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EDITED BY
Solomon Giwa,
Olabisi Onabanjo University, Nigeria

REVIEWED BY
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Università degli Studi della Campania Luigi Vanvitelli, Italy
Jesus Alejandro Franco Piña,
Universidad Nacional Autónoma de México, Mexico

*CORRESPONDENCE
Sachin Gorakshnath Chavan,
✉ s.chavan@westernsydney.edu.au
Premaratne Samaranayake,
✉ p.samaranayake@westernsydney.edu.au

‡PRESENT ADDRESS
Yi-Chen Lan,
College of Science and Engineering, Fu Jen Catholic University, New Taipei City, Taiwan

†These authors have contributed equally to this work and share first authorship

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Optimal energy-efficient shade screen and ventilation control settings for a greenhouse covered with light-altering films

Sachin Gorakshnath Chavan[1,2†]*, Premaratne Samaranayake[3†]*, Yi-Chen Lan[3‡], Chelsea Maier[1,2], Weiguang Liang[1], Christopher I. Cazzonelli[1,2], Zhong-Hua Chen[1,4,5] and David T. Tissue[1,2,5]

[1]National Vegetable Protected Cropping Centre, Hawkesbury Institute for the Environment, Western Sydney University, Penrith, NSW, Australia, [2]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, NSW, Australia, [3]School of Business, Western Sydney University, Penrith, NSW, Australia, [4]School of Science, Western Sydney University, Penrith, NSW, Australia, [5]Global Centre for Land-Based Innovation, Western Sydney University, Penrith, NSW, Australia

Introduction: Energy management in protected cropping is imperative to sustainably produce food. Optimal energy consumption in a protected cropping facility strongly depends on infrastructure control settings and meteorological conditions. This study aimed to optimise glasshouse energy management by investigating energy consumption under different shading, light-altering and ventilation conditions.

Methods: We compared energy consumption used in heating and cooling under two light-altering films and four different ventilation and shade screen positions. The light-altering glasshouse films, namely, light shifting film (LSF) - Luminescent Light Emitting Agriculture Film (LLEAF), and light blocking film (LBF) - low emissivity film ULR 80 (ultra-low reflectivity with 80% light transmission) were compared to a light diffusing hazed glass as the control.

Results: The mean combined energy consumption was significantly higher in summer compared to winter. The light treatment and ventilation/shade screen position combinations influenced total heating and cooling energy consumption mostly in summer. The LBF achieved the most efficient total energy consumption, particularly when ventilation was open and shade screens closed during winter, and when both ventilation and shade screens were closed during summer.

Discussion: Regardless of the season, cooling energy use was more dependent on the rooftop rather than the outside air temperature, indicating that incoming radiation is the major contributor to glasshouse warming during winter. Therefore, the minimization of energy consumption in protected cropping requires combined management of ventilation settings and light-altering methods to match the seasonal photoperiod and outside temperature environment.

KEYWORDS

temperature, light-altering film, greenhouse control systems, energy consumption, cooling energy, heating energy, ventilation, seasons

1 Introduction

The focus on sustainable food production is growing, especially in the investigation and implementation of protected cropping techniques to boost output in response to the rising needs of the agri-food supply chain. The key factors that emphasize the need for sustainable food production include the growth of the world population leading to increased fresh food demand, climate change impacting food production and supply, the sustainability of economic development and social wellbeing, declining arable land, and biotic as well as abiotic stresses to crops (Lambin and Meyfroidt, 2011; Torrellas et al., 2012; Food and Agriculture Organization, 2016; Bambara and Athienitis, 2019; Geilfus and Geilfus, 2019; Fedoroff, 2015; Gonzalez Guzman et al., 2022; Shabala et al., 2020; Wang et al., 2023). In response to global food demand, the production of horticultural produce such as tomatoes, capsicums, cucumbers, lettuce, and eggplants has seen a significant rise (Torrellas et al., 2012; Del Borghi et al., 2014; Bambara and Athienitis, 2019; Geilfus and Geilfus, 2019; Gruda et al., 2019; Chavan et al., 2022). Protected cropping enhances crop yield and quality by providing significant protection against detrimental weather conditions such as drought, flooding, extreme temperatures, and pressures from pests and diseases (Adem et al., 2020; Smagghe et al., 2023). In high-tech protected cropping facilities, the climate is controlled to establish an optimal growth environment, enabling crops to fully realize their genetic potential to maximize yields (Mahajan and Singh, 2006; Diouf et al., 2020; Maier et al., 2022). However, in high-tech protected cropping facilities, high ongoing operational expenses, primarily labour and energy consumption for maintaining climate conditions, adversely influence adoption of protected cropping practices by small-to-medium enterprises.

Energy consumption in protected cropping facilities is mainly cooling and heating during crop cycles. Depending on the facility's location, heating or cooling will dominate energy consumption. For instance, cooling is the most significant energy use in most regions of Australia due to high solar radiation and temperature, whereas heating is the most significant energy use in the Netherlands where the winter season is longer and temperatures are cooler (Rabbi et al., 2019; Lin et al., 2022). Shading screens are effective in reducing excess radiation, promoting cooling during the daytime and improving the nighttime climate (Montero et al., 2013). Ventilation methods help in the removal of trapped heat from greenhouses by replacing the warm inside air with cold outside air and for a naturally ventilated greenhouse, it is recommended that the total area of vent openings should be between 15% and 30% of the floor area as a further increase in vent openings gives marginal increase in performance (Ganguly and Ghosh, 2010) which may come at the cost of losing CO_2. A simulation study indicates that the configuration of vents influences the microclimate patterns within a greenhouse, as well as the spatial and temporal variations of its internal climate. Additionally, the size of the vent openings impacts the time required for dehumidification, as well as the air temperature and relative humidity during this process (He et al., 2015). The shading methods coupled with ventilation or evaporative cooling can improve the overall microclimate and the distribution of microclimatic parameters (Ahemd et al., 2016). Several researchers have compared energy use between open-field cultivation and protected cropping under different climate conditions across the globe (Stanhill, 1980; Khoshnevisan et al., 2014; Golzar et al., 2018). Many recent studies investigated the impact of various covering materials on greenhouse crop production and developed models of protected cropping energy, which has led to promising results to effectively manage energy consumption (He et al., 2023; Maier et al., 2023; Lee et al., 2012; Shen et al., 2018; Liu et al., 2010; Moghaddam et al., 2011; Lin et al., 2022; Lin et al., 2024).

Various innovative covering materials have been developed to reduce energy consumption and increase yield and nutritional value using high-transmission light-diffusing glass, wavelength selective photovoltaics, energy-generating photovoltaics (PV) and light-altering greenhouse covers (Cossu et al., 2016; Loik et al., 2017; Ezzaeri et al., 2018; Hassanien et al., 2018; Aroca-Delgado et al., 2019). It is emphasised that a better understanding of greenhouse covering materials with an energy-efficient focus is an opportunity for better yield and higher-nutrient vegetable production in response to global climate challenges (He et al., 2022). Some covering materials change light quality and quantity incident to the crop which can impact yield; however other covering materials optimized for crop production can increase energy consumption (Tani et al., 2014; Alsadon et al., 2016; Ahmadi et al., 2018; Ezzaeri et al., 2018; Mormile et al., 2019; Chavan et al., 2020; He et al., 2021; Zhao et al., 2021). For example, the commercially available (Solar Gard Saint-Gobain) Light blocking film (LBF) ULR-80 increases energy-, water-, and fertilizer-use efficiency, without affecting fruit quality (Chavan et al., 2020; Chavan et al., 2023). However, the energy savings were accompanied by yield reduction in both eggplant and capsicum crops in a cultivar-dependent manner (Chavan et al., 2020; Chavan et al., 2023; Lin et al., 2022). To understand their impact on energy consumption in protected cropping and whether covering materials designed for reducing energy consumption are effective in greenhouse operations requires additional investigation. Key passive climate controls within a protected cropping environment include the use of ventilation components and shade screens (Gruda et al., 2019; Rabbi et al., 2019). Given the range of covering materials that can impact light transmission and crop microclimate conditions differently, optimal ventilation and shading strategies should be determined for each covering material (Samaranayake et al., 2020; Samaranayake et al., 2021). There is still insufficient knowledge on the energy analysis and conservation in protected cropping in relation to the optimal shade screen and ventilation management protocols to utilise for different light-altering covering materials.

In this study the energy used to maintain greenhouse temperature setpoints using selected ventilation and shading configurations under different light-altering covering materials across the summer and winter seasons was assessed. The objectives were to (i) examine the differences across a temperature profile captured under different light-altering glasshouse films, (ii) determine the optimum shade screen and ventilation control configuration under each light-altering covering material for the summer and winter seasons, and (iii) provide guidelines to develop an optimal energy consumption strategy in protected cropping. Two light-altering covering materials and a control (diffused glass) with four ventilation/shade screen configurations were deployed within a high-tech greenhouse and tested during the summer and winter seasons of the south pacific climate. The differential impact of ventilation/shade screen settings on energy consumption according to the growing season and influence by the light-altering cover films can pave standard operating procedures to minimise energy consumption and enhance productivity.

