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Energy- and yield-based performance evaluation of a phase change material–integrated single-span double-layered with a thermal screen greenhouse

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A R T I C L E I N F O

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A B S T R A C T

Greenhouse technology emerged to ensure the optimum yield of the host crop —a prerequisite to achieving Sustainable Development Goals 7 and 2. To achieve this, supplemental energy is needed under extreme weather conditions at about half the operational cost. Researchers have focused and succeeded in reducing the energy demand using numerical methods with little focus on the impact of these methods on crop yield. A novel greenhouse system—phase change material–integrated single-span double-layered strawberry greenhouse with a thermal screen—is introduced herein. Furthermore, how the energy management method affects the yield of the host crop is explored. Moreover, the energy-saving potential and yield enhancement achieved by integrating PCMs and other passive thermal-management systems in a specific agricultural setting is investigated. TRNSYS 18 software is used to evaluate the effect of three passive variables on two performance indices. The passive variables are location: Daegu (DG), Seoul, and Jeju Island (JE); orientation: 90° (E-W), 45° (NE-SW), and 0° (N-S); and PCM type: "No-fill", water, and Paraffin (ParC_{13}–C_{24}). The effect of thermal screen control was also studied on the localized optium configuration. Finally, economic analysis was conducted to ascertain the most sustainable configuration. The performance indices are the heating demand and strawberry yield. The results show that the location, orientation, and PCM usage inside the greenhouse greatly affect the greenhouse's heating demand and crop yield. The configuration selected must be in such a way that the indoor nighttime temperature does not exceed 2 °C above the minimum nighttime optimum value of the host crop.

1. Introduction

The global agricultural industry has been facing increasing challenges in recent years due to the growing population, climate change, and the need for sustainable food production. To create controlled environments that optimize crop growth and maximize yield, innovative greenhouse technologies have been developed. Among these

Abbreviations: Adj, Adjacent; BC, Base case; BES, Building energy simulation; BF, Bench frames; CVRMSE, Coefficient of variance of the root mean squared error; DVBES, Discretized volume building energy simulation; Ext, External; FLF, First-layer frame; MW, Mineral wool; NMBE, Normalized mean bias error; NP, Net profit; *NS*, No screen; PCM, Phase change material; PO, Polyolefin; PP, Payback period; QGH, Q greenhouse; R, Solar reflectance; RGH, R greenhouse; RH, Relative humidity; RMSE, Root mean squared error; ST, Solar transmittance; T, Thickness; TC, Thermal conductivity; TRE, Thermal radiation emission; TRNSYS, Transient system simulation; TRNBuild, TRNSYS building model; TRT, Thermal radiation transmittance; TS, Thermal screen; VRR, Visible radiation reflectance; VRT, Visible radiation transmittance; Y, Strawberry yield.

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advancements, integrating phase change materials (PCMs), increased number of layers, thermal screens (TSs), and optimum orientation in greenhouse design have shown promising results in improving energy efficiency, thereby reducing the cost of production.

Nomenclature

Av	Mean of the experimental data points
Exp_i	Experimental value
Sim_i	Simulated value
N	Data population
T10	Closes when the indoor temperature falls below 10 °C
T13	Closes when the indoor temperature falls below 13 °C
X1	Average nighttime temperature (°C)
X2	Percentage of optimum nighttime temperature (%)
X8	Percentage of optimum daytime relative humidity (%)
X13	SR (W/m^2)
Y	Strawberry yield ($kg.plant^{-1}.week^{-1}$)

Using PCMs offers a unique approach to regulating the temperature inside greenhouses. These materials can absorb and release large amounts of thermal energy during phase transitions, providing thermal buffering effects. Incorporating PCMs into the greenhouse structure makes it possible to store excess heat during the day and release it at night when temperatures drop, creating a more stable and favorable growing environment for crops. This is evidenced by previous research. Kurklu *et al.* [1] used a PCM primarily for the reduction of peak temperatures in summer in greenhouses. In their experimental study, two greenhouses with and without PCMs were used. The study results demonstrated that the air temperature in the greenhouse with a PCM was ~3 °C lower than that in the control greenhouse during the daytime and vice versa at night. Further, fruit yield in the PCM greenhouse was almost twice than that in the control one. Huseyin and Aydin [2] experimentally studied the thermal performance of a PCM unit. The stored heat was utilized to heat ambient air before being admitted to a greenhouse. Compared with the conventional heating device, the unit provided ~18 %–23 % of the greenhouse's total daily thermal energy requirements for 3–4 h. Berroug *et al.* [3] studied the performance of a north wall made using a PCM as the storage medium in an E-W-oriented greenhouse. They developed a numerical thermal model to investigate the impact of the PCM on greenhouse temperature and relative humidity (RH). They found that at 32.4 kg of PCM/m^2 of the greenhouse ground surface area, plants and inside air temperature was 6 °C–12 °C more at nighttime in the winter period with fewer fluctuations. RH was found to be, on average, 10 %–15 % lower at night. To obtain optimum growing temperatures around the roots of plants, Beyhan *et al.* [4] developed a new root zone temperature control system based on thermal energy storage in PCMs for soilless agriculture greenhouses. The experiment result showed a maximum temperature difference of 2.4 °C. This

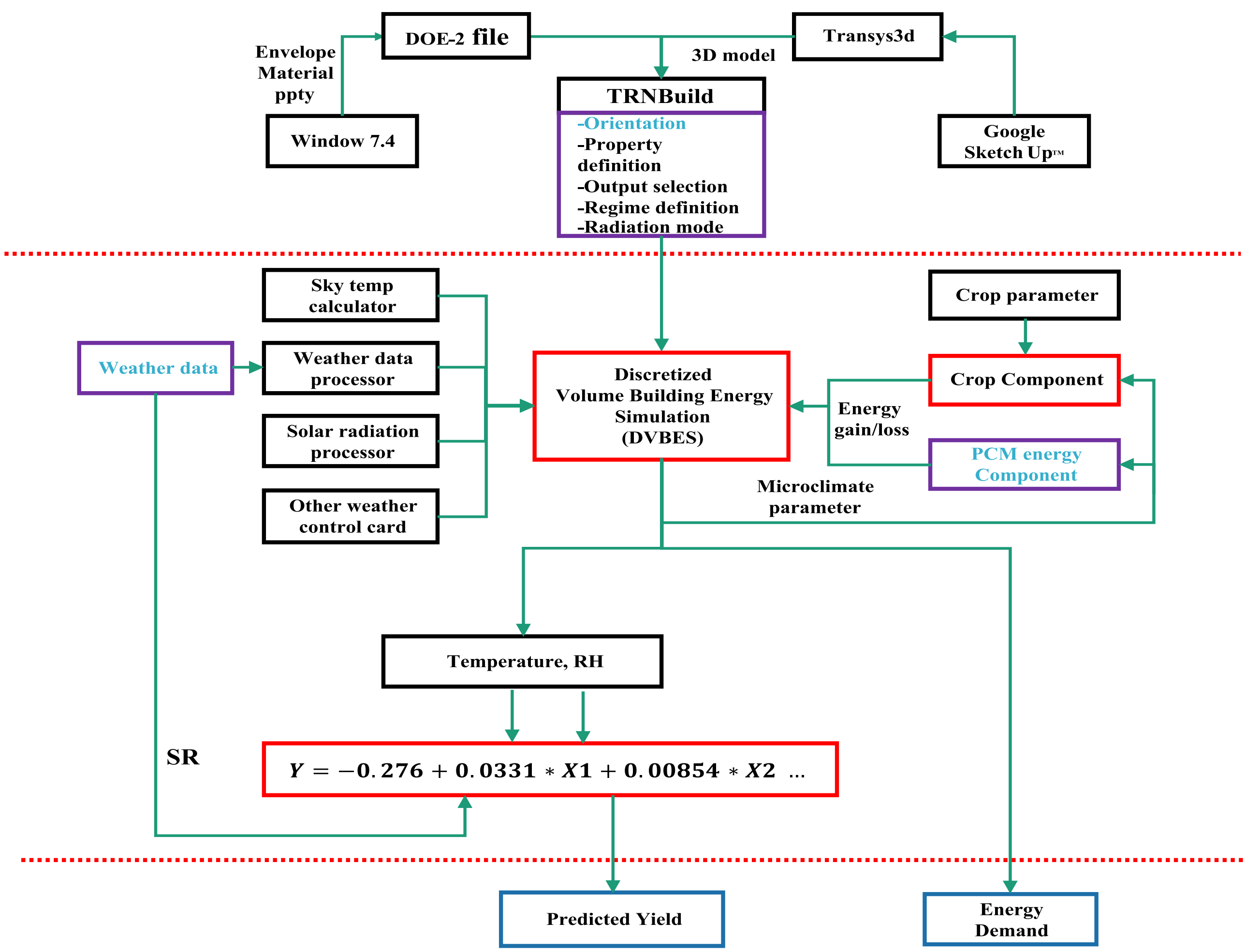

Fig. 1. Flowchart of the simulation.

