

Water, land, and energy use efficiencies and financial evaluation of air conditioner cooled greenhouses based on field experiments (Postprint)

Authors: Ibtihal AL-MANTHRIA, Abdulrahim M AL-ISMAILIA, Hemesiri KOTAGAMAB, Mumtaz KHANC, L H Janitha JEEWANTHAD, Ibtihal AL-MANTHRIA

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Abstract

High temperature and humidity can be controlled in greenhouses by using mechanical refrigeration cooling system such as air conditioner (AC) in warm and humid regions. This study aims to evaluate the techno-financial aspects of the AC-cooled greenhouse as compared to the evaporative cooled (EV-cooled) greenhouse in winter and summer seasons. Two quonset single-span prototype greenhouses were built in the Agriculture Experiment Station of Sultan Qaboos University, Oman, with dimensions of 6.0 m long and 3.0 m wide. The AC-cooled greenhouse was covered by a rockwool insulated polyethylene plastic sheet and light emitting diodes (LED) lights were used as a source of light, while the EV-cooled greenhouse was covered by a transparent polyethylene sheet and sunlight was used as light source. Three cultivars of high-value lettuce were grown for experimentation. To evaluate the technical efficiency of greenhouse performance, we conducted measures on land use efficiency (LUE), water use efficiency (WUE), gross water use efficiency (GWUE) and energy use efficiency (EUE). Financial analysis was conducted to compare the profitability of both greenhouses. The results showed that the LUE in winter were 10.10 and 14.50 kg/m² for the AC- and EV-cooled greenhouses, respectively. However, the values reduced near to 6.80 kg/m² in both greenhouses in summer. The WUE of the AC-cooled greenhouse was higher than that of the EV-cooled greenhouse by 3.8% in winter and 26.8% in summer. The GWUE was used to measure the total yield to the total greenhouse water consumption including irrigation and cooling water; it was higher in the AC-cooled greenhouse than in the EV-cooled greenhouse in both summer and winter seasons by almost 98.0%-99.4%. The EUE in the EV-cooled greenhouse was higher in both seasons. Financial analysis showed that in winter, gross return, net return and benefit-to-cost ratio were better in the EV-cooled greenhouse, while in summer, those were higher

in the AC-cooled greenhouse. The values of internal rate of return in the AC- and EV-cooled greenhouses were 63.4% and 129.3%, respectively. In both greenhouses, lettuce investment was highly sensitive to changes in price, yield and energy cost. The financial performance of the AC-cooled greenhouse in summer was better than that of the EV-cooled greenhouse and the pattern was opposite in winter. Finally, more studies on the optimum LED light intensity for any particular crop have to be conducted over different growing seasons in order to enhance the yield quantity and quality of crop.

Full Text

Preamble

Water, Land, and Energy Use Efficiencies and Financial Evaluation of Air Conditioner-Cooled Greenhouses Based on Field Experiments

Ibtihal AL-MANTHRIA¹, Abdulrahim M AL-ISMAILIA^{1*}, Hemesiri KOTAGAMA², Mumtaz KHAN³, L H Janitha JEEWANTHA^{4, 5}

¹ Department of Soils, Water and Agricultural Engineering, Sultan Qaboos University, Muscat PC123, Oman

² Department of Natural Resource Economics, Sultan Qaboos University, Muscat PC123, Oman

³ Department of Plant Science, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat PC123, Oman

⁴ Centre for Future Materials, University of Southern Queensland, Toowoomba QLD 4350, Australia

⁵ School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba QLD 4350, Australia

