highlighted the potential of integrating renewable energy to support sustainable cooling operations tailored to local climatic conditions. Based on the present results, the recommended operating ranges are 100–140 $m^3\ m^{-2}\ h^{-1}$ for Khartoum, 100–120 $m^3\ m^{-2}\ h^{-1}$ for El Obeid, whereas in Port Sudan increasing ventilation beyond 100–120 $m^3\ m^{-2}\ h^{-1}$ provided only limited additional thermal benefit, suggesting that supplementary climate-control measures may be required to further improve greenhouse performance. Operational optimization strategies include variable-speed fan control based on real-time environmental conditions and water recycling technologies, both of which can significantly reduce energy and water consumption (Allali et al., 2025; Kim et al., 2007).

The effect of pad efficiency (η)

Table 4 summarizes the influence of pad efficiency on annual evaporative cooling water consumption, crop thermal suitability, and the Specific Cooling Water Requirement (SCWR) in Khartoum. Increasing pad efficiency from 60% to 100% resulted in a nearly linear increase in annual cooling water consumption, from 5,372.1 to 9,132.4 kg m^{-2}, representing approximately a 70% increase. This trend reflects the greater quantity of water that must evaporate to achieve higher cooling efficiencies and maintain lower supply-air temperatures. The improvement in crop thermal suitability, however, was not proportional to the increase in water consumption. For tomato, the number of optimal thermal hours increased from 3,258 to 4,238 h as pad efficiency increased from 60% to 90%, corresponding to an increase in the Climate Suitability Ratio (CSR) from 61.5% to 80.0%. Further increasing efficiency to 100% reduced both HOp and CSR, indicating that excessive cooling shifted greenhouse temperatures below the optimum range. In contrast, cucumber reached its maximum thermal suitability at η = 70%, where HOp and CSR attained 3,148 h and 83.3%, respectively. Beyond this efficiency, both indicators declined steadily despite the continued increase in cooling capacity, demonstrating that cucumber is more susceptible to overcooling because of its higher optimum temperature range (22–30°C).

The Specific Cooling Water Requirement (SCWR) further illustrates the trade-off between cooling performance and water demand. For tomato, SCWR increased from 1.6 to 2.4 kg m^{-2}

h^{-1} as pad efficiency increased from 60% to 100%, indicating that progressively larger quantities of water were required to generate each hour of optimum thermal conditions. A similar but more pronounced trend was observed for cucumber, where SCWR increased from 2.0 to 6.1 kg m^{-2} h^{-1}. This sharp increase indicates that additional cooling water at high efficiencies produced progressively fewer suitable thermal hours, particularly after the optimum efficiency had already been exceeded.

Overall, Table 4 demonstrates that maximizing pad efficiency does not necessarily maximize greenhouse performance. While water consumption increased almost linearly with efficiency, thermal suitability reached an optimum before the maximum efficiency was attained. Consequently, the optimum operating efficiency is crop-dependent, with approximately η = 90% providing the best balance between cooling performance and water requirement for tomato, whereas η = 70% represents the most efficient operating point for cucumber under the climatic conditions of Khartoum. This crop-dependent optimum supports the design-parameter analysis presented by Saberian et al. (2020), who found that system configuration must be tailored to crop-specific thermal requirements rather than maximized for cooling output alone.

Table 4. Pad efficiency effects on water consumption, HOp, SCWR, and CSR for tomato and cucumber in Khartoum.

Efficiency (η)	Water consumption ($kg \cdot m^{-2}\ yr^{-1}$)	HOp-Tomato (h)	HOp-Cucumber (h)	SCWR-Tomato ($kg \cdot m^{-2} \cdot h^{-1}$)	SCWR-Cucumber ($kg \cdot m^{-2} \cdot h^{-1}$)	CSR-Tomato (%)	CSR-Cucumber (%)
η 60	5372.1	3258	2740	1.6	2.0	61.5	72.5
η70	6298.3	3743	3148	1.7	2.0	70.7	83.3
η80	7233.6	4051	2755	1.8	2.6	76.5	72.9
η 90	8178.2	4238	2069	1.9	4.0	80.0	54.7
η100	9132.4	3758	1509	2.4	6.1	71.0	39.9