Table 1
Description of the components.

Function	Component	Usage	Remark
Input	Windows 7.4	Generates a *DOE-2* file based on the properties of the envelope materials presented in Table 2.	Developed by Lawrence Berkeley National Laboratory.
	Google Sketch Up	It is a building 3D software. Generates a Trnsys3d file (a.*idf* file format).	Developed by Trimble Incorporation.
	TRNbuild	Defines the building's required envelope characteristics and regime, including: The geometry of the structure (Fig. 3), Radiation mode (standard), Infiltration and ventilation (natural), Number of zones/air nodes (112 discrete), Thermal and moisture capacitance of the zone/air node (Table 3), and Add gains (crop, PCM, etc.) Coupling (distribution fan)	An interface for the creation and edition of nongeometry information required by TRNSYS.
Simulation	Weather	Consists of Sky temperature calculator, which calculates the sky temperature from weather parameters such as ambient temperature and RH. Weather data processor, which reads the data from the data file. Solar radiation processor, which calculates the solar radiation incidence at every angle. Other components such as psychometric and orientation calculators.	Standard component domiciled in TRNSYS Simulation Studio.
	DVBES	Integrates all other components in the Simulation Studio. The number of discrete is defined in TRNBuild and imported into the DVBES.	Standard component domiciled in TRNSYS Simulation Studio.
	Crop	It calculates the energy gain or loss from the host crop based on the evapotranspiration and temperature difference between the crop and its environment.	Nonstandard components developed in TRNSYS based on the Penman–Monteith and conductive heat transfer model used by Baglivo *et al.* [21] and Shen *et al.* [22], respectively.
	PCM	It calculates the energy gain or loss from the PCM container.	Ogunlowo *et al.* [7] developed a nonstandard component in TRNSYS based on a temperature-based energy equation.
	Yield	Simulates the crop yield from the DVBES output temperature and relative humidity (RH) and measures solar radiation (SR).	The strawberry yield model developed by Ogunlowo *et al.* [20] was used. Equation (1) presents the strawberry yield model.
Output	Printer	Prints the output parameters in a.*txt* or.*xls* file.	Heating demand and strawberry yield are the outputs of interest.

difference achieved by the PCM mixture was higher around the roots of peppers than near the control plants. Naghibi *et al.* [5] evaluated the benefits of adding PCM to the water tank of a solar heating system numerically using TRNSYS as the tool. By changing the amount of the PCM added to the tank, the results showed that 10 %–14 % of energy performance improvements were observed by increasing the proportion of PCM amounts over the conventional system. After reviewing the application of PCM in greenhouses, Nishad and Krupa [6] proposed numerical models for optimizing greenhouse systems with PCM based on passive thermal management because it is free from operational cost. One popular numerical tool for such a task is TRNSYS. The tool has been used to develop a "PCM-in-container"—a model that can calculate the energy stored in a PCM-filled container that is in contact with direct greenhouse air temperature—by Ogunlowo *et al.* [7].

Furthermore, a TS in the greenhouse design enhances energy efficiency by reducing heat losses during colder periods. This feature acts as an additional insulating layer, preventing convective heat transfer between the interior and exterior of the greenhouse. Several researchers worked on the TS control strategy [8,9], the thermophysical properties of different materials [10–12], and effect of TS on greenhouse microclimate parameters [13–15] and energy savings [11,16–18]. Apart from TS, other design features have been used in greenhouse evaluations.

Rasheed *et al.* [18] developed and validated a building energy simulation (BES) model in TRNSYS capable of evaluating the effects of passive greenhouse design parameters, such as roof shape, orientation, double-glazing, natural ventilation, coverings, and thickness, on its energy conservation capacity. It was found that the most suitable design for a greenhouse located in Daegu (latitude: 35.53°N and longitude: 128.36°E), South Korea, would be E-W-oriented, with a gothic-shaped roof and double-glazing of polymethylmethacrylate covering. Natural ventilation reduces the inside temperature of the greenhouse, thereby reducing the energy demand for cooling. The model developed can help greenhouse farmers and researchers make predesign decisions regarding greenhouse construction, considering their local environment and specific needs.

Moreover, by developing and validating a TRNSYS BES, Choab *et al.* [19] investigated key passive design parameters affecting the thermal behavior and the heating/cooling energy need of a greenhouse in Agadir (Morocco). The parameters include the cladding material characteristics, shape, orientation, and air-change rate. The model was integrated with a crop evapotranspiration submodel to add heat and humidity gain into the heat and water balance of the greenhouse. The effect of evapotranspiration on the greenhouse thermal behavior was also examined in this study. The results of this study indicate that the E-W greenhouse orientation is the optimum orientation as it can reduce the annual cost of air-conditioning of the greenhouse by 9.28 % compared to the N-S orientation. Quonset shape is the optimum greenhouse shape in Morocco as it can save 14.44 % of the annual cost of air-conditioning instead of the even-span shape.

Rasheed *et al.* [16] also developed a TRNSYS BES model to evaluate the performance of a mutispan greenhouse. They also investigated the effect of passive greenhouse parameters, such as different thermal screens, natural ventilation, and heating setpoint controls, on the annual and maximum heating loads of the greenhouse located at Taean Gun (latitude: 36.88°N, longitude: 126.24°E, and elevation: 45 m) Chungcheongnam-do, South Korea. The results showed that the heating loads of the triple-layered screen were 70 % and 40 % less than those of the single-screen and double-screen greenhouses, respectively. Moreover, the maximum heating loads without a screen and for single-,

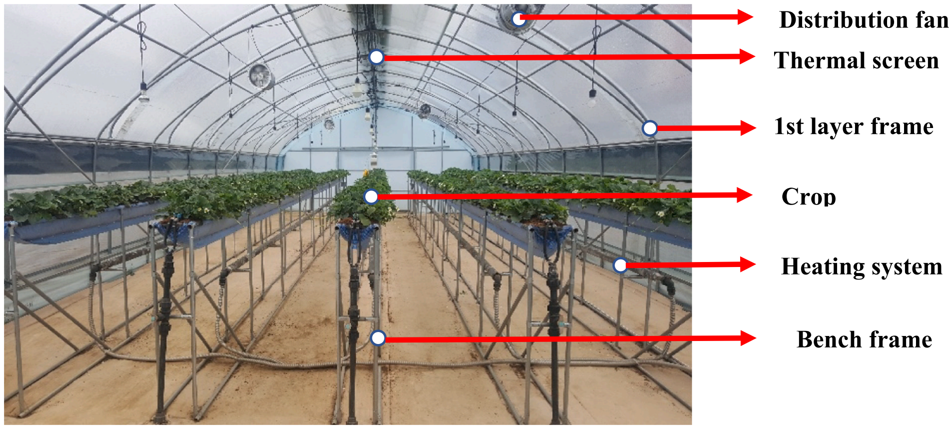

Fig. 2. Design features of the experimental greenhouse.

Table 2
Characteristics of the envelope materials as used in TRNBuild.

Surface type	Category	Material	Thickness (m)	U-value (W. $m^{-2}K^{-1}$)	Layer type
Opaque	Ext_Wall/Roof	Steel	0.05	5.769	Massive
	Adj_Wall	Steel	0.04	5.792	Massive
	Adj_Wall2	Air layer	0.00	2.948	Massless
	Adj_Wall3	PO-MW-PO	0.05	0.999	Massive
	Adj_Ceiling	Steel	0.04	5.792	Massive
	Adj_Ceiling2	Air layer	0.00	2.948	Massless
	Adj_Ceiling3	PO-MW	0.036	0.878	Massive
	Ground_Floor	Under_floor	0.15	2.04	Massive
Glazing	Ext_Window	PO	ST (0.08), R (0.10), VRT (0.89), VRR (0.08), TRT (0.18), TRE (0.79), TC (0.33), T(0.10)		
	Adj_Window1/2	PO-MW "No glazing"	(9 a.m.–6p.m.) (6p.m.–9 a.m.)		

Ext, external; Adj, adjacent: PO, polyolefin; MW, mineral wool; R, solar reflectance; ST, solar transmittance; VRT, visible radiation transmittance; VRR, visible radiation reflectance; TRT, thermal radiation transmittance; TRE, thermal radiation emission; TC, thermal conductivity ($W.m^{-1}K^{-1}$); T, thickness (mm).

Table 3
Regime definition in TRNBuild.