2 Methods and materials

2.1 Greenhouse hardware and software

The study was conducted at the National Vegetable Protected Cropping Centre (NVPCC) in a Venlo-style state-of-the-art research, education, and training greenhouse facility located in the Hawkesbury Campus of Western Sydney University, Richmond NSW, Australia (33.60°S, 150.75°E) to investigate the effect of two different light-altering film treatments on overall cooling energy consumption. We compared a control and two different light-altering glasshouse films under optimum ventilation and shading conditions using six 105-m^2 greenhouse compartments (two compartments for each configuration). The light-altering glasshouse films used in this research included (i) light blocking film (LBF) on the roof and walls, and (ii) light shifting film (LSF) on the roof and walls. The control consisted of a diffuse glass roof and transparent glass walls without additional film. The NVPCC greenhouse uses the Priva control system (Priva, Netherlands) with a sensor box in each compartment positioned at the gutter level to trigger ventilation and mechanical cooling methods. The energy consumption in six compartments was evaluated under four combinations of ventilation and shade screen positions (closed and open) during the day (08:00–17:00 h). Daily and average energy consumption were compared across light treatments as a basis for developing an optimal cooling strategy for energy management.

2.2 Light-shifting and light blocking films

The light-altering glasshouse films, namely, light shifting film (LSF) - Luminescent Light Emitting Agriculture Film (LLEAF), and light blocking film (LBF) – low emissivity film ULR 80 (ultra-low reflectivity with 80% light transmission) were compared to a light diffusing hazed glass as the control. LSF predominantly absorbs light from the green section and emits light in the red section of the light spectrum, which is more efficiently used in photosynthesis. The LBF is a commercially available window glazing material with low thermal emissivity (0.87). LBF blocks the light that mainly contributes to heat but transmits PAR. The HD1AR glass in the control compartments consists of 70% haze in roof glass and 5% haze in wall glass (Glasimport Greenhouses BV, Bovendijk 35, 2295 RV, Kwintsheul, Netherlands).

2.3 Research design

The current study builds on our previous study involving the reduction of cooling energy consumption by regulating the settings (opening/closing) of either shade screens (curtains) or ventilation during the day. The temperature of each compartment at three levels: rooftop (7 m from the floor), mechanical cooler (4.2 m from the floor), and gutter (1.5 m from the floor) was measured. The detailed schematic of the temperature sensors inside the experimental compartments is described in (Samaranayake et al., 2021). We extend this research design in the current study to investigate differences among covering materials in regulating the temperature difference between gutter level and rooftop level. The strategy was used to determine the optimum timeframes for reducing cooling energy via opening and closing of ventilation and shade screens.

2.4 Experimental configuration

The study utilised six research compartments (C1-C6), each configured as per the schematic shown in Figure 1A. The orientation as described in more detail by (Lin et al., 2022). Two replicates of each light-altering configuration were allocated such that one compartment was located in the southeast (SE) direction (C2, C4, and C6) and the other in the northwest (NW) direction (C1, C3, and C5). Unlike other regions where maximising light interception is crucial, greenhouses in Australia are typically oriented north-south to minimise shading effects caused by structural shadows due to Australia's high light levels. An east-west orientation can create consistent shadows in the same part of the crop throughout the day, potentially affecting productivity and plant health. In southern Australia, while an east-west orientation might allow slightly more light, cooling and ventilation needs are more critical (NSW, 2007). Figure 1B illustrates the light transmission characteristics of the respective films. Continuous ventilation systems, measuring 10 m × 1 m when fully open, spanned the length of each compartment (Figures 1C, D). These vents, coupled with Harmony 5,045 shade screens (Svensson, Sweden), which reduce photosynthetically active radiation (PAR) by 50% in direct light and 54% in diffuse light, were utilized across all compartments.

The research compartments implement cooling via mechanical coolers consisting of a fan that pulls air over a coil fed with 6°C water via a cold-water storage tank, chilled by a chiller (Supplementary Figure S1). Each cooler has a capacity of 30 kW at 28°C air temperature, 80% RH (relative humidity), and 6°C cooling water lifted to 16°C. The 6°C water is added to the circulation system of the fan with a modulating valve. The amount of

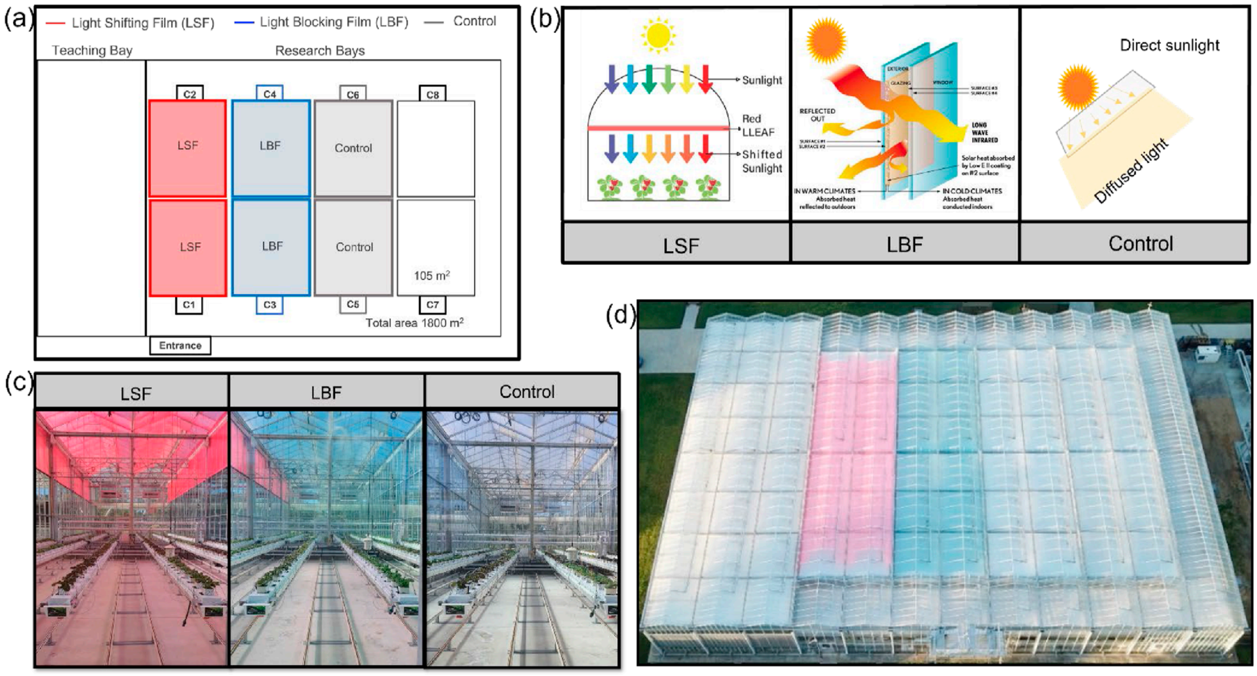

FIGURE 1
Research design and experimental configuration. **(a)** Schematic diagram of six compartments (C1-C6) inside the facility. **(b)** Light transmission diagrams for respective light-altering glasshouse films, **(c)** Side view of LSF, LBF, and control configuration, and **(d)** Roof-top view of light-altering glasshouse films.

6 °C water added to the system depends on the desired temperature of the room.

2.5 Research compartment parameters, light-altering settings, and ventilation options

The experiments were conducted over four time periods (3–4 days each) from 13 to 26 June 2021 (winter season) and 17–29 January 2022 (summer season). These days were selected because weather conditions were similar during each experimental period - cool (winter) and warm (summer) seasons. Four periods are based on a combination of opening and closing of the shade screen and ventilation, namely, Period 1 (P1, shade screen open and ventilation open), Period 2 (P2, shade screen open and ventilation closed), Period 3 (P3, shade screen closed and ventilation closed) and Period 4 (P4, shade screen closed and ventilation open) (Tables 1; Supplementary Table S1). Temperature and energy consumption data were captured from 08:00 to 17:00 each day throughout the entire experiment across four periods. During periods in which ventilation was fully open, the system could override the open setting to close the ventilation in the event of a storm as a protective strategy. These settings are similar to those used in earlier experiments (Samaranayake et al., 2021) to test the impact of ventilation and shade screen opening and closing under normal glass in a closed facility.