Abstract: High temperature and humidity in warm and humid regions can be controlled in greenhouses using mechanical refrigeration cooling systems such as air conditioners (AC). This study aims to evaluate the techno-financial performance of AC-cooled greenhouses compared to evaporative-cooled (EV-cooled) greenhouses during winter and summer seasons. Two quonset single-span prototype greenhouses (6.0 m × 3.0 m) were built at the Agriculture Experiment Station of Sultan Qaboos University, Oman. The AC-cooled greenhouse was covered with rockwool-insulated polyethylene plastic sheet and used light-emitting diodes (LED) as the light source, while the EV-cooled greenhouse was covered with transparent polyethylene sheet and used sunlight. Three cultivars of high-value lettuce were grown for experimentation. Technical efficiency was evaluated through land use efficiency (LUE), water use efficiency (WUE), gross water use efficiency (GWUE), and energy use efficiency (EUE). Financial analysis compared the profitability of both systems. Results showed that winter LUE values were 10.10 and 14.50 kg/m² for AC- and EV-cooled greenhouses, respectively, decreasing to approximately 6.80 kg/m² in both systems during summer. The AC-cooled greenhouse achieved 3.8% higher WUE in winter and 26.8% higher

in summer compared to the EV-cooled system. GWUE, measuring total yield against total water consumption (irrigation + cooling), was 98.0%-99.4% higher in the AC-cooled greenhouse across both seasons. However, EUE was higher in the EV-cooled greenhouse in both seasons. Financial analysis revealed that winter gross return, net return, and benefit-to-cost ratio favored the EV-cooled greenhouse, while summer performance was superior in the AC-cooled system. Internal rates of return were 63.4% and 129.3% for AC- and EV-cooled greenhouses, respectively. Both systems showed high sensitivity to price, yield, and energy cost changes. The AC-cooled greenhouse outperformed the EV-cooled system financially in summer, with the opposite pattern in winter. Further research is needed to optimize LED light intensity for specific crops across growing seasons to enhance yield quantity and quality.

Keywords: land use efficiency; energy use efficiency; water use efficiency; gross water use efficiency; financial evaluation; air conditioner-cooled greenhouse; evaporative-cooled greenhouse

*Corresponding author: Abdulrahim M AL-ISMAILIA (E-mail: abdrahim@squ.edu.om)

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Introduction

Oman is classified as an arid and semi-arid country with high temperatures and dry climate for most of the year. Summer temperatures may exceed 45°C, with average annual precipitation of only 100 mm. These conditions render open-field cropping unsuitable (Jayasuriya et al., 2017). Most vegetables—including tomato, cucumber, pepper, and lettuce—experience growth decline when temperatures exceed their optimal ranges of 29°C-30°C (Fath and Abdelrahman, 2005). Therefore, improved agricultural management and technology are key solutions to these challenges.

Controlled Environment Agriculture (CEA) facilities, primarily greenhouses, overcome harsh climatic conditions in water-scarce areas by controlling environmental factors to enhance crop yield quantity and quality for ornamentals, fruits, and vegetables (Fogg et al., 1979). Greenhouses in Oman have increased land productivity 12-fold compared to open-field farming (Tawfiq, 2009) and doubled water productivity (Mazid, 2011). Consequently, CEA facilities have increased significantly over the past 15 years (Mazid, 2011). Cucumber dominates greenhouse cultivation (90%), followed by tomato (5%-9%) (Mazid, 2011). However, monocropping of cucumber has been linked to disease issues (Kiyumi, 2009). The average seasonal net return for cucumber and tomato is 742.90 and

368.85 USD per greenhouse (351 m²), respectively (Mazid, 2011).

Fan-pad evaporative cooling systems are commonly used to cool greenhouse microclimates (Hasan et al., 2009), depending on outside air dryness and solar load (Xu et al., 2015). However, their efficiency decreases in summer, causing many farmers to cease planting and resulting in vegetable supply shortages and price fluctuations (Mazid, 2011). Furthermore, evaporative cooling systems consume approximately 98.0% of total electricity and 58.0% of total water in greenhouses under arid conditions (Fadel et al., 2014), with cooling water alone reaching 67.0% of total consumption (Al-Mulla, 2006).

