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Thermal Environment Analysis of Selected Polyethene Cladded Single-Span Greenhouse Shapes Models Towards Cooling Needs

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ABSTRACT

Greenhouse energy management is one of the most significant factors of consideration in greenhouse agriculture. Besides implementing energy supply systems to the facility, energy-saving measures must also be taken into consideration. To address the issue of energy demand by greenhouses in a tropical environment, three greenhouse models were developed to simulate their thermal environments utilizing the Transient Systems Simulation Program (TRNSYS 18) as a building energy simulation (BES) platform. The proposed models were used to examine the impact of greenhouse design parameters; roof shape, orientation, covering (polyethene), and ventilation, on their temperature, relative humidity (RH), vapour pressure deficit (VPD), and cooling load. It was found that the most suitable roof design and orientation was the split-gable roof design with the ventilation switched on and 0^o (E-W) orientation that had the lowest mean temperature of 24.12 ^oC and the least cooling demand of 454.59W. While the tunnel greenhouse had the highest cooling load of 21.30 kW. The split-gable greenhouse had. Also, the RH and VPD in the split-gable greenhouse with ventilation were within the acceptable ranges of 50-75% and 0.8 and 1.1 kPa, respectively, for successful greenhouse crop production. The developed models can aid greenhouse farmers in knowing the cost-benefit of a greenhouse before venturing into greenhouse agriculture in the tropical regions.

Keywords: BES model; polyethene; thermal environment; energy saving

Introduction

The world's population is forecast to rise by around 2.3 billion people, with Sub-Saharan Africa experiencing the highest growth between 2009 and 2050 as a result food demand is anticipated to increase from 59% to 98 %. To increase the supply of food in order to match the increasing demand new production systems must be adopted and one of such systems is the greenhouse farming system. Greenhouse farming is a farming technique that uses greenhouses to allow farmers to grow various crops in inhospitable environments and allows crop cultivation outside of their usual growing season (Taki *et al.*, 2018; Angmo *et al.*, 2019; Willett *et al.*, 2019; Ogunlowo *et al.*, 2022). Controlled environment plant production systems offer the possibility to provide large numbers of high-quality crops with greater predictability. The adoption of greenhouse technology is vital in tackling global

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issues such as food insecurity, fuel scarcity, ecosystem instability, and environmental pollution (Kozai *et al.,* 1997).

In greenhouse farming, crop output efficiency is highly dependent on the provision of appropriate climate conditions to obtain high and good quality yield at reasonable cost, and little environmental impact. To achieve these aims, the greenhouse environment is monitored and modified such that it is suitable for the selected crop to be cultivated. Environmental parameters that influence crop production are day- and night- time temperatures, relative humidity (RH), vapor pressure deficit (VPD), carbon dioxide (CO_2) concentration, and solar radiation (SR) (Shamshiri *et al.*, 2018a). The individual relationships and combined interactions among these parameters affect important plant processes, such as photosynthesis, respiration, transpiration, growth, development, and ultimately yield. Greenhouse microclimate conditions, most importantly air temperature and photoperiod, VPD, and CO_2 concentration, impact the organoleptic and functional quality of greenhouse vegetables (Wang *et al.*, 2008).

Due to the increased energy requirements for greenhouse cooling and heating and the rising cost of fossil fuels, the use of greenhouses for crop production has resulted in energy problems that call for the creation of effective energy-saving technology (Xamán *et al.,* 2014). Several energy-saving techniques and strategies have been used in the past to reduce greenhouse operational costs by lowering greenhouse cooling load during the hot season (Cuce *et al.,* 2016; Rasheed *et al.,* 2020; Rabiu *et al.,* 2022). The utilisation of solar energy, geothermal energy, thermal insulation, and other renewable sources of energy are some of the strategies used to reduce the cost of cooling in greenhouses (Ataei, 2016; Adesanya *et al.*, 2022). The major challenge for greenhouse farmers and researchers all over the world is the high costs of cooling greenhouses during warm or hot seasons where temperatures are high within the greenhouse atmosphere (Yano and Cossu, 2019; Baglivo *et al.,* 2020). Nevertheless, this persistent cooling demand must be managed and optimized to maintain the most favourable environment for optimum plant growth, enabling economical greenhouse production (Akpenpuun *et al.,* 2021).

Transient system simulation abbreviated as TRNSYS is a flexible component-based and extensible energy simulation software for basic and complex systems as well as comprehensive energy analysis of single and multi-zone structures (Sinha and Chandel, 2014). Building energy simulation (BES) is a suitable tool in TRNSYS software for investigating real-time energy demand and enables the study of buildings, agricultural buildings inclusive, and their characteristics while taking into consideration local weather conditions (Seo *et al.*, 2014; Rasheed *et al.*, 2018). BES models have been utilized in numerous researches for greenhouse energy management and analysis of various greenhouse energy systems (Adesanya *et al.*, 2022; Rabiu *et al.*, 2022). Vadiee and Martin (2014) investigated the viability of solar energy evolution to satisfy the energy demand of greenhouses, presenting alternatives to reduce energy demand and maximize solar energy utilization, while Chargui *et al.* (2012) investigated geothermal energy for heating and cooling of greenhouses microenvironment.

This study proposes a BES model that would simulate the greenhouse thermal environment of slected single-span greenhouse shapes covered with polyethene. The impact of greenhouse design parameters (roof shape, orientation, covering material (polyethene), and ventilation) on temperature, RH, VPD, and energy demand were analysed. This result from this study would aid potential greenhouse farmers in determining the cost-benefit of the cropping system before investing in it.