Area	Air nodes	Volume (m^3)	Capacitance (kJ. K^{-1})	Ref. floor area (m^2)
Floor	F1-25	3.04	18.26	4.68
Crop	A1-E5	4.68	28.08	4.68
Canopy	Ca1-5, Ca21-25	3.02	3.63	
	Ca6-10, Ca16-20	6.58	7.89	4.68
	Ca11-15	7.60	9.12	
Roof	R1-5, R21-25	3.56	4.28	7.16
	R6-10, R16-20	3.30	3.96	4.99
	R11-15	6.45	7.75	4.70
Corridor	Co1-10	1.49	1.78	0.90
West	West	122.99	737.87	35.00
East	East	24.60	29.52	7.00

double-, and triple-layered screens were 0.65, 0.46, 0.41, and 0.34 MJ.m^{-2}, respectively. The heating setpoint analysis predicted that using the designed day and nighttime heating control setpoints can result in 3 %, 15 %, 14 %, 15 %, and 40 % less heating load than when using the fixed value temperature control for November, December, January, February, and March, respectively.

However, numerical evaluation of greenhouses has always focused only on accessing the effect of greenhouse design parameters on energy management. Even though the aim of greenhouse technology is to ensure optimum crop growth and maximize yield, no researcher has been able to numerically evaluate the effect of energy-saving programs on the host crop. To create a pathway for this novel evaluation method, Ogunlowo *et al.* [20] established a base case scenario encompassing the energy behavior of the greenhouse and its direct influence on the yield of strawberries (*Seolhyang* sp.) They developed a ventilated discretized volume building energy simulation (DVBES) that predicts the energy demand, temperature, and relative humidity (RH) of a greenhouse and a predictive strawberry yield model that predicts the strawberry yield. The study used two single-span, double-layered experimental greenhouses with different features. For a single-span double-layer greenhouse at an E-W (90°) orientation, the total energy demand and strawberry yield were 113.861 MJ.m^{-2} and 0.466 kg.$plant^{-1}$.$season^{-1}$, respectively. They concluded that the findings are a foundation for further research on optimizing energy consumption in greenhouse environments without compromising crop yield.

Hence, the aim of this study is to conduct a comprehensive performance evaluation of a novel greenhouse system–the PCM-cum-crop integrated single-span double-layered with thermal screen strawberry greenhouse. This study investigates the energy-saving potential and yield enhancement achieved by integrating PCMs and other passive thermal management in a specific agricultural setting.

The findings of this study will hold great significance for the agricultural industry and contribute to the ongoing efforts of sustainable food production. This study will provide valuable insights into the feasibility and effectiveness of such advanced greenhouse technologies by evaluating the energy-saving potential and yield improvements achieved through the PCM-cum-crop integrated single-span double-layered thermal screen greenhouse.

Eventually, the study will provide scientific evidence and practical recommendations for greenhouse designers, farmers, and policymakers to adopt energy-efficient and high-yield cultivation systems to help meet the increasing demand for fresh produce while minimizing the environmental impact.

2. Materials and method

This section highlights the base case scenario, evaluation variables and indices, and data analysis method employed in this study.

2.1. Base case scenario

For possible future evaluation of the energy performance of

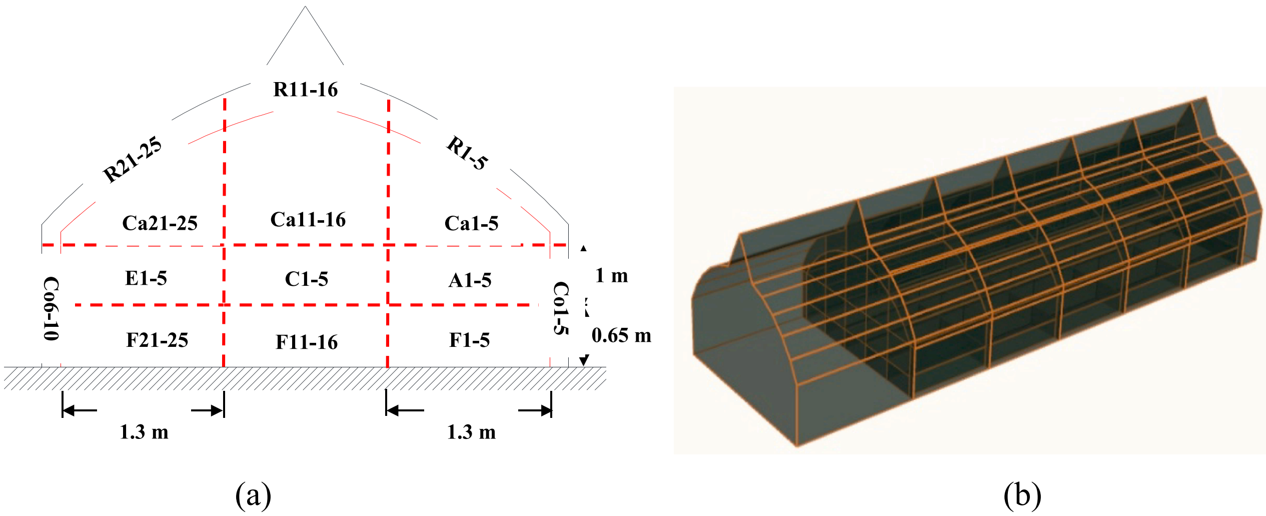

Fig. 3. Front view (a) and 3D isometric view (b) of the model greenhouse as designed in SketchUp.

Table 4
Summary of the validation result of the models.

	R^2	RSME	NMBE	CVRMSE
Energy	0.90	36.70 MJ	3.28	21.99
Temperature	0.89	1.74 °C	−7.29	14.24
RH	0.50	14.62 %	12.49	18.46
Y	0.98	0.008 kg	8.94	–

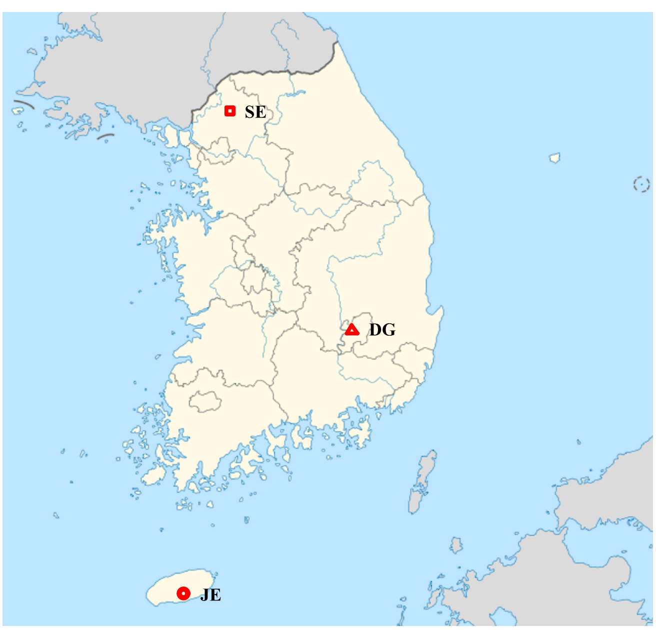

Fig. 4. Site locations on the South Korean map.

greenhouses and their impact on the yield of the host crop, Ogunlowo *et al.* [20] developed a PCM-cum-crop yield–integrated DVBES model. The model established the base case heating demand and strawberry yield of a single-span double-layer with a TS greenhouse. This study evaluated the system's performance based on the specified base case value. The following subsections elaborate on the model composition, validation method, and results.

2.1.1. Modelling tool

The evaluation model consists of two primary models: a TRNSYS DVBES model that predicts energy demand, microclimate temperature, and RH of the greenhouse and a strawberry yield model that predicts the strawberry yield by taking the expected microclimate output from the DVBES as input. Fig. 1 shows the flowchart of the model mechanism. Table 1 describes each component of the entire model.

2.1.2. Experimental validation

The model numerically recreated the design features of a single-span double-layer with a thermal screen greenhouse located at Kyungpook National University, Daegu, South Korea. The model was validated using the greenhouse. According to Ogunlowo *et al.* [20], the experimental greenhouse's first layer is an 18 m × 6.5 m floor area, enclosed in a 24 m × 7 m second layer. Both layers are enveloped by a polyolefin (PO) screen from 6p.m. to 9 a.m., with the TS layer on top of the first layer. During the day (from 9 a.m. to 6p.m.), the TS and PO screens on the first layer are rolled up, making the greenhouse single-layered during this period. Fig. 2 shows the design features of the experimental greenhouse. The first-layer frame (FLF) and bench frame (BF) were considered a container for the PCM; in this case, a "No-fill." The greenhouse is a typical double-layer, single-span greenhouse for growing strawberry plants consisting of five 14-m-long benches to support the crop substrate.