El Obeid exhibited the same general response observed in Khartoum, with annual evaporative cooling water consumption increasing almost linearly from 4,501 to 7,641 kg m^{-2} as pad efficiency increased from 60% to 100% (Table 5). However, total water consumption remained 16–19% lower than in Khartoum, reflecting the lower evaporative demand under the relatively milder climatic conditions of El Obeid. Despite this reduction in water demand, improvements in thermal suitability were not proportional to the increase in cooling efficiency. For tomato, optimal thermal hours increased from 2,422 h at η = 60% to a maximum of 3,178 h at η = 80%, after which further increases in pad efficiency produced no additional benefit. HOp remained virtually unchanged between η = 80% and 90% (3178 vs. 3171 h) before declining sharply to 2,607 h at η = 100%. This plateau indicates that the additional cooling achieved beyond η = 80% no longer improved the greenhouse thermal environment but instead promoted overcooling. In contrast, cucumber exhibited a continuous decline in optimal thermal hours from 2,298 h at η = 60% to 1,039 h at η = 100%, indicating that the higher cooling intensity rapidly shifted greenhouse temperatures below its optimum range (22–

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30°C). The Climate Suitability Ratio (CSR) confirms this behavior. Tomato CSR increased from 61.4% at η = 60% to 80.5% at η = 80%, after which no meaningful improvement occurred, remaining almost unchanged at η = 90% (80.4%) before decreasing to 66.1% at η = 100%. Cucumber showed an even stronger response, with CSR decreasing steadily from **86.8%** at η = 60% to **39.3%** at η = 100%. These results indicate that, under the relatively moderate climate of El Obeid, excessive evaporative cooling becomes detrimental at lower pad efficiencies than in Khartoum because the greenhouse temperature reaches the lower boundary of the optimum range more rapidly.

The Specific Cooling Water Requirement (SCWR) provides additional insight into cooling-water utilization. Tomato SCWR remained almost constant (approximately 1.9 kg m^{-2} h^{-1}) between η = 60% and 80%, indicating that improvements in cooling efficiency were accompanied by proportional gains in optimal thermal hours. Beyond η = 80%, however, SCWR increased to 2.9 kg m^{-2} h^{-1}, demonstrating that additional cooling water generated progressively fewer suitable thermal hours. The effect was considerably stronger for cucumber, where SCWR increased from 2.0 to 7.4 kg m^{-2} h^{-1}**,** indicating a more than threefold increase in the amount of cooling water required to obtain one hour of optimal thermal conditions. This sharp deterioration occurred because increasing pad efficiency beyond the optimum mainly increased cold stress rather than improving thermal suitability. Overall, Table 5 demonstrates that the optimum operating efficiency in El Obeid is lower than that in Khartoum. The climatic modulation of these efficiency thresholds is consistent with Al-Helal et al. (2007), who established that evaporative demand and ventilation intensity govern resource requirements, and confirms that milder climates require lower operating efficiencies to avoid overcooling. While water consumption continued to increase almost linearly with pad efficiency, both CSR and SCWR indicate that η ≈ 80% provides the best balance between cooling performance and water requirement for tomato. For cucumber, the optimum occurs at an even lower efficiency (approximately η = 60–70%), beyond which additional cooling water provides little thermal benefit while substantially increasing water demand.

Table 5. Pad efficiency effects on water consumption, HOp, SCWR, and CSR for tomato and cucumber in El Obeid.

Efficiency (η)	Water consumption (kg·m^{-2} yr^{-1})	HOp-Tomato (h)	HOp-Cucumber (h)	SCWR-Tomato (kg·m^{-2}·h^{-1})	SCWR-Cucumber (kg·m^{-2}·h^{-1})	CSR-Tomato (%)	CSR-Cucumber (%)
η 60	4501	2422	2298	1.9	2.0	61.4	86.8
η70	5275	2823	2250	1.9	2.3	71.5	85.0
η80	6057	3178	1800	1.9	3.4	80.5	68.0
η 90	6845	3171	1334	2.2	5.1	80.4	50.4
η100	7641	2607	1039	2.9	7.4	66.1	39.3