The research compartments were set to maintain temperatures within ranges at particular times of day (Table 2). To be specific, the temperature was set to activate heating if it reached 21°C or below between 08:00 and 17:00 (the first time bracket). During the second time bracket (17:00 to 00:00), the heating was set to activate at 15°C or below. In the third time bracket (00:00 to 08:00), 16°C was the set temperature to activate the heating. Regarding the cooling strategy, temperatures were set to 25°C, 17°C, and 18°C for the respective time brackets. No humidity control was utilised during the experiment because there were no crops. In general, when temperatures fell below heating temperatures, heating was activated. When temperatures rose above cooling temperatures, mechanical coolers were activated.

The compartment temperatures were monitored with a temperature sensor connected with the Priva system, they were located at the growing gutter level of the room, and data were logged every 5 min. In addition, Hobo pendant temp/light data loggers (UA-002-08, Onset, MA, United States) were used to monitor temperature at the rooftop, mechanical coolers, and gutter levels. The data loggers recorded the temperature every 15 min. Outside temperatures were also monitored on the southwestern side of the glasshouse facility. Table 2 presents the dates of each period in the winter and summer seasons, shade screen and ventilation status in each period and the corresponding descriptions for this study.

2.6 Data and statistical analysis

Experimental data for temperature and energy consumption were mainly used for the analysis. The daily sums of combined energy consumption, cooling energy consumption and heating energy consumption in each compartment (C1-C6) during

TABLE 1 Experimental periods defined according to the shade screen and ventilation status in each period in C1-C6 greenhouse compartments in experiment 1 (E1) and experiment 2 (E2) conducted during winter and summer, respectively.

Experiment/Season (E)	Dates	Status between 8:00–17:00		Period (P)
		Shade screen	Vent	
E1 - Winter June 2021	13–16	Open	Open	P1
	17–20	Open	Closed	P2
	21–23	Closed	Closed	P3
	24–26	Closed	Open	P4
E2 - Summer January 2022	17–19	Open	Open	P1
	20–22	Open	Closed	P2
	27–29	Closed	Closed	P3
	24–26	Closed	Open	P4

TABLE 2 Summary of variables for experiment 1 (E1) and experiment 2 (E2) in the greenhouse compartment.

Experiment variable	Description
Date	Experiment 1 period from 13 to 26 June 2021, Experiment 2 period from 17 to 29 January 2022
Time	15 min interval from 08:00 to 17:00 each day
T Gutter Level (°C)	Temperature captured at the gutter level
T Rooftop Level (°C)	Temperature captured at the rooftop level
T Outdoor (°C)	Outdoor temperature captured from the weather station installed above the north-western corner of the facility
Instantaneous energy reading - Cooler (kWh)	Energy usage measured in kilowatt-hour for cooling units (>0 active; 0 = inactive) for each time period (15 min)
Instantaneous energy reading - Heater (kWh)	Energy usage measured in kilowatt-hour for heating units (>0 active; 0 = inactive) for each time period (15 min)
Total Energy Consumption	Total energy consumption of each day (08:30–17:00) over the experiment period is evaluated using both heating and cooling energy consumption and refers to the overall sum of the combined energy consumption during a period and/or in a compartment and/or in an experiment (e.g., season)
Combined energy consumption	Combined cooling and heating energy consumption

each experimental period were evaluated, without crops, using the recorded instantaneous energy reading. A summary of energy consumption across treatments, periods and seasons is shown in Table 3.

Descriptive statistics and analysis of variance (ANOVA) of combined energy consumption (cooling and heating) and air temperatures (at gutter, mechanical cooler, rooftop levels and outdoor) under all combinations of shade screen/ventilation settings (P1-P4) and glasshouse films (two light treatments and one control) in winter (June 2021) and Summer (January 2022) seasons are shown in Tables 4, 5. The selection of all combinations of shade screen/ventilation settings for further analysis of the energy profile is based on the need for a comparative analysis of the energy consumption across all combinations, particularly the possible shift of the best ventilation settings when the temperature profile changes from very low in winter to very high in the summer season. Furthermore, this provides an opportunity to explore possible shift of the best combination of ventilation settings of P4 (shade screen closed and ventilation open) in winter for energy consumption under standard lighting conditions (Samaranayake et al., 2020) when light treatments are introduced across two seasons (winter and summer).

Statistical analyses were performed using R statistical programming software R Core Team (2024). Linear regression examined the bivariant relationship among parameters over LSF, LBF and Control. $p \leq 0.05$ was considered as statistical significance. Levene's test from the *car* package was used to test the homogeneity of variance. Welch's t-test for unequal variances was used for parameters showing unequal variance. Shapiro-Wilk test for normality was used to test the normal distribution. Parameters

TABLE 3 The total/sums of cooling, heating and combined energy consumption (kWh) across different statuses of ventilation and shade screens (Periods) and six greenhouse compartments in winter (E1) and summer (E2) experiments.

Exp No (Season)	Period	Shade screen/ Ventilation status	Treatment (Film)	Comp num	Combined energy (KWh)	Cooling (KWh)	Heating (KWh)	Total by period (KWh)	Total by exp (KWh)
E1 (Winter)	1	Open/Open	Control	5	194.77	107	87.77	1331.63	4928.99
				6	202.77	110	92.77		
			Light Blocking	3	269.82	186	83.82		
				4	195.53	103	92.53		
			Light Shifting	1	235.97	165	70.97		
				2	232.77	159	73.77		
	2	Open/Closed	Control	5	229.84	168	61.84	**1670.36**	
				6	250.84	194	56.84		
			Light Blocking	3	**324.84**	263	61.84		
				4	284.84	231	53.84		
			Light Shifting	1	280	231	49		
				2	300	252	48		
	3	Closed/Closed	Control	5	145	105	40	971	
				6	139	101	38		
			Light Blocking	3	184	135	49		
				4	155	107	48		
			Light Shifting	1	**171**	128	43		
				2	177	134	43		

(Continued on the following page)

TABLE 3 (*Continued*) The total/sums of cooling, heating and combined energy consumption (kWh) across different statuses of ventilation and shade screens (Periods) and six greenhouse compartments in winter (E1) and summer (E2) experiments.

Exp No (Season)	Period	Shade screen/ Ventilation status	Treatment (Film)	Comp num	Combined energy (KWh)	Cooling (KWh)	Heating (KWh)	Total by period (KWh)	Total by exp (KWh)
	4	Closed/Open	Control	5	155	120	35	**956**	
				6	125	90	35		
			Light Blocking	3	188	151	37		
				4	**117**	82	35		
			Light Shifting	1	197	165	32		
				2	174	143	31		
E2 (Summer)	1	Open/Open	Control	5	467.91	467.91	0	3176.43	14,072.21
				6	484.87	452.87	32		
			Light Blocking	3	536	471	65		
				4	534.87	436.91	97.96		
			Light Shifting	1	617.87	586.87	31		
				2	534.91	502.91	32		
	2	Open/Closed	Control	5	546.83	546.83	0	3323.97	
				6	527.83	527.83	0		
			Light Blocking	3	565.85	565.85	0		
				4	538.89	538.89	0		
			Light Shifting	1	585.83	585.83	0		
				2	558.74	558.74	0		

(Continued on the following page)

TABLE 3 (*Continued*) The total/sums of cooling, heating and combined energy consumption (kWh) across different statuses of ventilation and shade screens (Periods) and six greenhouse compartments in winter (E1) and summer (E2) experiments.

Exp No (Season)	Period	Shade screen/ Ventilation status	Treatment (Film)	Comp num	Combined energy (KWh)	Cooling (KWh)	Heating (KWh)	Total by period (KWh)	Total by exp (KWh)
	3	Closed/Closed	Control	5	555.84	523.84	32	3339.19	
				6	526.87	495.87	31		
			Light Blocking	3	505.91	505.91	0		
				4	462.88	462.88	0		
			Light Shifting	1	706.82	675.82	31		
				2	580.87	548.87	32		
	4	Closed/Open	Control	5	666.15	666.15	0	4232.62	
				6	651.02	651.02	0		
			Light Blocking	3	665.29	665.29	0		
				4	669.29	669.29	0		
			Light Shifting	1	**849**	849	0		
				2	731.87	731.87	0		

Bold values indicate the lowest or highest numbers for energy consumption.

TABLE 4 Descriptive statistics and analysis of variance (ANOVA) of combined energy consumption in winter experiment 1 (E1) and summer experiment 2 (E2).