Mechanical refrigeration cooling systems, such as air conditioners (AC), offer an alternative for year-round optimal temperature control for high-value crops. Although less common commercially, AC cooling has been successfully employed in hot, humid regions like Taiwan, where growers achieve good profits (Fang, 1995). Advantages include meeting optimal temperature ranges for most vegetables and fruits, providing more crop choices, better temperature control, reduced humidity, year-round cultivation, and restored water evapotranspiration, indicating high water use efficiency (WUE). Main disadvantages include CO₂ depletion, high energy consumption, and high initial and operational costs (Baird et al., 1993). In warm climates, CO₂ enrichment can be achieved through ventilation (Ioslovich et al., 1995).

Energy consumption in ventilated greenhouses can be minimized through proper fan management—activating fans immediately when temperature exceeds the upper limit and deactivating when it falls below the lower limit (Avila et al., 2013). This approach can also reduce energy consumption in AC-cooled greenhouses. Another method involves reducing solar heat input through full or partial radiation elimination, though this reduces photosynthesis and crop growth (Choi et al., 2015). Light-emitting diodes (LED) can provide necessary light for photosynthesis while emitting less heat than sunlight. The combination of red and blue wavelengths suffices for crop cultivation (Choi et al., 2015), with studies showing high strawberry yields using only red and blue LED lights for 40 days (Folta and Childers, 2008). Thus, LED lights can reduce AC-cooled greenhouse energy consumption while supporting photosynthesis.

A third method for reducing heat load involves diminishing conductive heat transfer through covering materials. Materials with lower k (thermal conductivity) and U (heat transfer rate) values provide better insulation (Li et al., 2015). However, these materials typically have light transmittance exceeding 74.0%, contradicting the objective of eliminating solar heat input. To resolve this, thermal insulation approaches from poultry houses can be adopted, using rockwool, plastic foam, glass wool mat, or mineral-filled foam (Yoshioka and Otani, 2002). Rockwool is a versatile material for thermal insulation in industrial, commercial, and domestic applications.

Financial feasibility studies are essential, as profitability is prerequisite for private technology adoption. In greenhouse agribusiness analysis, profitability bud-

gets and cash flow budgets are critical measures. Profitability budgets analyze all returns and costs during a production cycle, while cash flow budgets examine cash inflows and outflows for specific periods.

This study evaluates techno-financial differences between AC-cooled and evaporative-cooled (EV-cooled) greenhouses across winter and summer seasons.

Materials and Methods

The study was conducted at the Agricultural Experiment Station (AES) of Sultan Qaboos University, Oman. Two prototype quonset greenhouses (6.0 m × 3.0 m × 2.5 m) were built to examine seasonal effects on yield, profitability, and water and energy consumption. The control was an EV-cooled quonset greenhouse commonly used in Oman (Al-Ismaili et al., 2017), equipped with a fan-pad evaporative cooling system, two hydroponic irrigation frames, and covered with 200 μ m polyethylene plastic sheet (Fig. 1a [Figure 1: see original paper]). The hydroponic frames measured 1.20 m height, 1.00 m length, 0.25 m top width, and 0.85 m bottom width, divided into four vertical floors using nutrient film technique. Sunlight served as the light source. In summer, irrigation water was cooled to approximately 24°C using a water cooling box.

The AC-cooled quonset greenhouse (Fig. 1b [Figure 1: see original paper]) used a 2.4×10^4 Btu/h window-type air conditioner, rockwool insulation (50 mm thick), and double polyethylene layers. The rockwool eliminated solar heat input and conductive heat gain. Since CO₂ concentration in sealed greenhouses drops below the atmospheric 350×10^{-6} – 400×10^{-6} required for photosynthesis (Vox et al., 2010), early morning ventilation via a small fan was conducted when necessary to enrich CO₂ without hot air intrusion. CO₂ concentration was measured using an SCT-108.002.41 SCT NAVID CO₂ Detector (ScichemTech, USA). The AC-cooled greenhouse also contained two hydroponic frames. Ten red and blue LED lights (500 W LED Grow Light, CASTNOO, China) provided photosynthetic light at four intensity levels, positioned 0.30 m above the frames (Fig. 1b [Figure 1: see original paper]).