Port Sudan exhibited a fundamentally different response from the inland locations. Annual evaporative cooling water consumption increased almost linearly from 2,477.4 to 4,165.3 kg m^{-2} as pad efficiency increased from 60% to 100% (Table 6). Despite the increase, total water consumption remained approximately 54% lower than that of Khartoum under the same efficiency levels, reflecting the reduced evaporative demand imposed by the humid coastal climate. Unlike Khartoum and El Obeid, improvements in thermal suitability continued throughout the entire efficiency range without evidence of performance decline at high η. Tomato optimal thermal hours increased continuously from 1,553 h at η = 60% to 4,755 h at η = 100%, while cucumber optimal hours increased from 2,685 h to 3,972 h over the same range. This continuous improvement contrasts sharply with the inland locations, where optimal thermal hours declined after reaching an efficiency threshold because of overcooling. In Port Sudan, the high ambient humidity limits the wet-bulb depression achievable by evaporative cooling, preventing greenhouse temperatures from falling below the lower boundary of the crop optimum temperature range within the simulated efficiency levels. The Climate Suitability Ratio (CSR) further illustrates the strong climatic limitation imposed by the coastal environment. At η = 60%, tomato achieved a CSR of only 26.1%, indicating that nearly three-quarters of the operating period remained outside the optimum thermal range. Increasing pad efficiency progressively improved tomato suitability, reaching 80.0% at η = 100%. In contrast, cucumber exhibited substantially higher suitability throughout the efficiency range, with CSR increasing from 67.6% at η = 60% to 100% at η = 100%. The different responses reflect the wider overlap between the greenhouse thermal conditions and the higher optimum temperature range required by cucumber (22–30°C), whereas tomato required greater cooling intensity to approach its optimum range.

The Specific Cooling Water Requirement (SCWR) revealed a contrasting pattern compared with the inland locations. For tomato, SCWR decreased steadily from 1.6 to 0.9 kg m^{-2} h^{-1} as pad efficiency increased, indicating that each additional unit of cooling water generated progressively more optimal thermal hours. This behavior reflects the initially severe thermal limitation experienced under low pad efficiencies, where improvements in cooling produced substantial gains in crop suitability. In contrast, cucumber SCWR remained nearly constant (0.923–1.049 kg m^{-2} h^{-1}) throughout the efficiency range. The slight increase at η = 100% indicates that the additional cooling water produced only marginal improvements once cucumber had already achieved near-complete thermal suitability. Overall, Table 6 demonstrates that the humid coastal climate fundamentally alters the relationship between pad efficiency and greenhouse performance. Unlike the inland locations, where excessive cooling eventually reduced crop suitability, no overcooling was observed within the simulated efficiency range in Port Sudan. Instead, increasing pad efficiency continued to improve tomato thermal suitability while maintaining high cucumber performance. These results indicate that, under humid coastal conditions, the primary limitation is

the thermodynamic restriction imposed by the small wet-bulb depression rather than excessive cooling. Consequently, operating at η ≈ 100% represents the most appropriate strategy for maximizing thermal suitability in Port Sudan. This fundamental difference in coastal climate response aligns with Hegazy et al. (2022), who found that evaporative cooling performance is strongly mediated by ambient humidity levels, and supports the need for technology-specific strategies rather than uniform efficiency targets across climatic zones.

Table 6. Pad efficiency effects on water consumption, HOp, SCWR, and CSR for tomato and cucumber in Port Sudan.

Efficiency (η)	Water consumption ($kg \cdot m^{-2}\ yr^{-1}$)	HOp-Tomato (h)	HOp-Cucumber (h)	SCWR-Tomato ($kg \cdot m^{-2} \cdot h^{-1}$)	SCWR-Cucumber ($kg \cdot m^{-2} \cdot h^{-1}$)	CSR-Tomato (%)	CSR-Cucumber (%)
η 60	2477.44	1553	2685	1.6	0.923	26.1	67.6
η70	2896.65	2187	3120	1.3	0.928	36.8	78.5
η80	3317.69	2924	3600	1.1	0.922	49.2	90.6
η 90	3740.58	3819	3927	1.0	0.953	64.2	98.8
η100	4165.33	4755	3972	0.9	1.049	80.0	100.0