Exp number (Season)	Period	Shade screen/ Ventilation status	Combined energy consumption (KWh d-1)		One way ANOVA/ Welch's F test/ Kruskal test	Ranked two way ANOVA - T*P			Mean combined energy consumption (KWh d-1)	Ranked two way ANOVA T*E		
			Treatment film	Mean ± se		Treatment	Period	Interaction		Treatment	Experiment	Interaction
E1 (Winter)	1	Open/Open	Control	49.6 ± 3.1	0.27	0.08	0.23	0.93	58.7 ± 2.3	0.053	2×10^{-16}	0.83
			Light Blocking	58.1 ± 5.5								
			Light Shifting	58.5 ± 5.2								
	2	Open/Closed	Control	60 ± 10.3	0.56							
			Light Blocking	76.2 ± 11.1								
			Light Shifting	72.5 ± 11.6								
	3	Closed/Closed	Control	47.3 ± 5.9	0.54							
			Light Blocking	56.5 ± 7.3								
			Light Shifting	58 ± 9.2								
	4	Closed/Open	Control	46.6 ± 2.6	0.02							
			Light Blocking	50.8 ± 5.6								
			Light Shifting	61.8 ± 3.6								
E2 (Summer)	1	Open/Open	Control	158.7 ± 51.8	0.70	0.044	0.00096	0.89	195.4 ± 8.2			
			Light Blocking	178.4 ± 50.2								
			Light Shifting	192.1 ± 59.7								
	2	Open/Closed	Control	179.11 ± 5.7	0.41							
			Light Blocking	184.1 ± 6.3								
			Light Shifting	190.7 ± 6.1								

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TABLE 4 *(Continued)* Descriptive statistics and analysis of variance (ANOVA) of combined energy consumption in winter experiment 1 (E1) and summer experiment 2 (E2).

Exp number (Season)	Period	Shade screen/ Ventilation status	Combined energy consumption (KWh d-1)		One way ANOVA/ Welch's F test/ Kruskal test	Ranked two way ANOVA - T*P			Mean combined energy consumption (KWh d-1)	Ranked two way ANOVA T*E		
			Treatment film	Mean ± se		Treatment	Period	Interaction		Treatment	Experiment	Interaction
	3	Closed/Closed	Control	180.4 ± 7	0.01							
			Light Blocking	161.4 ± 11.1								
			Light Shifting	214.6 ± 10.6								
	4	Closed/Open	Control	219.5 ± 9.9	0.02							
			Light Blocking	222.4 ± 10.4								
			Light Shifting	263.4 ± 13.3								

with non-normal distribution were then analysed using a non-parametric equivalent of one-way analysis of variance (ANOVA), the Kruskal–Wallis Test. Non-parametric two-way ANOVA was performed using the ranked transformation method. Other packages used included *lubridate* (for effective use of dates in plots), *sciplot* (for plotting), *tidyverse and dplyr* (for data manipulation), *HIEv* (for data download from local sever), and *doBy* (for calculating means and standard errors). The effects impact of light treatments and experiments and their interactions on energy consumption and temperature parameters were analysed using one-way and two-way ANOVA functions in the *car* package. The Tukey *post hoc* test was performed using TukeyHSD function in *agricolae* package. Linear modelling function in R was used for correlation analysis. The significance levels were non-significant (ns),*,**, and ***indicated $p > 0.05$, $p \le 0.05$, $p \le 0.01$, and $p \le 0.001$, respectively.

3 Results

3.1 Comparison of total (sum of cooling and heating) energy consumption across periods, light treatments, and seasons

The total energy consumption (sum of the combined cooling and heating energy consumption) of each experimental period (shade screen-ventilation settings) was evaluated using the recorded instantaneous energy reading (Table 3). In winter, the period sum of energy consumption was highest in P2 at 1,670 kWh and lowest in P4 at 956 kWh (Table 3). Among individual light treatments in each period, both the maximum (324 KWh in P2) and minimum (117 KWh in P4) energy consumptions were observed only under the LBF. The most energy-efficient setup for winter was found to be P4 covered with the LBF. The highest energy consumption in winter was more than 2.75 times the lowest (Table 3).

In contrast, the summer experiment showed an opposite trend. The P4, which was the most energy-efficient in winter, had the highest period sum of energy consumption in summer at 4,232 kWh. All other periods (P1, P2, and P3) had lower and similar energy consumption levels, ranging from 3,176 kWh to 3,339 kWh (Table 3). Among individual light treatments in each period, the highest energy consumption (849 kWh) occurred with the shade screen closed and ventilation open (P4) under the LSF. In contrast, the lowest energy consumption (462.88 kWh) was observed when both the shade screen and ventilation were closed (P3) under the LBF. Interestingly, the ventilation setting P4 (shade screen closed and ventilation open) was more effective in reducing total energy consumption in winter, yet less effective in summer (Table 3).

It is worth noting that the light treatment and ventilation settings (periods) significantly affected the net SW and long-wave radiation in both winter and summer experiments. While periods P3 and P4 (shade screen closed in both periods) had significantly lower short-wave radiation than periods P1 and P2 (shade screen opened in both periods), LBF significantly reduced the short-wave radiation in all periods (−68% to −73%, p < 0.001) (Supplementary Table S2; Supplementary Figure S2). Moreover, compartment numbers C1, C3 and C5 (located on the northwest side of the facility) exhibited generally high total energy consumption compared to C2, C4 and C6 (located on the southeast side of the facility) depending on the period and light treatment (Table 3; Supplementary Figures S3, S4). For instance, the orientation effect was stronger in LBF in winter and in LSF in summer.

Overall, total energy consumption (across all periods and light treatments) during summer (14,072 kWh) was almost 3-fold higher than winter (4,928 kWh) and the LBF film with both shade/ventilation closed (P3) was more effective in reducing energy consumption in summer rather than LBF film with shade closed and ventilation open in winter.

3.2 Comparison of combined energy consumption across periods, light treatments, and seasons

The daily sum of combined energy consumption was compared by comparing "treatment" (light-altering glasshouse film) and "season" as well as "treatment" and "period" (shade screen-ventilation settings) factors (Table 4). The summer season showed a significantly higher mean energy consumption (increasing from 58.7 KWh to 195.4 KWh (+233%), $p < 0.001$) compared to winter (Table 4; Figure 2). When comparing energy consumption between treatment and period in each season, the summer season showed a statistically significant effect of light treatment ($p < 0.04$) and period ($p < 0.009$) on the mean energy consumption. In contrast, during the winter season there was no significant difference in daily energy consumption between treatment and period. Moreover, the lowest daily energy consumption was recorded (46.6 KWh) in P4 under Control while the highest energy consumption was recorded (76.2 KWh) in P2 under the LBF during the winter season (Table 4).

When comparing energy consumption among treatments in each period, a significant increase (+33%, $p = 0.02$) in energy consumption (evident from one-way ANOVA) was observed for the LSF in P4 during winter (despite a non-significant impact of light treatment evident from two-way ANOVA; $p < 0.08$) and in P3 (+19%; $p < 0.01$) and P4 (+20%; $p < 0.02$) during summer (Table 4; Figure 2). The LSF exhibited the largest mean combined energy consumption compared to LBF and Control glass, except in P2 during winter (Table 4). Within individual periods, light treatment significantly affected energy consumption in P4 (shade screen closed and ventilation open) during winter. In fact, the daily energy consumption under control treatments was the lowest across all periods, compared to that of the LBF and LSF. This could be attributed to the low rooftop temperature during the winter season relative to summer. Similarly, in summer, the daily energy consumption under the control treatment was the lowest across all periods except P3, compared to that of the LBF and LSF. Moreover, the impact of compartment orientation on mean total energy consumption was not statistically significant (Supplementary Figures S3, S4). Overall, while the mean combined energy consumption was significantly higher in summer compared to winter, the treatment and ventilation settings combined reduced energy consumption only in summer.

TABLE 5 *(Continued)* Descriptive statistics and analysis of variance (ANOVA) of air temperatures at base, rooftop and outside during winter experiment 1 (E1) and summer experiment 2 (E2).

Exp number (Season)	Period	Shade screen/Ventilation status	Treatment (film)	Daily mean temperatures (°C)			One way ANOVA	Rooftop temp – Two-way ANOVA		
				Outside (O)	Base (B)	Rooftop (T)		Treatment	Period	Interaction
	4	Closed/Open	Control	27.9 ± 0.2	25.7 ± 0.1	51.5 ± 0.5	0.503			
			Light Blocking		25.3 ± 0.1	53.8 ± 0.7				
			Light Shifting		26.8 ± 0.1	55.7 ± 0.7				

TABLE 5 Descriptive statistics and analysis of variance (ANOVA) of air temperatures at base, rooftop and outside during winter experiment 1 (E1) and summer experiment 2 (E2).