To ascertain the effect of greenhouse microclimate temperature, RH, and SR on the "*Seolhyang*" cultivar of strawberries, Ogunlowo *et al.* [20] developed and validated an empirical model. Equation (1) yields the regression model for the strawberry yield and was adopted in this study.

$$Y = -0.276 + 0.0331 \times X1 + 0.00854 \times X2 - 0.002363 \times X8 - 0.000111 \times X13 - 0.000804 \times X1 \times X2 \tag{1}$$

where Y is the predicted strawberry yield (kg.plant^{-1}.week^{-1}), $X1$ is the average nighttime temperature (°C), $X2$ is the percentage optimum nighttime temperature (%), $X8$ is the percentage optimum daytime RH (%), and $X13$ is the SR (W/m^2).

To determine the accuracy of the models for deployability, they were validated using the following metrics: coefficient of determination (R^2), root mean squared error (RMSE), normalized mean bias error (NMBE), and coefficient of variance of the root mean squared error (CVRMSE), as defined in Eqn. (2)–(5).

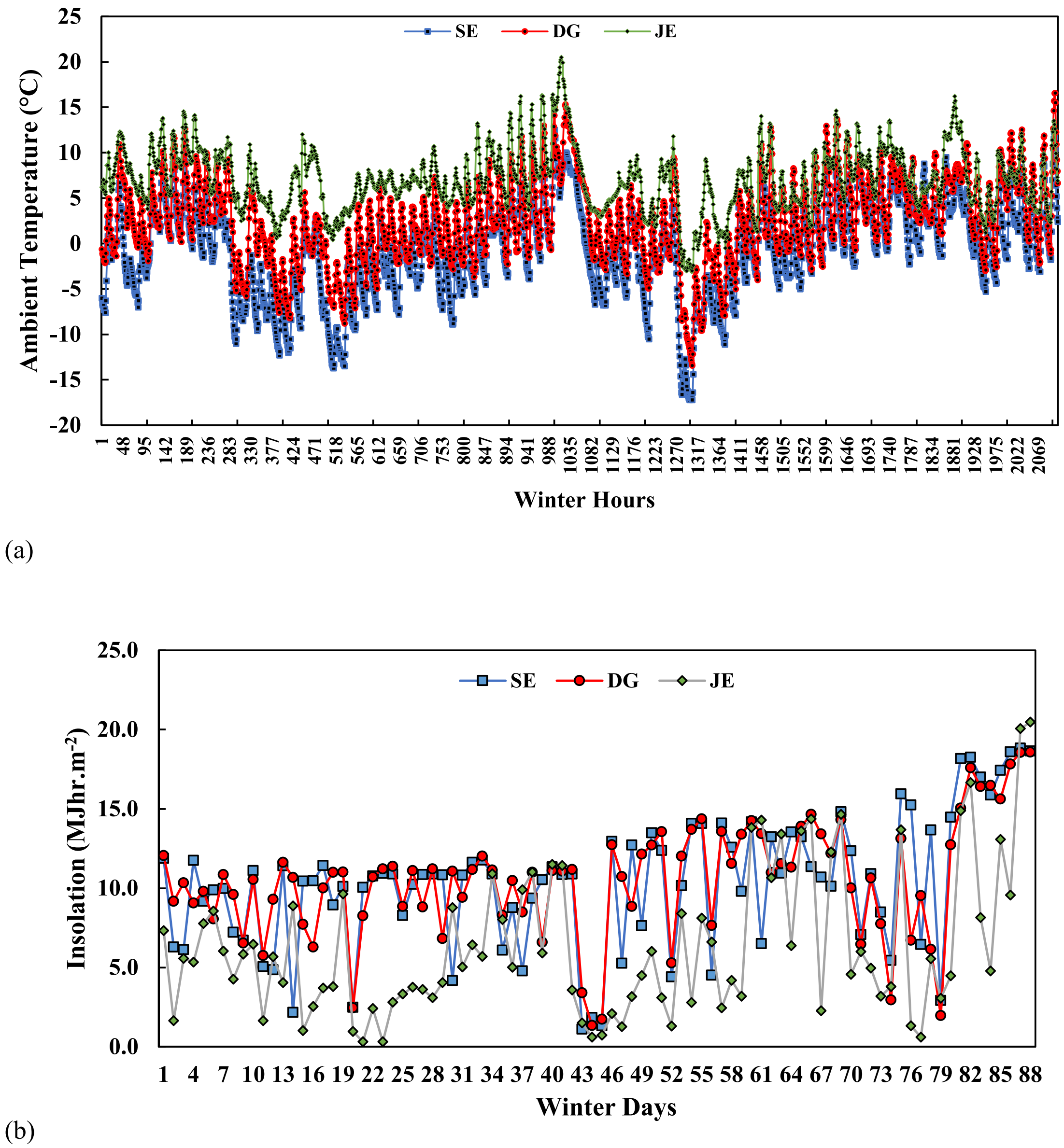

Fig. 5. Locations of (a) ambient temperature and (b) solar insolation for the evaluated duration.

Table 5
Thermophysical properties of the PCMs.

Property	Water	ParC$_{13}$–C$_{24}$
Specific heat capacity (kJ.(kg K)$^{-1}$)	4.186	2.1
Density (kg.m^{-3})	998	0.9
Thermal conductivity (W.(m·K)$^{-1}$)	2.16	0.756
Heat of fusion (kJ.kg^{-1})	333	189
Melting point (°C)	0	23

Source: Cabeza *et al.* [26].

Table 6
Thermal screen control strategies for the systems' evaluation.

Control Type	Description
Time	Opens (i.e. rolled-up) at 9 a.m. and closes (rolled-down) at 6p.m.
T13	Closes when the indoor temperature falls below 13 °C
T10	Closes when the indoor temperature falls below 10 °C
NS	No screen

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Exp_i - Sim_i)^2}{\sum_{i=1}^{N}(Exp_i - Av)^2}, Av = \frac{1}{N}\sum_{i=1}^{N} Exp_i \tag{2}$$

$$RSME = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Exp_i - Sim_i)^2} \tag{3}$$

$$NMBE = \frac{\sum_{i}^{N}(Exp_i - Sim_i)}{(N-1)*Av}*100\% \tag{4}$$

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i}^{N}(Exp_i - Sim_i)^2}{N-1}}}{Av}*100\% \tag{5}$$

where Av is the mean of the experimental value, Exp_i is the experimental value, Sim_i is the simulated value, and N is the data population.

2.1.3. Validation result

Table 4 presents the validation results of the model. In summary, the model demonstrates a good correlation with the actual values for the three variables, namely, energy demand, temperature, and yield, with

Table 7
Cost of inputs and output in greenhouse strawberry production.

Parameters	Unit	Quantity	Unit cost (Won/unit)	Total Quantity(Unit)	Total cost (Won)
Initial investment					
PO	m^2	120	82,000*	214.2	146,000
Thermal screen	m^2	13.8	61,200*	214.2	949,930
Paraffin	m^3	1	1,579,500‡	0.163	258,000
Variable cost					
Electricity	kWh	1	299!	579.4	173,417.40
Fertiliser					350,000
Pesticide					200,000
Heating	$MJ.m^2$	36.7	1,500.72||	4,784	
Output					
Yield	kg.plant	1	20,000ʅ	1,320,000	

* shopping.naver.com [27]; ‡ alibaba.com [28];! kepco.co.kr [29]; || globalpetrolprices.com [30]; ʅ kpi.or.kr[31].

Table 8
Summary of heating demand and strawberry yield for each system.

System	Location	Orientation (°)	PCM	HD (MJ. m^{-2})	Y (kg. $plant^{-1}$)
BC	DG	90	No fill	113.861	0.223
a	DG	90	Water	92.980	0.037
b	DG	90	$ParC_{13}$-C_{24}	100.142	0.161
c	DG	45	No fill	116.371	0.210
d	DG	45	Water	96.216	0.031
e	DG	45	$ParC_{13}$-C_{24}	103.099	0.153
f	DG	0	No fill	120.503	0.216
g	DG	0	Water	99.540	0.036
h	DG	0	$ParC_{13}$-C_{24}	106.791	0.159
i	SE	90	No fill	194.810	0.337
j	SE	90	Water	152.400	0.144
k	SE	90	$ParC_{13}$-C_{24}	169.643	0.282
l	SE	45	No fill	196.985	0.332
m	SE	45	Water	156.491	0.141
n	SE	45	$ParC_{13}$-C_{24}	172.934	0.277
o	SE	0	No fill	205.955	0.331
p	SE	0	Water	163.674	0.141
q	SE	0	$ParC_{13}$-C_{24}	180.464	0.277
r	JE	90	No fill	31.462	0.111
s	JE	90	Water	29.134	−0.157
t	JE	90	$ParC_{13}$-C_{24}	29.555	0.006
u	JE	45	No fill	31.587	0.103
v	JE	45	Water	29.419	−0.160
w	JE	45	$ParC_{13}$-C_{24}	29.681	0.000
x	JE	0	No fill	32.426	0.108
y	JE	0	Water	30.207	−0.158
z	JE	0	$ParC_{13}$-C_{24}	30.627	0.002

the magnitude of prediction errors (RMSE), bias (NMBE), and variation (CVRMSE) within the requirements and tolerances of its application. According to ASHRAE [23], a model requires calibration if the NMBE and CVRMSE are above 10 % and 30 %, respectively. Hence, the RH was calibrated and the model was considered adequate for deployment.