Fig. 1 Illustration of evaporative-cooled (EV-cooled) prototype greenhouse (a) and air conditioner-cooled (AC-cooled) prototype greenhouse (b). The EV-cooled greenhouse is equipped with a fan (A)-pad (B) evaporative cooling system, 200 μ m thick polyethylene plastic sheet (C), and two hydroponic irrigation system frames (D). The AC-cooled greenhouse is equipped with an air conditioner (E), 50 mm thick rockwool insulation material sheet and double layers of polyethylene plastic sheets (F), a small fan (G), two hydroponic irrigation system frames (D), and four different height levels of red and blue light-emitting diode (LED) lights (H).

Technical Efficiency

To evaluate technical performance, Watt-meters recorded electricity consumption for the air conditioner, LED lights, and irrigation pumps in the AC-cooled greenhouse, while water meters measured irrigation water consumption. Similarly, the EV-cooled greenhouse used Watt-meters for fans, cooling pump, and irrigation pumps, with water meters recording cooling and irrigation water consumption.

Performance was evaluated using four efficiency indices: land use efficiency (LUE, kg/m²), water use efficiency (WUE, kg/m³), gross water use efficiency (GWUE, kg/m³), and energy use efficiency (EUE, dimensionless). These were calculated at each season's end using the following equations (Fernández et al., 2007; Al-Busaidi and Al-Mulla, 2014; Fan et al., 2014; Tabook and Al-Ismaili, 2016):

$$\text{LUE} = Y/A, \quad (1)$$

where Y represents yield (kg) and A indicates cultivated area (m²). Land use efficiency (land productivity) calculates crop weight per unit area for any period.

$$\text{WUE} = Y/ET, \quad (2)$$

where ET is evapotranspiration loss (m³). In hydroponic systems, ET equals daily irrigation water multiplied by total season days. WUE establishes the relationship between water consumption and crop growth development.

$$\text{GWUE} = Y/(IW + CW - RW), \quad (3)$$

where IW is irrigation water (m³), CW is cooling system water (m³), and RW is water recovered from the air conditioner (m³). GWUE compares total yield to total greenhouse water consumption, including irrigation and cooling water (Tabook and Al-Ismaili, 2016).

$$\text{EUE} = \frac{\text{Energy output}}{\text{Energy input}}, \quad (4)$$

where energy output (MJ/hm²) represents energy equivalents of all outputs (primarily crop yield), and energy input (MJ/hm²) indicates the summation of energy equivalents for all production inputs, including labor, diesel fuel, machinery, manure, chemical fertilizers, electricity, pesticides, seeds, and water (Tabook, 2017).

Table 1 provides energy equivalent factors for converting input and output units into energy values.

Table 1 Energy equivalents of different input and output values used in agricultural production

Input/output	Energy equivalent per unit input/output (MJ/hm ²)	Reference
Human labour		Singh et al. (2002)
Rotavator		Alam et al. (2005)
Knapsack sprayer		Gezer et al. (2003)
Diesel-oil		Taki et al. (2012)
Electricity		Singh and Kamal (2012)
Water for irrigation/cooling		Ozkan et al. (2011)
Nitrogen		Yaldiz et al. (1993)
Phosphorus		Singh et al. (2002)
Potassium		Singh et al. (2002)
Sulfate		Singh et al. (2002)
Calcium		Mohammadi and Omid (2010)
Micro-nutrients		Mohammadi and Omid (2010)
Farm yard manure		Banaeian et al. (2011)
Pesticides		Taki et al. (2012)
Fungicides		Kuswardhani et al. (2013)
Energy input		Kuswardhani et al. (2013)

Input/output	Energy equivalent per unit input/output (MJ/hm ²)	Reference
Energy output		Hatirli et al. (2005)
Crop yield (lettuce)		