Exp number (Season)	Period	Shade screen/Ventilation status	Treatment (film)	Daily mean temperatures (°C)			One way ANOVA	Rooftop temp – Two-way ANOVA		
				Outside (O)	Base (B)	Rooftop (T)		Treatment	Period	Interaction
	1	Open/Open	Control	15.3 ± 0.2	22.5 ± 0.2	28.7 ± 0.4	0.333	0.01	0.37	0.9
			Light Blocking		22.7 ± 0.1	26.8 ± 0.3				
			Light Shifting		23.2 ± 0.1	28.8 ± 0.3				
	2	Open/Closed	Control	15.2 ± 0.1	23.6 ± 0.1	27.8 ± 0.3	0.378			
			Light Blocking		23.6 ± 0.1	26.1 ± 0.3				
			Light Shifting		24.1 ± 0.1	28.6 ± 0.3				
	3	Closed/Closed	Control	14.5 ± 0.2	23.5 ± 0.1	28.8 ± 0.6	0.584			
			Light Blocking		23.5 ± 0.1	28.3 ± 0.6				
			Light Shifting		24 ± 0.1	31.2 ± 0.6				
	4	Closed/Open	Control	17.4 ± 0.2	23.3 ± 0.1	28.7 ± 0.5	0.029			
			Light Blocking		23.3 ± 0.1	25.7 ± 0.4				
			Light Shifting		23.8 ± 0.1	29.7 ± 0.5				
	1	Open/Open	Control	24.1 ± 0.3	25.6 ± 0.2	30.8 ± 0.5	0.393	0.6	8.6×10^{-11}	0.9
			Light Blocking		25.4 ± 0.2	30.1 ± 0.5				
			Light Shifting		26 ± 0.2	31.1 ± 0.5				
	2	Open/Closed	Control	22.3 ± 0.1	25.3 ± 0.1	33.3 ± 0.3	0.963			
			Light Blocking		25.2 ± 0.1	33.6 ± 0.4				
			Light Shifting		25.7 ± 0.1	33.2 ± 0.3				
	3	Closed/Closed	Control	25.4 ± 0.1	25 ± 0	40.1 ± 0.4	0.4			
			Light Blocking		24.8 ± 0	38.5 ± 0.4				
			Light Shifting		25.5 ± 0.1	41.5 ± 0.5				

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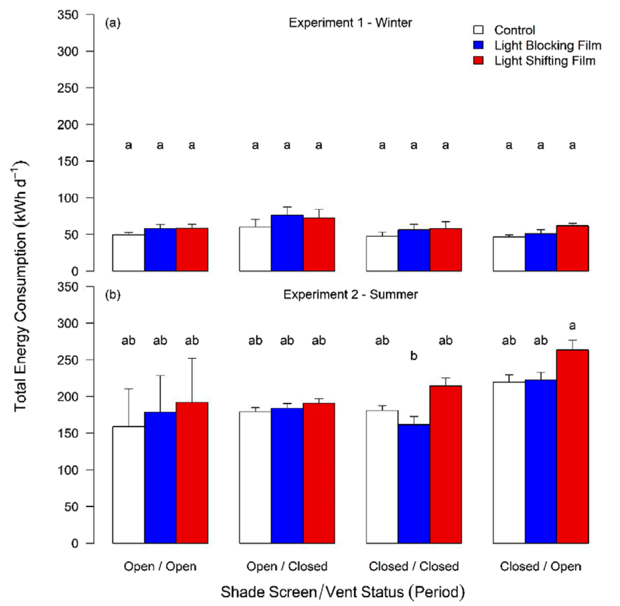

FIGURE 2
Effect of light-altering films on the total (combined) energy consumption across seasons and periods. Bar plot depicting combined energy consumption during Period 1 (Shade screen open and Ventilation open), Period 2 (Shade screen open and Ventilation closed), Period 3 (Shade screen closed and Ventilation closed) and Period 4 (Shade screen closed and Ventilation open) – Under light shifting film, Under light blocking film, and Under control film in **(a)** Experiment 1 (Winter), **(b)** Experiment 2 (Summer). Values are means ± standard errors.

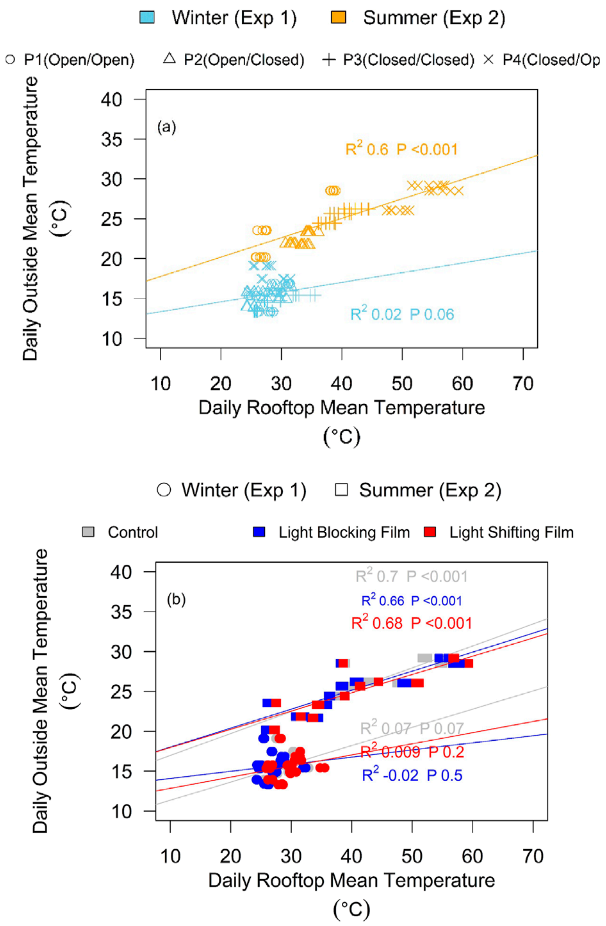

FIGURE 3
Correlation between daily mean outside air temperatures and daily mean rooftop air temperatures. **(a)** shows the effect of seasons. Experiments 1 and 2 are depicted in sky blue and orange, respectively and periods (shade screen/ventilation status) 1, 2, 3 and 4 are shown using circle, triangle, plus and cross symbols respectively. **(b)** shows the effect of light treatments. Experiments 1 and 2 are shown using circle and square symbols, respectively and light treatments light shifting film (LSF), light blocking film (LBF) and control are shown in red, blue and grey respectively.

3.3 Influence of light treatment and period on the rooftop level temperature

Winter mean rooftop level temperatures ranged between 25.7°C and 31.2°C and the summer mean rooftop level temperatures ranged between 30.1°C and 55.7°C indicating the maximum mean rooftop level temperatures in summer were significantly higher compared to winter (Table 5; Figures 3, 4). The rooftop level temperatures using "treatment" (light-altering glasshouse film) versus "period" (shade screen-ventilation settings) factors displayed a significant effect of the light treatment on rooftop temperatures only during winter and ventilation settings (period) only during summer (Table 5). During winter, the LBF significantly reduced rooftop level temperatures (−10%, $p = 0.03$) in Period 4 (Table 5). In contrast, there was a significant increase in rooftop temperatures ($p < 3.8 \times 10^{-6}$) from periods 1 to 4 during summer, that is the period 4 rooftop temperature was 75% higher than Period 1 (Table 5). There was a significant effect of light treatment on both energy consumption and rooftop-level temperature in period 4 during winter, and a significant effect of the period on both energy consumption and rooftop temperatures during summer. Therefore, there was a significant effect of light treatment on (i) energy consumption under ventilation settings of shade screen closed and ventilation open (P4) and (ii) rooftop temperatures during winter.

3.4 Relationships between daily energy consumption, outdoor temperature and rooftop-level temperature

Next, we analysed the relationships between daily energy consumption, outdoor temperature and rooftop temperature were considered across periods (shade screen-ventilation settings) and light treatments during both winter and summer seasons. Daily outside and rooftop mean air temperatures showed a significant positive correlation during summer ($R^2 = 0.60$, $p < 0.001$) but not during winter ($R^2 = 0.02$, $p < 0.06$) (Figure 3A). However, the correlation between daily outside and rooftop mean air temperatures was unaffected by the light treatment during both winter and summer seasons (Figure 3B). Daily cooling energy consumption showed a significant positive correlation with daily outside mean air temperatures during summer ($R^2 = 0.62$, $p < 0.001$) but not winter ($R^2 = 0.04$, $p < 0.02$) (Figure 4A). While the daily cooling energy