The base case (BC)-simulated heating demand for the three months of the winter season of the greenhouse was 113.861 $MJ.m^{-2}$, while the strawberry yield for the period was 0.223 $kg.plant^{-1}$.

2.2. Evaluation variables and indices

To evaluate the performance of the greenhouse, three passive variables and two performance indices were considered in this study. The passive variables are location, orientation, and PCM type, while the performance indices are the heating demand and strawberry yield. The variables are depicted by the blue letters in the purple box, while the outputs (performance indices) are shown in the blue box, as shown in Fig. 1. Furthermore, three locations in South Korea: Daegu (DG), Seoul (SE), and Jeju Island (JE); three orientations: 90° (E-W), 45° (NE-SW), and 0° (N-S); and PCM type: no fill, water, and Paraffin ($ParC_{13}$-C_{24}) were considered for this study.

Figs. 4 and 5 show the locations on the South Korean map and variations in the ambient temperature and solar radiation at each location, respectively, for the evaluation period. The longitude and latitude of DG, SE, and JE were 128.36°E and 35.35°N, 126.99°E and 37.55°N, and 126.55°E and 33.38°N, respectively. Fig. 5a shows that the lower the latitude of the location, the higher the temperature, and these differences informed the choice of location selection.

Table 5 shows the properties of the PCM materials used in this study. According to Mu et al. [24], the choice of the PCM must be based on the thermal requirement of the crop. In particular, the PCM melting point temperature should be close to the optimum daytime temperature of the crop. In the case of the water, it was selected because it practically cost nothing. The orientations are commonly used in literature, as evidenced by Rasheed *et al.* [18] and Kutty *et al.* [25].

The effect of localized optimum systems control on the heating demand and yield was tested by varying the thermal screen control parameters as described in Table 6. Finally, the selected optimized systems were subjected to economic analysis to determine which system has the lowest payback period (PP). According to Investopedia, the shorter the PP, the more desirable the investment. The PP is as defined in Eqn (6).

$$Payback\ \ period = \frac{Cost\ \ of\ \ investment}{Net\ \ profit} \tag{6}$$

In this study, the cost of investment is referred to as the amount spent on energy-saving materials such as the PO, TS, and paraffin ($ParC_{13}$-C_{24}). The net profit is the difference between the income from the output (strawberry yield) and the variable cost. Table 7 presents the list of inputs and output utilized in the analysis.

2.3. Data analysis

A 3 × 3 factorial combinations of the location (L_1 = DG, L_2 = SE, and L_3 = JE), orientation ($O_1 = 90°$, $O_2 = 45°$, and $O_3 = 0°$) and PCM usage (P_1 = No fill, P_2 = water, and P_3 = $ParC_{13}$-C_{24}) resulted in 27 systems. Each system, represented by a letter, was simulated, and the outputs, heating demand, and yield were observed. Comparative analysis was conducted to analyse the effect of the variables on the outputs.

3. Results and discussion

Table 8 summarises each system's features, heating demand, and strawberry yield through DVBES. Each system is represented by the alphabet as presented in the table. The lowest heating demand of 29.134

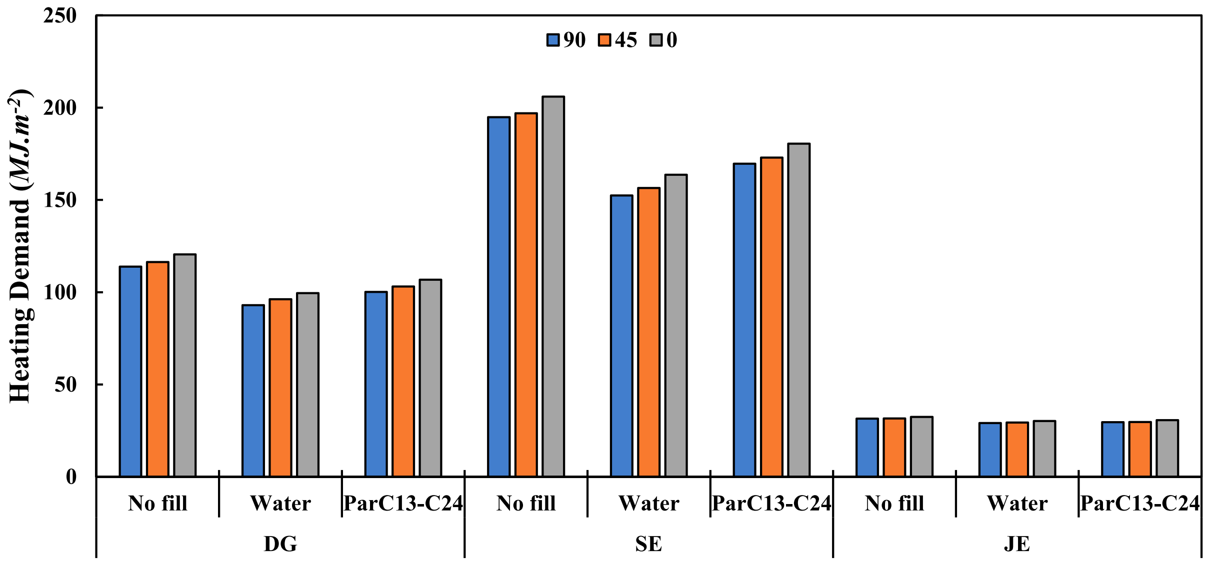

Fig. 6. Heating demand at different locations in South Korea and for different orientations and PCMs. 90: E-W, 45: NE-SW, 0: N-S, DG: Daegu, SE: Seoul, and JE: Jeju Island.

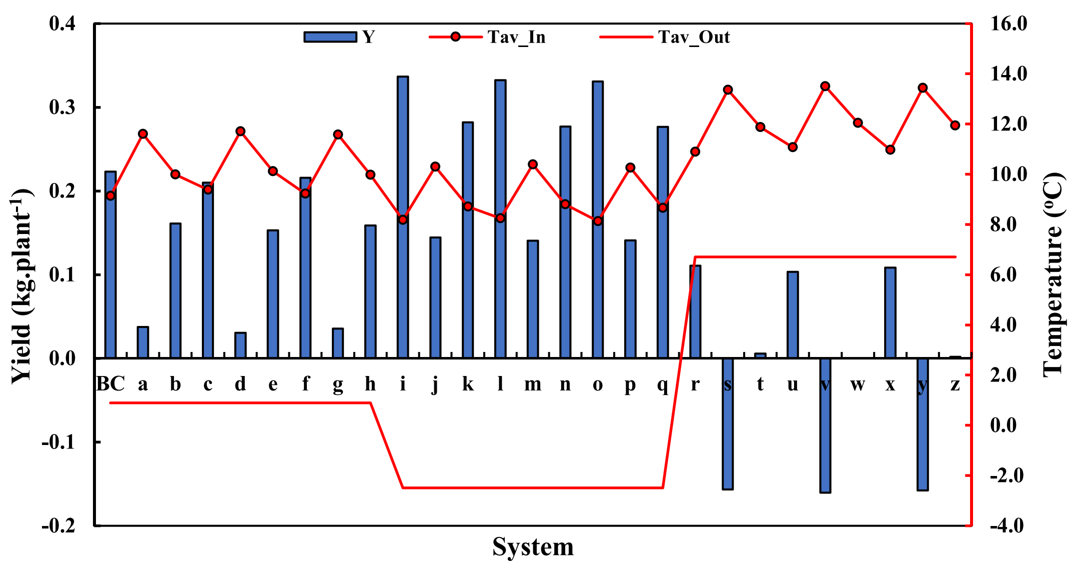

Fig. 7. Strawberry yield for each system compared to the average indoor (Tav_In) and outdoor nighttime temperature (Tav_Out) for a time-controlled thermal screen.