The three locations exhibited distinct responses to evaporative cooling because of their contrasting climatic conditions. Khartoum and El Obeid required higher annual cooling water consumption (5,372.1–9,132.4 and 4,501.0–7,641.0 kg m^{-2} yr^{-1}, respectively) owing to their high evaporative demand, but they also achieved greater cooling effectiveness, with maximum tomato CSR values of 80.0% and 80.5%, respectively (Tables 4 and 5). However, increasing pad efficiency beyond the optimum level resulted in overcooling and reduced thermal suitability. In contrast, Port Sudan required substantially less cooling water (2,477.4–4,165.3 kg m^{-2} yr^{-1}) because high ambient humidity limited evaporation (Table 6). Nevertheless, the same humid conditions restricted evaporative cooling by reducing the wet-bulb depression, requiring η = 100% to achieve a tomato CSR comparable to that obtained at η = 80–90% in the inland locations. These findings demonstrate that the optimum pad efficiency is climate-dependent and should be selected according to local psychrometric conditions rather than maximizing cooling efficiency alone. These climate-dependent optima underscore the sustainability framework outlined by Allali et al. (2025), who argued that cooling strategies must balance thermal improvement against resource consumption rather than pursuing maximum efficiency alone. They also align with Gooroochurn et al. (2022), who identified improving greenhouse cooling efficiency as a critical research priority under climate change, and with Omar et al. (2021), who demonstrated that integrating solar photovoltaic systems can reduce grid dependence and enhance the sustainability of

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location-specific cooling operations. Although evaporative cooling systems have been extensively investigated, most previous studies have focused primarily on maximizing cooling efficiency and temperature reduction. Comparatively little attention has been given to crop-specific optimization that simultaneously considers thermal suitability, heat stress mitigation, and resource consumption across different climatic conditions. Furthermore, the optimal cooling efficiency may vary substantially among crops and locations, indicating that maximizing cooling performance does not necessarily correspond to the most sustainable or economically viable operating strategy. Consequently, determining crop-specific cooling requirements and identifying optimal evaporative cooling efficiencies remain critical challenges for sustainable greenhouse production in hot-arid and semi-arid environments.

Implications for greenhouse management

The findings of this study carry several practical implications for growers, agricultural engineers, and policymakers operating evaporatively cooled greenhouses in hot climates:

1. Adopt climate-specific ventilation setpoints

Growers should avoid defaulting to maximum ventilation rates. For hot-arid environments similar to Khartoum, ventilation should be capped at 100–140 m^3 m^{-2} h^{-1} for tomato production, with recognition that cucumber requires less airflow to eliminate heat stress. In semi-arid zones comparable to El Obeid, the practical ceiling is 100–120 m^3 m^{-2} h^{-1}. For humid coastal regions like Port Sudan, investments should prioritize system efficiency and complementary technologies rather than simply scaling up airflow beyond 120 m^3 m^{-2} h^{-1}.

2. Implement crop-specific pad efficiency calibration

Pad efficiency must be selected according to the cultivated crop, not installed at maximum capacity. For tomato, operators in Khartoum should target $\eta \approx 90\%$, while cucumber growers should not exceed $\eta \approx 70\%$ to avoid overcooling and excessive water consumption. In milder inland climates such as El Obeid, these thresholds drop to approximately $\eta = 80\%$ for tomato and $\eta = 60–70\%$ for cucumber. In humid coastal settings, $\eta \approx 100\%$ is justified because thermodynamic constraints prevent overcooling, but growers must accept higher residual heat stress or integrate auxiliary cooling.

3. Deploy variable-speed fan control

Fixed-speed operation at maximum ventilation is economically and environmentally inefficient. Installing variable-speed drives (VSDs) linked to real-time indoor temperature and crop heat stress thresholds allows dynamic modulation of airflow within the identified practical ranges. This prevents the sharp escalation of Marginal Water Cost observed beyond optimum ventilation rates while maintaining thermal suitability.

4. Integrate water recycling technologies

Given the linear relationship between ventilation rate and water consumption, recirculation and treatment of cooling pad drainage can substantially offset total water

demand without compromising cooling capacity. This is particularly critical in water-scarce arid regions where evaporative cooling demand rivals or exceeds irrigation water use.