Experimental Setup

To avoid the monocropping prevalent in Omani greenhouses and achieve high returns, three high-value lettuce cultivars were planted: Butterhead lettuce ‘Flandria’, Lollo Rose lettuce ‘Carmoli’, and Frisse lettuce ‘Korbi’. Cultivation lasted 31 days (19 February–21 March 2019) in winter and 28 days (20 May–16 June 2019) in summer. Seeds were germinated in sponge cubes (0.04 m diameter \times 0.03 m height) compatible with hydroponic system holes. Crop productivity is adversely affected when temperature falls below 10°C–12°C or exceeds 30°C–35°C for extended periods (Salih and Aydrous, 2015). The minimum daily radiation requirement is approximately 8.5 MJ/(m² · d), achieved with about 6 hours of light daily (Castilla and Baeza, 2013). Greenhouse relative humidity should be 60%–80% (Vox et al., 2010). During experiments, air temperature, relative humidity, and CO₂ concentration were maintained at 24°C, 60%–70%, and 350×10^{-6} – 400×10^{-6} , respectively (Brechner et al., 2013). pH was adjusted to 5.8–6.0 (Brechner et al., 2013), and electrical conductivity was 0.15–0.20 S/m (MAF, 2013).

Each floor in both hydroponic frames contained 9 plants per cultivar (27 plants per floor) with 0.15 m spacing between lettuce heads. The AC-cooled greenhouse used four light intensity levels: 890 $\mu\text{mol}/(\text{m} \cdot \text{s})$ at 0.30 m below LEDs, 350–400 $\mu\text{mol}/(\text{m} \cdot \text{s})$ at 0.80 m (optimal for lettuce) (Singh et al., 2015), and $<150 \mu\text{mol}/(\text{m} \cdot \text{s})$ at 1.30 m and 1.80 m.

Financial Analysis

For each greenhouse and season, total variable and fixed production costs were calculated for seasonal budgeting. Fixed costs included greenhouse frames, insulation covers, electrical wires, cooling systems, irrigation pumps, hydroponic systems, and LED lights. Variable costs comprised seedlings, nutrients, electricity, and water. Financial productivity (FP, USD/kg), total revenue (TR, USD/hm²), gross return (GR, USD/hm²), and net return (NR, USD/hm²) were calculated using:

$$\text{FP} = \text{TC}/Y, \quad (5)$$

$$\text{TR} = P \times Y, \quad (6)$$

$$GR = TR - VC, \quad (7)$$

$$NR = TR - TC, \quad (8)$$

where Y is per-unit-area yield (kg/hm^2), TC is total production cost (USD/hm^2), P is product sale price (USD/kg), and VC is variable production cost (USD/hm^2).

Discounted cash flow analysis estimated benefit-to-cost ratio and internal rate of return (IRR). Net annual cash flow was calculated as the difference between total cash outflow and inflow. Net cash outflow included variable and fixed costs, while inflow comprised crop yield revenue (Banik and Ganguly, 2017). A 20-year greenhouse lifetime was used in calculations, excluding land cost, tax deductions, and depreciation. In Oman, water pricing is 0.10×10^{-3} USD/L for consumption under 1.89×10^4 L and 0.17×10^{-3} USD/L above this threshold. Agricultural investments are tax-exempt. A 6.0% interest rate (average commercial bank rate for agricultural loans) was applied. Annualization factor (FC) and annualized rate (AN, %) were calculated as:

$$FC = \frac{\text{cost} \times R}{1 - (1 + R)^{-\text{life}}}, \quad (9)$$

where R is interest rate (%), life is greenhouse lifetime (years), and cost is initial investment cost (USD).

Given Oman's policy of removing energy subsidies, sensitivity analysis evaluated impacts of yield, market price, and energy cost changes on greenhouse profitability.