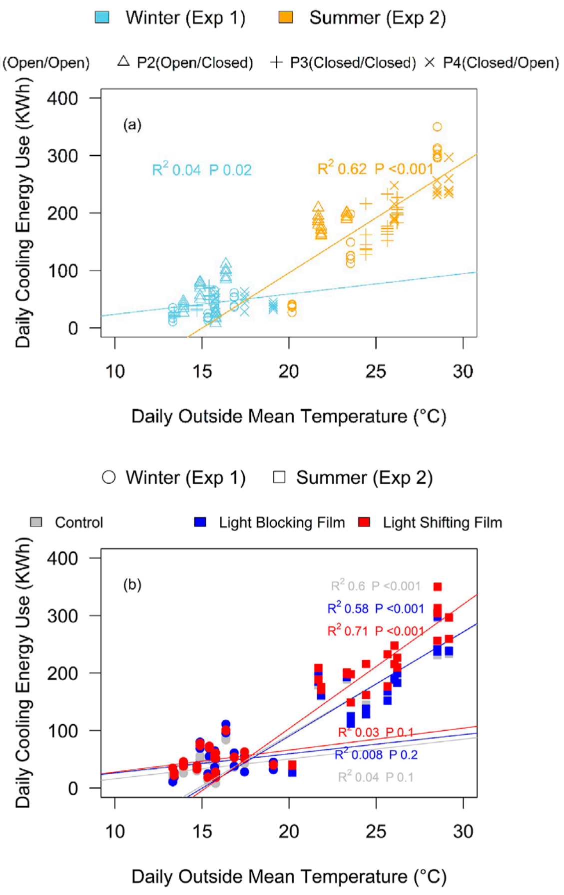

FIGURE 4
Correlation between daily cooling energy use and daily mean outside temperatures. **(a)** shows the effect of seasons. Experiments 1 and 2 are depicted in sky blue and orange, respectively and periods (shade screen/ventilation status) 1, 2, 3 and 4 are shown using circle, triangle, plus and cross symbols respectively. **(b)** shows effect of light treatments. Experiments 1 and 2 are shown using circle and square symbols, respectively and light treatments light shifting film (LSF), light blocking film (LBF) and control are shown in red, blue and grey respectively.

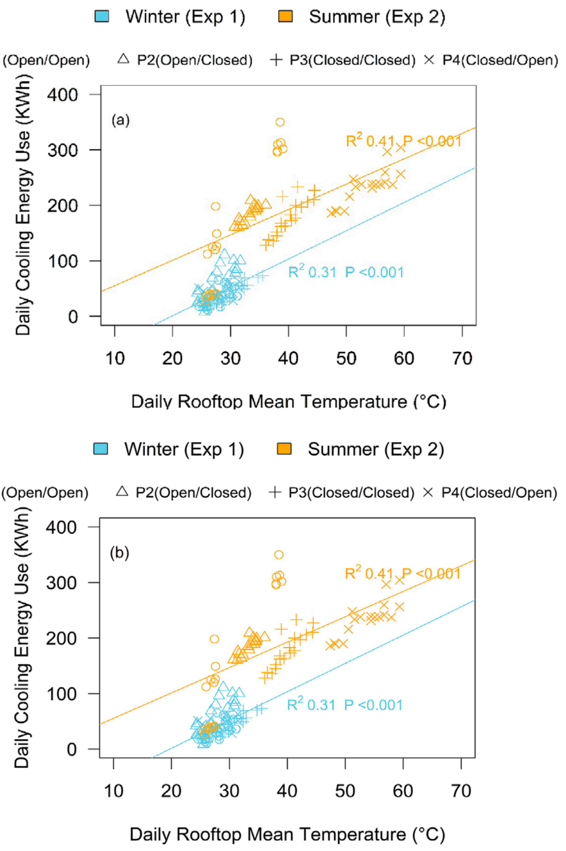

FIGURE 5
Correlation between daily cooling energy use and mean outside rooftop temperatures. **(a)** shows the effect of seasons on the correlation between daily cooling energy use and daily rooftop mean temperatures Experiments 1 and 2 are shown using circle and square symbols, respectively and light treatments light shifting film (LSF), light blocking film (LBF) and control are shown in red, blue and grey respectively. **(b)** shows correlation between daily cooling energy use and daily rooftop mean temperatures. Experiments 1 and 2 are shown using circle and square symbols, respectively and light treatments light shifting film (LSF), light blocking film (LBF) and control are shown in red, blue and grey respectively.

consumption showed a stronger correlation with outside mean air temperature under the LSF ($R^2 = 0.71$, $p < 0.001$) compared to the LBF ($R^2 = 0.58$, $p < 0.001$) or control ($R^2 = 0.6$, $p < 0.001$) during summer, there was no significant correlation between the daily cooling energy consumption and outside mean air temperatures across light treatments during winter (Figure 4B). The daily cooling energy consumption showed a significant positive correlation with daily rooftop mean air temperatures during both summer ($R^2 = 0.41$, $p < 0.001$) and winter ($R^2 = 0.31$, $p < 0.02$) (Figure 5A). The correlation between daily cooling energy consumption and the rooftop air temperatures appeared to be unaffected by the light treatment during summer yet the daily cooling energy consumption showed a stronger correlation with rooftop mean air temperatures when using the LSF ($R^2 = 0.46$, $p < 0.001$) and control ($R^2 = 0.45$, $p < 0.001$) when compared to the LBF during winter ($R^2 = 0.29$, $p < 0.001$; Figure 5B). In summary, there was a large increase in mean rooftop temperature, and hence higher cooling energy consumption, with a small increase in outside temperature across all periods, indicating incoming radiation contributed to heating. Furthermore, the light treatments slightly modified the relationships between daily cooling energy consumption, daily mean rooftop temperature, and daily outside temperature (Figures 3–5).

3.5 Diurnal changes affect energy consumption and rooftop-level temperature interactions during winter

To ascertain if diurnal changes affected the relationship between energy consumption, outside temperature and rooftop-temperature during winter, we compared P2 and P4, previously identified as the worst and best configurations, respectively in terms of combined energy consumption (Samaranayake et al., 2021). P2 had the least favourable combination of ventilation settings with the highest daily energy consumption and second highest rooftop temperature,

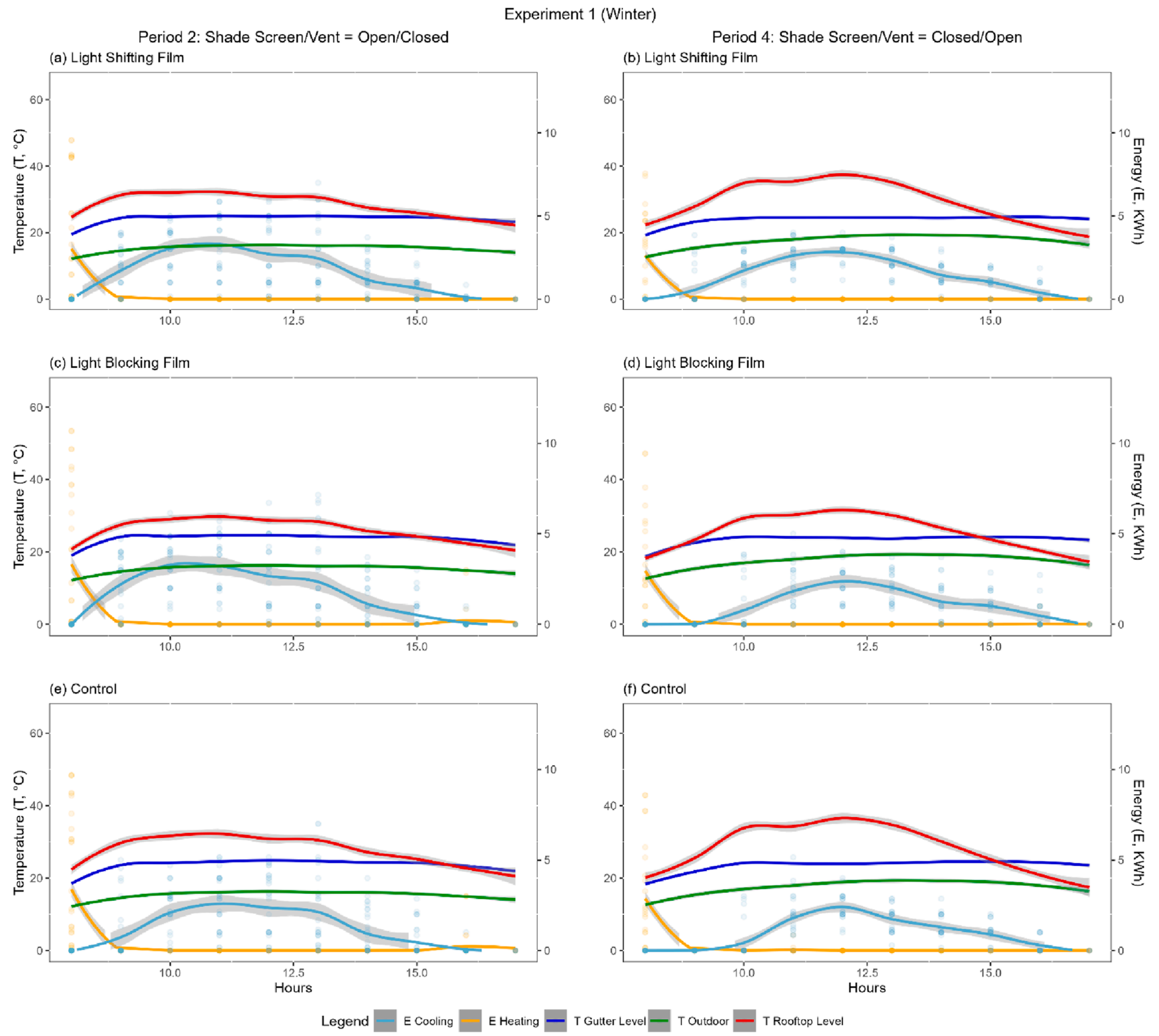

FIGURE 6
Temperature and energy use in Period 2 and Period 4 under light shifting film, light blocking film, and control in Winter. Temperature and energy use in Period 2 (Shade screen open and Ventilation closed) and Period 4 (Shade screen closed and Ventilation open) – **(a, b)** Under light shifting film, **(c, d)** Under light blocking film, and **(e, f)** Under control in Experiment 1 (winter season). Air temperatures collected at the gutter level, rooftop level, and outside are depicted in blue, red, and green lines respectively. Energy use on cooling and heating are depicted over time using sky blue and orange colour shaded regions.

whereas P4 was the most favourable combination of ventilation settings, exhibiting the lowest daily energy consumption and the lowest rooftop temperature (Tables 4, 5; Figure 6).