$MJ.m^{-2}$ was simulated when the greenhouse was located in JE at an E-W (90°) orientation and the FLF and BF were water-filled. In contrast, the highest heating demand of 205.955 $MJ.m^{-2}$ was observed when it is located in SE at an N-S (0°) orientation and the frames at no fill. For the strawberry yield, the highest yield of 0.337 $kg.plant^{-1}$ was observed for the i-system, i.e., in SE at an E-W orientation with no fill. In contrast, the PCM filling was detrimental to the strawberry yield for JE-located systems.

3.1. Effect of design features on heating demand

3.1.1. Location

Fig. 6 shows the heating demand for the feature's combination. For the location, energy demand can be seen as lowest in JE, whereas the heating demand was highest in SE. The average heating demand for DG, SE, and JE was 105.500, 177.040, and 30.455 $MJ.m^{-2}$, respectively. The result negatively correlated with the variation in the ambient temperature of each location, as shown in Fig. 5a. In particular, the lower the ambient temperature, the higher the heating demand.

3.1.2. Orientation

Based on Fig. 6, the E-W (90°) orientation has the least heating demand, whereas the N-S (0°) orientation has the highest demand. The average heating demand for 90°, 45°, and 0° orientations were 101.554, 103.643, and 107.799 $MJ.m^{-2}$, respectively. The result is consistent with the report by Choab *et al.* [19]. They reported that heating demand during the winter season in Morroco is highest for the N-S orientation. Moreover, Rasheed *et al.* [16] reported that for a similar double-layer single-span greenhouse located in Daegu, South Korea, the heating demand is the highest for the N-S orientation and the least for the E-W orientation.

3.1.3. PCM

The least heating demand was observed when the frames were water-filled and Paraffin-filled (Fig. 6). The average heating demand when the frames were water-, and Paraffin-filled and "No-fill" were 94.451, 102.548, and 116.0 $MJ.m^{-2}$, respectively. This can be attributed to water storing more energy, as shown by its specific heat capacity value (Table 5). The energy delivered from the water raises the microclimate

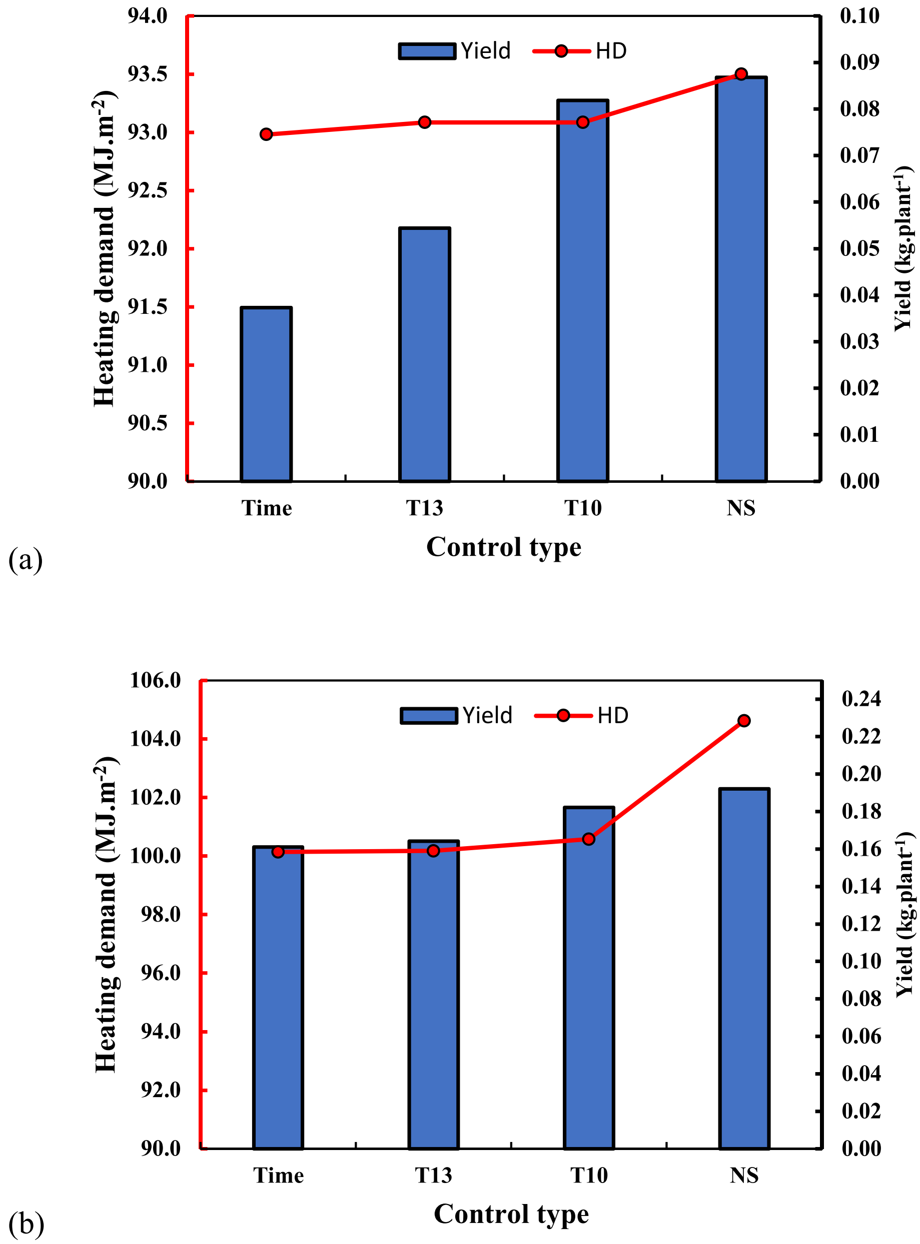

Fig. 8. Effect of thermal screen control on the strawberry yield of (a) water- and (b) paraffin-filled PCM-integrated greenhouse on an east–west orientation at Daegu (average outdoor nighttime temperature of 0.9 °C).

temperature, as evidenced in the report by Ogunlowo *et al.* [7] and Zhao *et al.* [32]. Through experimental analysis, Zhao *et al.* [32] studied the effect of water- and Paraffin-filled solar array tubes on the thermal environment of the greenhouse. The water scenario had higher temperatures than the Paraffin one due to more energy stored and delivered by the water. A similar result was noted in the study by Ogunlowo *et al.* [7] through experimental and numerical analyses.

3.2. Effect of design features on strawberry yield

3.2.1. Location

Fig. 7 presented the strawberry yield for the systems when the TS was time-controlled. The average yield in DG, SE, and JE was 0.136, 0.251, and −0.016 kg.plant^{-1}, with an average outdoor nighttime temperature of 0.9, −2.3 and 6.7 °C, respectively. This result may be attributed to the fact that apart from ensuring optimum temperature and RH, another factor that affects strawberry yield is the amount of SR received within the greenhouse, as supported by Zakir *et al.* [13], Akpenpuun *et al.* [14], and Tang *et al.* [33]; Fig. 5b shows DG receiving more insolation.

Another major factor could be the average nighttime temperature within the greenhouse systems when the thermal screen is outrightly closed from 6p.m. till 9 a.m. the next day. Fig. 7 shows JE having a temperature range of about 11 to 14C, as the average outdoor nighttime temperature was 6.7C. This can be seen as detrimental to the strawberry yield, whose optimum range was between 8 and 13 °C. The figure also shows that the closer the indoor nighttime temperature gets to the least value of 8 °C the better the yield for the SE systems.