Results and Discussion

Winter Season Analysis

Winter performance is presented in **Table 2**. Lettuce grows vertically, with yields calculated per growing floor area (Touliatos et al., 2016). The EV-cooled greenhouse yield exceeded the AC-cooled system by 30.0% due to decreasing light intensity with distance from LEDs in the AC-cooled system. Consequently, AC-cooled LUE ($10.10 \text{ kg}/\text{m}^2$) was lower than EV-cooled LUE ($14.50 \text{ kg}/\text{m}^2$). Both values exceeded the $6.80 \text{ kg}/\text{m}^2$ reported for hydroponic greenhouse lettuce in Arizona, USA (Barbosa et al., 2015). AC-cooled WUE ($100.32 \text{ kg}/\text{m}^3$) surpassed EV-cooled WUE ($96.52 \text{ kg}/\text{m}^3$) due to higher irrigation water consumption in the EV-cooled system from air flow. Both WUE values exceeded the $30.00 \text{ kg}/\text{m}^3$ reported elsewhere for lettuce (Ünlükara et al., 2008).

Table 2 Performance of the AC-cooled greenhouse and EV-cooled greenhouse in winter

Performance index	AC-cooled greenhouse	EV-cooled greenhouse
Yield per cultivation period (kg)		
LUE (kg/m ²)	10.10	14.50
WUE (kg/m ³)	100.32	96.52
GWUE (kg/m ³)		
EUE		

Note: AC-cooled greenhouse, air conditioner-cooled greenhouse; EV-cooled greenhouse, evaporative-cooled greenhouse; LUE, land use efficiency; WUE, water use efficiency; GWUE, gross water use efficiency; EUE, energy use efficiency. The greenhouse area is 18 m².

GWUE evaluated total water consumption (cooling + irrigation). The EV-cooled evaporative system consumed 20.0%-50.0% of total greenhouse water in winter (Tabook and Al-Ismaili, 2016), resulting in GWUE of 1.98 kg/m³ compared to 100.32 kg/m³ in the AC-cooled system, which used no water for cooling.

Energy performance showed total output lower than input in both systems. EV-cooled EUE (0.10) exceeded AC-cooled EUE (0.08), but both were below the 0.30 reported by Barbosa et al. (2015). Low energy output (crop yield) and high input explained this discrepancy. Tabook (2017) reported that evaporative cooling alone consumed ~99.5% of total electricity. Maximizing EUE requires solar energy use, yield improvement, and minimized energy input (Taki et al., 2012).

Financial analysis assumed six cultivation periods per season (25-31 days in winter, 20-30 days in summer). Average sale prices for the three lettuce cultivars were estimated from Omani market data. Annualized investment costs were calculated at 6.0% interest. Initial capital investments for six winter cultivation periods are shown in **Tables 3** and **4**.

Table 3 Initial capital and annualized investments of an AC-cooled greenhouse (18 m²) with lettuce production in winter

Item	Lifetime (a)	Initial investment cost (USD)	Annualized investment cost (USD)
Hydroponic irri- ga- tion sys- tem frames PVC ac- ces- sories Aluminum door Rockwool sheet with dou- ble lay- ers of polyethy- lene sheets Water tank Foot valve Electrical 1.5 mm wires Cooling fans AC cool- ing sys- tem Irrigation pump Binding wires			

Item	Lifetime (a)	Initial investment cost (USD)	Annualized investment cost (USD)
Electrical panel en- clo- sure LED lights Electrical ac- ces- sories Hydroponic irri- ga- tion sys- tem in- stal- la- tion Water me- ter* Thermocouple wires* Watt me- ter* PAR me- ter* RHT sen- sor* Anemometer* pH/EC me- ter			
Total		13810.42	

Note: indicates meters and sensors used experimentally but optional for farm-

ers; ** represents total initial capital investment for an 18 m² AC-cooled greenhouse with lettuce production. PVC, polyvinyl chloride; LED, light-emitting diode; PAR, photosynthetically active radiation; RHT, relative humidity and temperature transmitter; EC, electrical conductivity.*

Table 4 Initial capital and annualized investments of an EV-cooled greenhouse with lettuce production in winter

Item	Lifetime (a)	Initial investment cost (USD)	Annualized investment cost (USD)
Hydroponic irri- ga- tion sys- tem frames PVC ac- ces- sories Aluminum door Polyethylene plas- tic sheet Water tank Foot valve Electrical 1.5 mm wires Two cool- ing fans Cooling pads Irrigation pump Binding wires			