Periods 2 and 4 showed stable ambient gutter level and outdoor temperatures with negligible diurnal changes, but rooftop level temperatures peaked in the middle of the day with corresponding diurnal changes in cooling energy use (Figure 6) indicating the accumulation of heat could be due to incoming radiation. P2 showed slightly higher combined energy use than P4. This could be attributed to the open shade screen and closed ventilation status of P2 which allowed incoming radiation and heat retention respectively in contrast to the closed shade screen open ventilation status of P4 which blocks incoming radiation and heat escape respectively. Furthermore, light treatment significantly affected the rooftop level temperatures and cooling energy use in P4 but not in P2 (Tables 4, 5; Figure 6). In P4, LSF showed significantly higher energy consumption (Table 4, One-Way ANOVA $p = 0.02$) than LBF which could be explained by significantly high rooftop temperatures (Table 5, One-Way ANOVA $p = 0.029$) in LSF compared to LBF. Overall, there is a strong relationship between combined daily energy consumption and rooftop temperature, particularly the lowest daily energy consumption correlates with a low rooftop-level temperature in P4 in winter.

3.6 Diurnal changes in the correlation between energy consumption and rooftop-level temperature in summer

We considered all four periods (shade screen and ventilation settings) for further analysis of diurnal changes in the correlation between energy consumption and rooftop-level temperature in summer as both light treatment and period significantly affected the energy consumption (Table 4) and the rooftop temperature (Table 5). While P1 exhibited the lowest daily energy consumption and rooftop temperature, P4 exhibited the highest daily energy consumption and rooftop temperature in summer (Table 4; Figure 2) emphasising the strong correlation between energy consumption and rooftop temperature (Figure 5). Despite stable ambient gutter level and outdoor temperatures with negligible diurnal changes, rooftop temperatures were significantly higher in P4 compared to P2 and peaked during morning hours with corresponding diurnal changes in cooling energy only in P4 (Figure 7). The P4 rooftop temperatures were generally high in the morning hours (from the monitored start time 8 am to 12 pm) and started to decline after midday. Furthermore, energy consumption was generally high in all periods under LSF with statistically significant increases in P3 ($p = 0.01$) and P4 ($p = 0.02$). In summary, compared to all other periods, P4 with closed shade screen and open ventilation exhibited the highest rooftop temperatures and consequently high energy consumption for cooling during the summer season which has higher outside temperatures.

4 Discussion

This study investigated energy consumption under different light-altering methods and ventilation settings across winter and summer in a high-tech glasshouse in a subtropical climate of Eastern Australia. The overall energy consumption strongly depended on light-altering methods, ventilation settings and meteorological conditions (external temperature). Since cooling energy consumption in protected cropping is found to be a significant portion of total energy consumption in many regions in Australia, the optimal energy cost efficiency can be best achieved during the winter season, compared to that of the summer season. The LBF was identified as the most effective for optimising total energy consumption in winter with ventilation settings of ventilation open and shades closed, and in summer with both ventilation and shades closed. In conclusion, during the summer, the most efficient combination involves LBF light treatment with both ventilation and shades closed. In contrast, for winter, the optimal configuration is LBF light treatment with ventilation open and shades closed (Table 3). Given that LBF light treatment is the most effective for optimising total energy consumption in both winter and summer, the impact of ventilation settings can be considered a significant aspect of control for reducing cooling energy consumption, particularly in summer, and achieving overall energy consumption (Rabbi et al., 2019; Samaranayake et al., 2021). We concluded that the combined effect of light-altering methods and ventilation settings on optimal energy consumption is much higher than the sum of individual effects. The sum of combined effects can be used as a guide for developing a framework for selecting the right combinations of ventilation settings and light-altering methods under different meteorological conditions for optimum energy consumption during crop cycles.

4.1 Light-altering films and shade screen ventilation settings affect energy consumption in a season-dependent manner

While combining shading with cooling methods can lower greenhouse air temperature (−5°C–10°C), increase relative humidity (+15–20%), and reduce solar radiation (−30%–50%) in sunny regions, shading materials act as insulators, maintaining greenhouse air temperature 5°C higher than outside and saving 15%–20% on heating energy in cold regions (Montero et al., 2013; Ahemd et al., 2016). In the current study, the summer recorded significantly higher energy consumption relative to winter, and light treatment and ventilation settings' impact on energy consumption was further modified by significant outside temperature differences between the summer and winter seasons. In winter, both ventilation settings (periods) and light treatment showed slight differences in total (overall sum) energy consumption (Table 3); however, these differences were masked by within-treatment variation between compartments potentially due to their orientation (SE and NW) when mean energy consumption was compared using two-way ANOVA (Table 4). The impact of orientation can be explained by high heating due to the afternoon radiation in compartments C1, C3 and C5 compared to C2, C4 and C6 (Soussi et al., 2022).

Despite the non-significant impact of either the light treatment or period (shade screen ventilation setting) on mean combined energy consumption in winter (Table 4), the total (overall sum) of the energy consumption showed significantly higher energy consumption under open shade screen and closed vents (Table 3) that allow heat accumulation due to incoming radiation and heat-trapping, respectively. Thus, the effect of shade screen ventilation settings on energy consumption was more prominent than the light-altering film treatment during the winter season, which could be attributed to less influence of the low outside temperature on the overall temperature of the facility. In contrast, both the mean and absolute total energy consumption (Tables 3, 4) significantly increased from periods P1 to P4, and mean energy consumption was significantly higher under the LSF in P3 and P4 during summer (Table 4). Thus, P4 with the highest energy consumption allows heat transfer through open vents and heat build-up via closed shade screens in hot summer conditions, and high energy consumption under LSF during summer can be potentially due to the North to South sequence of LSF, LBF and Control compartment locations which leads to a more light reception in LSF (Lin et al., 2022). Noteworthily, compartment 4 fitted with LBF recorded the lowest energy consumption in P4 and P3 of winter and summer respectively. Low energy consumption under LBF (when not affected by afternoon heating, e.g., compartment 3) is in line with previous studies in eggplant (brinjal) that have demonstrated low energy consumption under LBF (Chavan et al., 2020; Lin et al., 2022). Furthermore, the inability of ventilation settings to reduce energy consumption in summer can be explained by the physical phenomenon of no effect of pushing hot air out of the room when