5. Monitor marginal water cost (MWC) as an Operational Metric

Greenhouse managers should track MWC alongside conventional temperature metrics. A rising MWC signals that additional water is yielding diminishing thermal returns, providing an objective trigger to reduce ventilation or investigate system maintenance rather than continuing to increase resource input.

6. Consider hybrid systems in humid coastal zones

In climates resembling Port Sudan, where evaporative cooling alone cannot fully mitigate heat stress even at maximum configuration, standalone pad-and-fan systems are insufficient. Managers should evaluate integrated approaches—such as desiccant-assisted dehumidification, fogging supplements, or solar-driven mechanical cooling—to address the fundamental thermodynamic limitation imposed by high ambient humidity.

7. Prioritize crop physiology in system design

The divergent responses of tomato and cucumber underscore that greenhouse cooling systems should be designed around the thermal optimum of the target crop rather than generic temperature targets. Cucumber's higher temperature optimum makes it more susceptible to overcooling at high pad efficiencies, whereas tomato's lower optimum demands more intensive cooling but still reaches a definite ceiling. Crop rotation schedules should account for these differing efficiency optima when configuring system setpoints between growing seasons.

By implementing these management implications, greenhouse operators can move beyond the conventional paradigm of maximum cooling toward precision climate control that aligns technical performance with crop physiology, local climate, and resource sustainability.

Conclusion

This study demonstrates that the performance of evaporative cooling systems in greenhouses is governed by a complex interplay between local climatic conditions, ventilation intensity, pad efficiency, and crop-specific thermal requirements. The three investigated locations—Khartoum, El Obeid, and Port Sudan—exhibited fundamentally distinct responses that preclude universal operating recommendations. In the hot-arid climate of Khartoum and the semi-arid conditions of El Obeid, fan-and-pad systems achieved considerable thermal gains, reducing Heating Stress Hours (HSH) substantially at moderate ventilation rates. However, both locations exhibited clear thresholds of diminishing returns. In Khartoum, ventilation beyond 140 $m^3\ m^{-2}\ h^{-1}$ produced only marginal reductions in tomato HSH while causing Marginal Water Cost (MWC) to escalate sharply, indicating that continued increases in airflow primarily waste water rather than improve crop thermal conditions. Similarly, El Obeid's practical optimum was reached at 100–120 $m^3\ m^{-2}\ h^{-1}$. Cucumber, with its higher optimum temperature range, reached zero HSH at lower ventilation rates than tomato, confirming that cooling requirements

must be calibrated to crop physiology, not just climatic extremes.

Pad efficiency optimization reinforced the necessity of crop-specific strategies. In Khartoum, tomato achieved maximum Climate Suitability Ratio (CSR) at $\eta = 90\%$, whereas cucumber peaked at $\eta = 70\%$ before overcooling reduced suitability. El Obeid followed a comparable pattern but with lower optimal efficiencies, reflecting its milder climate. The Specific Cooling Water Requirement (SCWR) confirmed that operating beyond these crop-specific optima generates progressively fewer suitable thermal hours per unit of water consumed, undermining both economic and environmental sustainability.

Port Sudan presented a contrasting paradigm. The humid coastal climate constrained evaporative potential through limited wet-bulb depression, resulting in the lowest absolute water consumption but also the smallest reductions in HSH per unit of ventilation. Neither tomato nor cucumber reached zero HSH even at maximum ventilation, and overcooling was absent across the entire efficiency range. Consequently, $\eta \approx 100\%$ represented the most appropriate strategy for Port Sudan, though supplementary dehumidification or hybrid cooling technologies may be necessary to achieve full thermal suitability.

Collectively, these results refute the assumption that maximizing cooling capacity—whether through higher ventilation or greater pad efficiency—automatically translates into optimal greenhouse performance. Instead, sustainable operation requires location-specific and crop-specific thresholds that balance thermal gains against resource consumption. Operational optimization strategies, including variable-speed fan control and water recycling, offer viable pathways to maintain crops within these identified practical ranges while minimizing unnecessary water and energy use. Future research should prioritize real-time adaptive control systems that integrate crop heat stress indices with climatic feedback to automate these optimized setpoints under dynamic field conditions.

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