3.2.2. Orientation

Based on Fig. 7, the E-W (90°) orientation had the highest yield, whereas the NW-SE (45°) orientation had the lowest yield. The average yield for 90°, 45°, and 0° orientation were 0.127, 0.121, and 0.123 kg. plant^{-1}, respectively. This is because of more SR reception when the greenhouse is at its E-W orientation, a factor that also affects the energy

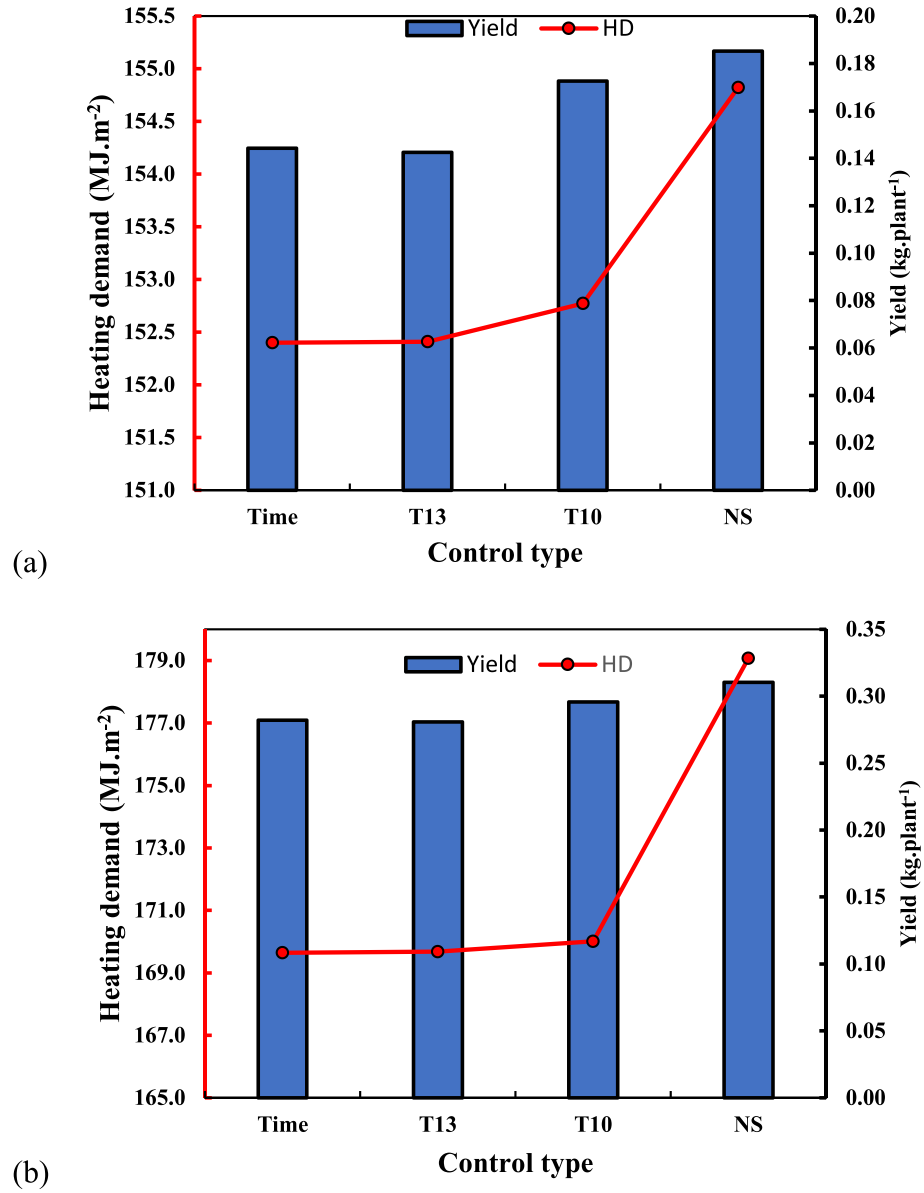

Fig. 9. Effect of thermal screen control on the strawberry yield of (a) water- and (b) paraffin-filled PCM-integrated greenhouse on an east–west orientation at Seoul (average outdoor nighttime temperature of −2.5 °C).

demand of the greenhouse, as stated by Choab *et al.* [19] and Rasheed *et al.* [16].

3.2.3. PCM

The average yield when the frames were water-, Paraffin- and "No-fill"-filled were 0.006, 0.146, and 0.219 kg.plant^{-1}, respectively. Compared to when the systems were water-filled, a higher yield was recorded when the greenhouse's FLF and BF were Paraffin-filled (Fig. 7). As suggested by Mu *et al.* [24] and Zhao *et al.* [32], crop yield is beneficial if the transition temperature of the PCM selected is close to the crop optimum temperature. Hence, paraffin (ParC$_{13}$-C$_{24}$) was chosen due to its transition point (23 °C) being close to the optimum daytime temperature for strawberries. The selection effectively ensured a better yield.

Fig. 7 shows a correlation between the indoor nighttime temperature and yield as expressed the yield model and supported by Tang *et al.* [28]. Higher yields were recorded at SE when the average indoor nighttime temperature was closer to the least optimum nighttime temperature of 8 °C. As the temperature rises to 13 °C and above, there was a negative response to the yield. Hence, the application of water delivered more energy, raising the temperature above 13 °C, thereby causing a negative effect on the yield.

3.3. Effect of thermal screen control on heating demand and yield

Having established that the highest yield and lowest heating demand could be realised by siting the system on E-W orientation, further evaluation was conducted to determine the effect of the TS control on the two indices. Fig. 8 shows the response of heating demand and yield to the TS control strategy for PCM-filled DG greenhouses on an E-W orientation. In Fig. 8a, where the system was water-filled (system *a*), the result shows that instead of outright closure of the TS when it was time-controlled, the yield could increase by 118 % and 132 % when the TS is temperature-controlled at 10 °C (*T10*) and outrightly opened (*NS*), respectively. At the same time, the heating demand were 0.113 % and 0.551 % respectively for the *T10* and *NS*. The result also shows that even though there was no difference in the heating demand between *T13* and *T10*, there was a 50 % increment in the yield. In Fig. 8b, where the

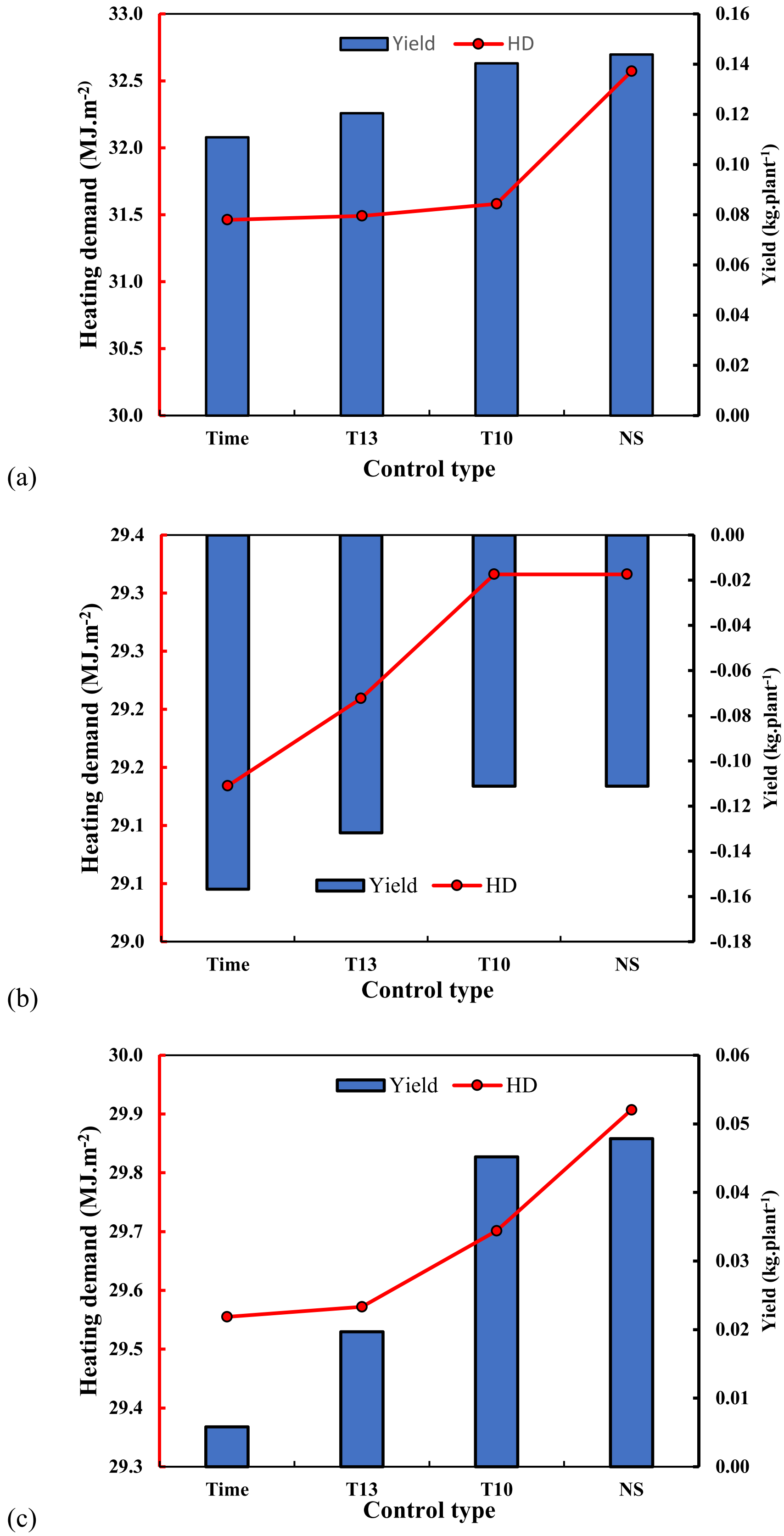

Fig. 10. Effect of thermal screen control on the strawberry yield of (a) No-fill, (b) water- and (c) paraffin-filled PCM-integrated greenhouse on an east–west orientation at Jeju Island (average outdoor nighttime temperature of 6.7 °C).