Item	Lifetime (a)	Initial investment cost (USD)	Annualized investment cost (USD)
Electrical panel en- clo- sure			
Electrical ac- ces- sories			
Hydroponic irri- ga- tion sys- tem in- stal- la- tion			
Water me- ter			
Thermocouple wires			
Watt me- ter			
PAR me- ter			
RHT sen- sor			
Anemometer pH/EC me- ter			
Total		11535.42	

*Note: ** represents total initial capital investment for an 18 m² EV-cooled greenhouse with lettuce production.*

Table 5 presents winter agricultural budgets. AC-cooled total investment

exceeded EV-cooled due to LED lights and rockwool with double polyethylene layers. Consistent with previous studies (Mohammadi and Omid, 2010), fixed costs were lower than variable costs, which were 70.0% and 80.0% higher in AC- and EV-cooled systems, respectively. AC-cooled total production cost was 30.0% higher than EV-cooled. Total winter yields for six cultivation periods were 780.00 kg (AC-cooled) and 1305.00 kg (EV-cooled) for 18 m².

Table 5 Agricultural budgets of the AC- and EV-cooled greenhouses in winter

Cost and return components	AC-cooled greenhouse	EV-cooled greenhouse
Total yield in winter (kg)		
Price (USD/kg)		
Gross value of production (USD)		
Variable cost of production (USD)		
Fixed cost of production (USD)		
Total cost of production (USD)		
Per kilogram cost of production (USD/kg)		
Gross return (USD)		
Net return (USD)		
Benefit-to-cost ratio		
Financial productivity (kg/USD)		

Summer Season Analysis

Table 6 shows summer performance. Yields were nearly equal at 102.00–103.20 kg during six cultivation periods. LUE was approximately 6.80 kg/m² in both systems, matching the 6.80 kg/m² reported for hydroponic greenhouse lettuce (Barbosa et al., 2015). As in winter, WUE and GWUE were lower in the EV-cooled system due to high irrigation and cooling water consumption. WUE values were 41.83 kg/m³ (AC-cooled) and 30.61 kg/m³ (EV-cooled). High evaporative cooling water consumption caused GWUE to reach 47.77 kg/m³ in the AC-cooled system versus 0.29 kg/m³ in the EV-cooled system. For comparison, summer cucumber WUE in Oman ranged 47.00–64.00 kg/m³ (Tabook, 2017). EUE remained below 1.00 in both systems due to low yield (energy output) and high cooling energy consumption (energy input).

Table 6 Performance of the AC- and EV-cooled greenhouses in summer

Performance index	AC-cooled greenhouse	EV-cooled greenhouse
Yield per cultivation period (kg)		
LUE (kg/m ²)		
WUE (kg/m ³)		
GWUE (kg/m ³)		
EUE		

Table 7 shows summer agricultural budgets. Yield decreased 15.5% (AC-cooled) and 50.0% (EV-cooled) compared to winter. Elevated summer electricity and water consumption raised variable costs to 1.07×10^3 USD (AC-cooled) and 1.60×10^3 USD (EV-cooled). However, lettuce sale prices increased in summer as most farmers stop EV-cooled greenhouse cultivation during hot periods. AC-cooled net return exceeded EV-cooled net return. EV-cooled financial productivity was <0.40 , while AC-cooled reached 0.46. AC-cooled benefit-to-cost ratio was 2.37, exceeding the EV-cooled value of 1.77. Summer lettuce cultivation was profitable in both systems, with AC-cooled more profitable due to higher yield and lower water consumption.