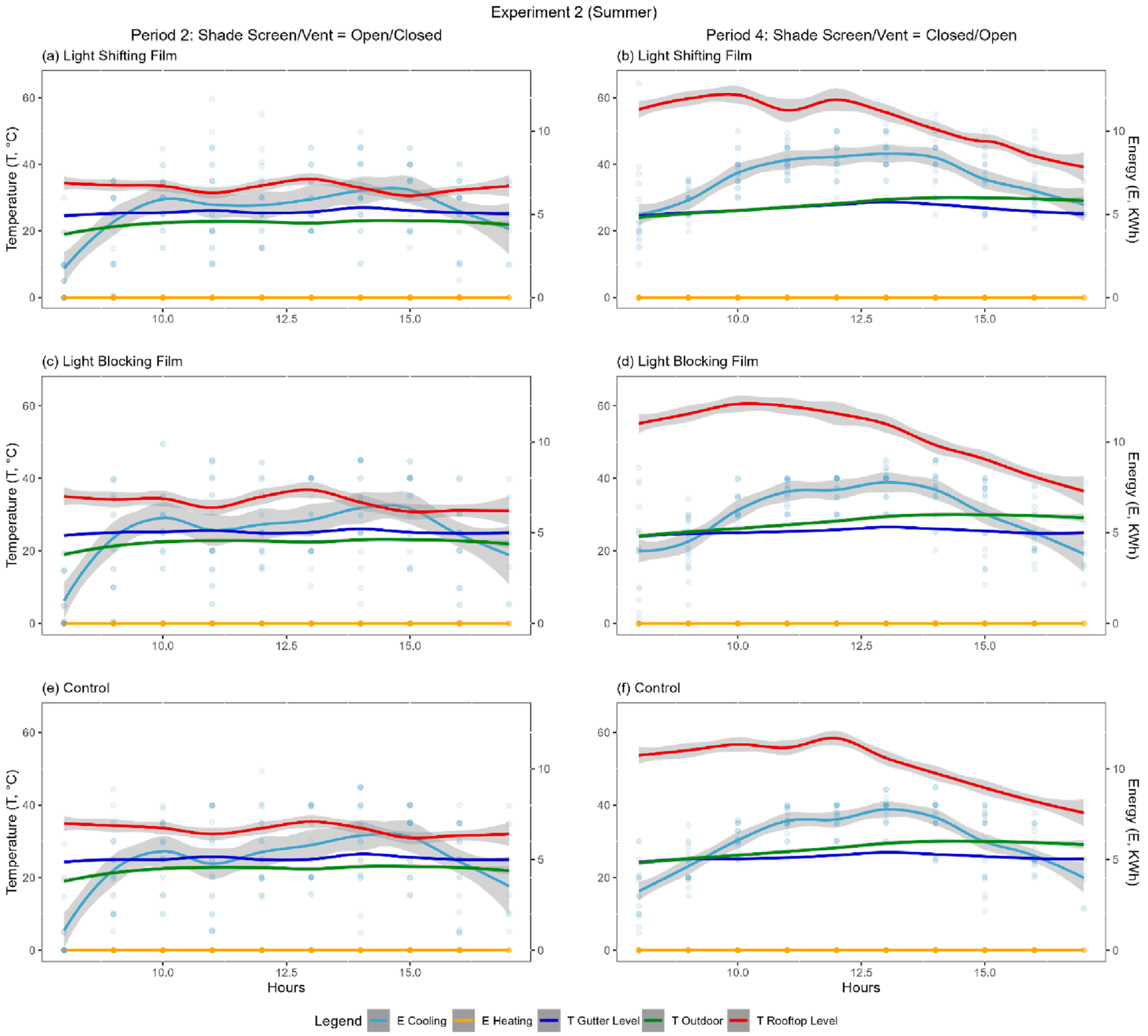

FIGURE 7
Temperature and energy use in Period 2 and Period 4 under light shifting film, light blocking film, and control in Summer. Temperature and energy use in Period 2 (Shade screen open and Ventilation closed) and Period 4 (Shade screen closed and Ventilation open) – **(a, b)** Under light shifting film (LBF), **(c, d)** Under light blocking film, and **(e, f)** Under control film in Experiment 2 (Summer season). Air temperatures collected at the gutter level, rooftop level, and outside are depicted in blue, red, and green lines respectively. Energy use on cooling and heating are depicted over time using sky blue and orange colour shaded regions.

the inside temperature is already above the outside temperature at different dates and times of the summer season. This observation is aligned with the concept of heat transfer, particularly the concept of "natural convection" and "thermal equilibrium" where the effectiveness of ventilation depends on the temperature difference between the inside and outside. When the temperatures are similar, or the inside temperature is higher, the ventilation system cannot efficiently expel heat (Ganguly and Ghosh, 2010; Kreith et al., 2011).

In addition, a significant reduction in net short-wave (SW) under LBF did not correlate with combined energy consumption. However, despite a significant blockage in net SW radiation by LBF the energy on cooling was not reduced under LBF. This could be explained by the transfer of heat through the convection of the glass and ventilation (Lin et al., 2022). The best combination of ventilation and shade screen settings for optimal energy consumption depended on the season and the effect of light treatment on energy consumption noted in this research is aligned with the notion of improving light transmission and solar energy capture while promoting energy-saving (He et al., 2021). Overall, there was a shift in the effect of the period on energy consumption in summer compared to winter. P4, the best period in terms of efficient energy consumption in winter became the least effective period with the highest energy consumption in summer (Tables 3, 4; Figure 2). This could be attributed to the following factors, (i) very high outside temperature during summer (e.g., the higher average temperature of 17.4 in winter, compared to 27.9 in summer), leading to significantly high rooftop temperature in all periods (e.g., 55.7 in P4), and (ii) less effectiveness of ventilation settings in high outside temperature.

4.2 Rooftop level temperature drives energy consumption in both winter and summer

Since summer energy consumption is significantly higher than that in winter and much of the total energy is attributed to cooling (even in the winter season), temperature profile (particularly the warmer temperatures) plays a significant role in the energy consumption. The roof vent affects the temperature and air velocity at the roof level and vent closure increases the roof temperatures as the air becomes stagnant above the height of the roof vent (Akrami et al., 2020). In the current study, the rooftop temperature and hence cooling energy use positively correlated with outside air temperatures in summer but not winter suggesting that outside temperatures contributed to an increase in the rooftop temperatures in summer but not in winter (Figures 3, 4). However, daily cooling energy use positively correlated with rooftop-level temperatures in both winter and summer (Figure 5) suggesting that rooftop-level temperatures were key drivers of energy consumption. Hence, the cooling energy consumption in the winter season may have been due to the incoming radiation and high rooftop temperatures preserved during the nighttime. This in conjunction with the lowest energy consumption recorded during P4 in winter suggests that mild outside air temperatures lead to heat build-up at the rooftop level and periodic ventilation opening during winter can release this heat build-up which demands cooling.

In addition, it is worth noting that open ventilation and closed shade screen in P4 during summer allowed extremely high rooftop temperatures because of the heat transfer from outside hot air to inside the glasshouse since early morning but not during P1 with open ventilation and open shade screen (Figure 7). This suggests the potential role of closed shade screens in contributing to extremely high rooftop temperatures in P4 during summer. Furthermore, while light-altering films did not affect the correlation between the rooftop temperature and outside air temperatures, periods significantly affected this correlation in only summer further confirming that overall light-altering films have no effect in either winter or summer, but periods affected rooftop temperature and hence energy consumption in summer. Taken together, significantly high energy consumption in summer compared to that in winter and the significant effect of light treatment on energy consumption in summer could be attributed to the high rooftop temperature of the facility in summer, influenced by high outside temperature.

4.3 Optimal strategies for greenhouse energy management

An optimal strategy for energy management using multi-temperature acquisition points for opening/closing of ventilation and shade screens under each configuration could be used to improve the overall energy consumption efficiency of the selected protected cropping facility (Chavan et al., 2020; Samaranayake et al., 2020). The current study extends previous experiments that demonstrate the use of shade nets to improve microclimate, crop production, and crop quality while saving energy (Kittas et al., 2012; Zhang et al., 2022).

Since cooling energy consumption is a significant proportion of total energy consumption, the potential saving of cooling using the optimal conditions of light-altering methods and ventilation settings could be significant. Furthermore, significant cost savings can be achieved over a crop cycle using the optimal settings, by selecting an appropriate timeframe (i.e., start and end dates) for the crop cycle, depending on the meteorological conditions. The temperature profile significantly impacts the ventilation settings and light-altering methods that affect energy consumption. Therefore, selecting optimum ventilation settings and light-altering methods for minimal energy use requires considering the weather season. In this context, selecting the optimum settings in conjunction with the facility's temperature profiles across varying meteorological conditions can inform the development of guidelines for scheduling crop cycles. Overall, these research findings can be used to develop a protected cropping operational framework of light-altering methods, and ventilation settings for optimum energy consumption, aligned with specific requirements of crop cycles and expected meteorological conditions.

5 Conclusion

The current study demonstrates optimal glasshouse energy management strategies by investigating energy consumption under different shading, light-altering and ventilation conditions. Key findings of this research study include (i) the effect of light treatment and shade screen ventilation settings on energy consumption changes with the seasons, and (ii) the significant role of rooftop level temperature as the primary driver of energy consumption in both winter and summer. These findings form a basis for selecting the best combination of light treatment methods and ventilation settings (opening or closing of ventilation and shade screens), using the most reliable temperature measurements within the facility, to reduce energy costs during 6–9 months of cropping cycles. However, there was a limitation to this research in that each experimental setting is run only for 3–4 days in two seasons (winter and summer).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SC: Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review and editing. PS: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. Y-CL: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing–original draft, Writing–review and editing. CM: Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. WL: Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. CC: Funding acquisition, Validation, Writing–original draft, Writing–review and editing. Z-HC: Conceptualization, Funding acquisition, Investigation, Validation, Writing–original draft, Writing–review and editing. DT: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2025.1515479/full#supplementary-material

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