Table 9
Payback period of localized optimum greenhouse systems in South Korea.

System	HD (MJ. m^{-2})	Yield (kg. $plant^{-1}$)	Net Profit (Won)	Initial Capital (won)	PP
BC	113.861	0.223	1,675,456.77	1,095,930	0.65
a_T10	93.085	0.081	− 99,548.14	1,095,930	No PP
a_NS	93.497	0.087	− 22,319.20	146,000	No PP
b_T10	100.574	0.182	1,197,823.51	1,353,930	1.13
b_NS	104.63	0.192	1,310,419.08	404,000	0.31
i	194.81	0.337	2,792,986.23	1,095,930	0.39
j_T10	152.772	0.172	816,101.49	1,095,930	1.34
j_NS	154.821	0.185	977,898.81	146,000	0.15
k_T10	170.006	0.295	2,357,251.80	1,353,930	0.57
k_NS	179.078	0.31	2,511,850.17	404,000	0.16
r	31.461	0.111	591,269.09	1,095,930	1.85
r_T10	31.58	0.14	973,499.77	1,095,930	1.13
r_NS	32.57	0.143	1,008,363.49	146,000	0.14

BC: "No-fill" on E-W orientation located at Daegu; *a*: water-filled on E-W orientation located at Daegu; *b*: paraffin-filled on E-W orientation located at Daegu; *i*: "No-fill" on E-W orientation located at Seoul; *j*: water-filled on E-W orientation located at Seoul; *k*: paraffin-filled on E-W orientation located at Seoul; *r*: "No-fill" on E-W orientation located at Jeju Island; *T10*: temperature-controlled thermal screen at 10 °C; *NS*: No screen; No PP: no payback period.

system is paraffin-filled (system *b*), the result shows that instead of outright closure of the TS when it was time-controlled, the yield could increase by 1.86 %, 13 %, and 19.3 % at *T13, T10* and *NS*, respectively. At the same time, the heating demand were 0.03 %, 0.4 % and 4.5 % respectively for the *T13, T10* and *NS*. Compared to *BC* (0.223 kg.$plant^{-1}$, 113.861 MJ.m^{-2}), the b-system without TS (0.192 kg.$plant^{-1}$, 104.630 MJ.m^{-2}) requires lesser energy (9.231 MJ.m^{-2}) to achieve a closer strawberry yield (0.03 kg.$plant^{-1}$). Hence, the greenhouse must have an E-W orientation with Paraffin-filled frames to achieve the highest possible strawberry yield with less heating demand in DG or other locations on the same latitude.

Fig. 9 shows the response of heating demand and yield to TS control strategy for PCM-filled SE greenhouses on an E-W orientation. In Fig. 9a, where the system was water-filled (system *j*), the result shows that instead of outright closure of the TS when it was time-controlled, the yield could increase by 20.14 % and 28.47 % when the TS was temperature-controlled at 10 °C (T10) and outrightly opened (NS), respectively. At the same time, the heating demand were 0.2 % and 1.59 % respectively for the *T10* and *NS*. In Fig. 9b, where the systems was parafin-filled (system *k*), the result shows that instead of outright closure of the TS when it was time-controlled, the yield could increased by 4.96 %, and 9.92 % at T10 and NS, respectively. At the same time, the heating demand were 0.21 % and 5.56 % respectively for the T10 and NS. Compared to system *i* (0.337 kg.$plant^{-1}$, 194.810 MJ.m^{-2}), the *k*-system without TS (0.310 kg.$plant^{-1}$, 179.078 MJ.m^{-2}) requires lesser energy (15.732 MJ.m^{-2}) to achieve a closer strawberry yield (0.027 kg.$plant^{-1}$). Hence, the greenhouse must have an E-W orientation with Paraffin-filled frames to achieve the highest possible strawberry yield with less heating demand in SE or other locations on the same latitude.

Fig. 10 shows the response of heating demand and yield to the TS control strategy for a "No-fill" and PCM-filled JE greenhouses on an E-W orientation. The results in Fig. 10b and 10c, show that although there was a reduction in heating demand (Fig. 6), integrating the PCM with the greenhouse either in a single-, or double-layer, with or without TS, will be detrimental to the strawberry yield, especially in a region where the average outside winter temperature is about 6.7 °C. In Fig. 10a, where the system was "No-fill" (system *r*), the result shows that instead of outright closure of the TS when it is time-controlled, the yield could increase by 8.1 %, 26.1 %, and 28.8 % when the TS is temperature-controlled at 13 °C (*T13*), 10 °C (*T10*) and outrightly opened (NS), respectively. At the same time, the heating demand were 0.096 %, 0.38 %, and 3.53 % respectively for the *T13*, *T10* and *NS*. Compared to the time-controlled *r*-system (0.111 kg.$plant^{-1}$, 31.461 MJ.m^{-2}), the *NS* scenario (0.143 kg.$plant^{-1}$, 32.570 MJ.m^{-2}) requires higher energy (1.109 MJ.m^{-2}) to achieve a higher strawberry yield (0.032 kg.$plant^{-1}$).

3.4. *Economic anaalysis*

PCM-integrated greenhouses are well suited for regions with low outdoor temperatures (less than 1 °C). Setting the TS control 2 °C above the minimum optimum nighttime temperature or non-use of TS favours the system's average indoor nighttime temperature being around 8 °C. Economic analysis was conducted to decide which control best suits a greenhouse configuration. Table 9 presents the payback period (PP) of the localized optimized systems compared to their respective base case scenarios. Compared to the BC, the *a*-system, irrespective of the control, was not profitable despite no or less cost of water used in the filling. Compared to the *b*-system, the configuration with *NS* has the lowest PP (0.31) while the BC with PP of 0.65 has the highest net profit (NP). While the BC and *b_NS* have PP less than a year, the *b_T10* was more but less than two years.

Compared to the *i*-system (PP of 0.39), *j*- and *k*-systems with no screen have the lower PP (0.15 and 0.16) and lesser NP, respectively. The *T_10* configurations, however, have higher PP (1.34 and 0.57) with less NP. These results imply that it is more attractive to farmers to avoid using thermal screen with paraffin-filled system in regions with nighttime outdoor temperature less than 1 °C. The energy delivered by the system ensures the indoor nighttime temperature is closer to the minimum nighttime optimum temperature for strawberries.

Compared to the *r*-system (PP of 1.85), the *NS* reduces the PP to 0.14 and has the highest NP, which makes it suitable for for JE with nighttime outdoor temperature averaging 6.7 °C.

4. Conclusion

The comprehensive performance evaluation of a novel greenhouse system—the PCM-cum-crop integrated single-span double-layered with thermal screen strawberry greenhouse—was performed.

The location, orientation, and PCM usage inside the greenhouse greatly affected the heating demand of the greenhouse. The heating demand was lowest in JE, at an E-W orientation, and water was used as the PCM. These three factors also had a significant effect on the strawberry yield. While the location and orientation play a vital role in the amount of solar reception during the day, the PCM role is in the greenhouse's indoor nighttime temperature.

For a sustainable greenhouse practice, siting the greenhouse in a region with an average nighttime outdoor temperature of less than 1 °C requires the greenhouse to be at an E-W orientation and use $ParC_{13}$-C_{24} as PCM. Meanwhile, the PCM integration is only beneficial where the average outdoor temperature is above 1 °C with further system control to ensure the indoor nighttime temperature is within the optimum value (2 °C above the minimum).

TRNSYS offers a cheaper and faster means to evaluate the performance of a greenhouse system in achieving a sustainable practice. The evaluation does not end with energy savings alone but also on its effect on the crop yield. Henceforth, researchers are recommended to include the impact of energy-saving management on host crops, ensuring affordable and cleaner energy (SDG7) and zero hunger (SDG2).

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CRediT authorship contribution statement

Qazeem Opeyemi Ogunlowo: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Timothy Denen Akpenpun:** Writing – review & editing, Resources, Investigation, Data curation. **Wook Ho Na:** Visualization, Resources, Investigation, Data curation. **Misbaudeen Aderemi Adesanya:** Writing – review & editing, Investigation. **Anis Rabiu:** Writing – review & editing, Investigation. **Prabhat Dutta:** Writing – review & editing, Investigation. **Hyeon-Tae Kim:** Supervision, Resources, Investigation. **Hyun-Woo Lee:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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