Table 7 Agricultural budgets of the AC- and EV-cooled greenhouses in summer

Cost and return components	AC-cooled greenhouse	EV-cooled greenhouse
Total yield in summer (kg)		
Price (USD/kg)		
Gross value of production (USD)		
Variable cost of production (USD)		
Fixed cost of production (USD)		
Total cost of production (USD)		
Per kilogram cost of production (USD/kg)		
Gross return (USD)		
Net return (USD)		
Benefit-to-cost ratio		
Financial productivity (kg/USD)		

Cash Flow Model

Two cash flow models were developed for AC- and EV-cooled greenhouses (Hood et al., 2005). Average sale prices for the three lettuce cultivars were obtained from market data for both seasons. High-value lettuce cultivation resulted in

negative net cash flow in year one due to initial investment. From year two onward, net cash flow became positive, ranging 3.04×10^3 – 5.42×10^3 USD/year for AC-cooled and 8.55×10^2 – 6.52×10^3 USD/year for EV-cooled systems, indicating profitability from the second year. The AC-cooled system showed another negative value in year 10 due to major maintenance (LED lights, AC cooler, rockwool sheet). Net present value was 4.34×10^4 USD with IRR of 63.4% for AC-cooled, and 5.94×10^4 USD with IRR of 129.3% for EV-cooled. The EV-cooled system's higher profitability stemmed from greater winter yield and lower investment cost. Both systems outperformed greenhouse cucumber cultivation (IRR = 47.0%) (Tabook, 2017).

Sensitivity analysis evaluated effects of sale price, yield, and energy cost changes on profitability (**Figure 2 [Figure 2: see original paper]**). Figures 2a and 2d show IRR response to annual sale price increases from 0.75 to 3.12 USD/kg. AC-cooled investment became unprofitable (IRR = 0) at 0.75 USD/kg, becoming profitable with near-linear price increases. EV-cooled investment started unprofitable (IRR = 3.6%, below the 6.0% interest rate) then became profitable with exponential growth as prices increased, consistent with literature showing direct price-profitability relationships (Hartz et al., 2007). Figures 2b and 2e demonstrate that IRR increased directly with yield in both systems, more significantly in the EV-cooled greenhouse. Figures 2c and 2f illustrate IRR impacts from projected electricity subsidy removals (20.0%, 40.0%, 60.0%, 80.0%, 100.0%). While IRR decreased in both systems, high-value lettuce cultivation remained profitable even with complete subsidy removal. Greenhouse investment is extremely sensitive to market price, yield, and energy costs.

Fig. 2 Relationships of internal rate of return (IRR) with sale price, yield, and electricity cost after subsidy in the AC-cooled greenhouse (a, b, and c, respectively) and EV-cooled greenhouse (d, e, and f, respectively).

Benefits of the AC-Cooled Greenhouse in Arid Areas

Agricultural growth and sustainability in arid regions are adversely affected by high temperature and water scarcity (Jayasuriya et al., 2017). The AC-cooled greenhouse system offers an alternative solution for year-round optimal temperature control for high-value crops. AC coolers enable temperature control in both seasons, facilitating year-round cultivation and restoring water evapotranspiration for high WUE. The system is particularly valuable in chronically water-scarce arid areas, reducing total water consumption (irrigation + cooling) by 98.0%–99.4% compared to evaporative cooling. Consequently, AC-cooled variable costs were lower in both seasons. Fixed costs can be covered through high-value crop cultivation such as lettuce.

Conclusions and Recommendations

Both greenhouses exhibited higher LUE in winter than summer due to lower summer yields. EV-cooled water consumption (irrigation + cooling) was 98.0%-99.4% higher than AC-cooled, primarily from evaporative cooling system usage. EUE was higher in the EV-cooled system across both seasons. EV-cooled variable costs exceeded AC-cooled costs, while AC-cooled fixed costs were higher. AC-cooled initial investment can be recovered through high-value crop cultivation. High-value lettuce investment was extremely sensitive to market price, yield, and energy costs. AC-cooled performance exceeded EV-cooled in summer, with the opposite pattern in winter.

Further research should examine AC-cooled greenhouses over longer periods to understand management and maintenance requirements. We recommend utilizing renewable energy sources to reduce AC-cooled greenhouse electricity costs.

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