Materials and Methods

Description of greenhouse models

The single-span simulated greenhouse designs; even gable, split-gable, and tunnel were covered with polyethene 150 µmm. The dimensions of the greenhouses were 10 × 5 × 4 m with a total floor area of 50 m^2. The specifications of the simulated greenhouses are presented in table 1.

Table 1: Greenhouse specifications.

Parameters	Condition for the BES Model		
Greenhouse type	Single span	Single span	Single span
Roof type	Tunnel roof	Split-gable roof	Gable roof
Roof glazing	Polyethene	Polyethene	Polyethene
Side glazing	Polyethene	Polyethene	Polyethene
Dimension	10 × 5 × 4 m	10 × 5 × 4 m	10 × 5 × 4 m
Surface area	186.24 m^2	147.33 m^2	149.50 m^2
Greenhouse volume	287.62 m^3	168.75 m^3	207.20 m^3
Floor area	50 m^2	50 m^2	50 m^2

Material properties

There were no preset greenhouses covering material properties in the TRNbuild. As a result, the properties of the materials were established in the Windows 7.4 program and then imported into TRNbuild using the DOE-2 file that was generated. The properties of polyethene used in the simulation were obtained from (Rasheed *et al.,* 2019).

BES modelling

The three major stages of the modelling process are pre-processing, modelling, and simulation.

Pre-Processing

The following tools and add-ons were used for pre-processing: Google SketchUpTM and Transys3d. Each was utilized to give the necessary input for TRNSYS 18 to execute the greenhouse simulation. TRNBuild (formerly known as PREBID) is a TRNSYS program's building interface module that was used to establish the greenhouse model's basic project data and output selection. It generates a BUI file that contains all of the information about the structure (greenhouse), including the 3D design, orientation, heating, cooling, construction materials, output selection, and radiation mode. To begin, a 3D model of a greenhouse was created in Trnsys3d, a Google SketchUpTM plug-in that generates an .idf file with 3D geometry data that can be read by TRNBuild. TRNBuild simulates only the thermal environment of the greenhouse, for natural ventilation, and requires air flows between the thermal zone and the outside environment.

Modelling

Using the TRNSYS 18 application, three BES models were created to examine the effects of the greenhouse design parameters on the inside thermal environment. Shown in Figure 1 is the flowchart of the TRNSYS model processes and development stages.

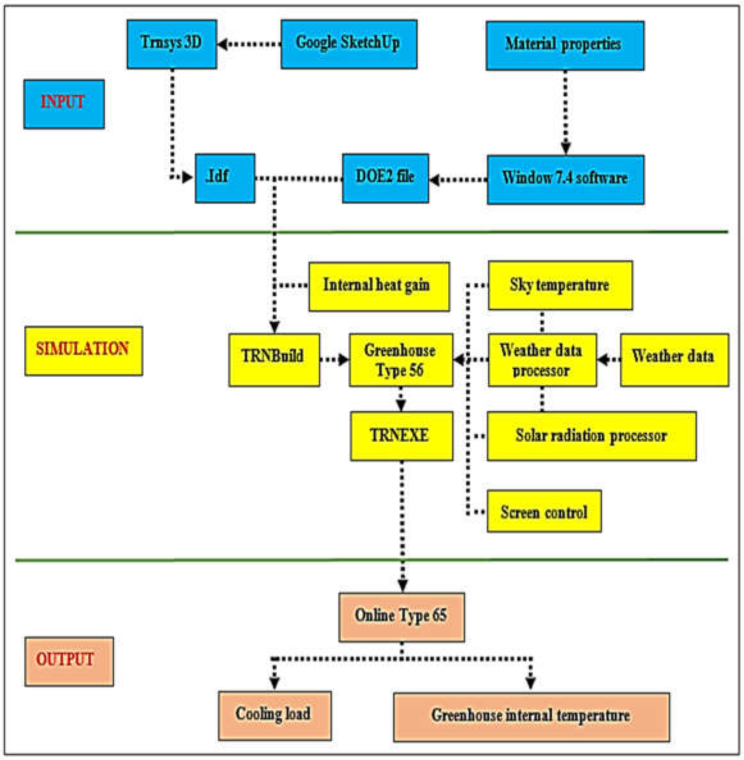

Figure 1: TRNSYS model flowchart.

The greenhouses' three-dimensional (3D) models were created using the trans3d plugin for Google SketchUp, which was then imported into TRNbuild to characterise the components. The project's fundamental description was entered using TRNbuild and TRNSYS simulation studio.TRNbuild to input the basic description of the project.

Simulation

The BES models of the greenhouses were created using the Simulation Studio in TRNSYS 18 and the the physical and light properties of the cladding materials defined. Figure 2 shows the BES model of the greenhouses. The weather data reader component is attached to Type-56 in the TRNSYS userinterface (UI) for a realistic simulation of the greenhouse environment. In the TRNSYS UI, a variety of components and controllers were used for the opening and closing of the vents/thermal screen and triggring of the cooling system using inside centre temperature and cooling set-points, respectively. Table 2 provides a full overview of the various components (Types) of a typical BES model. Table 3 shows the different simulating scenarios that were studies.

Table 2: Simulation scenarios

Parameter	Test condition
Orientation	0,45,90 (degrees)
Covering material	Polyethene
Ventilation	0 (off) and 1 (on)
Greenhouse shape	Even gable, split-gable, and tunnel
Measured variable	Temperature, Relative humidity, VPD

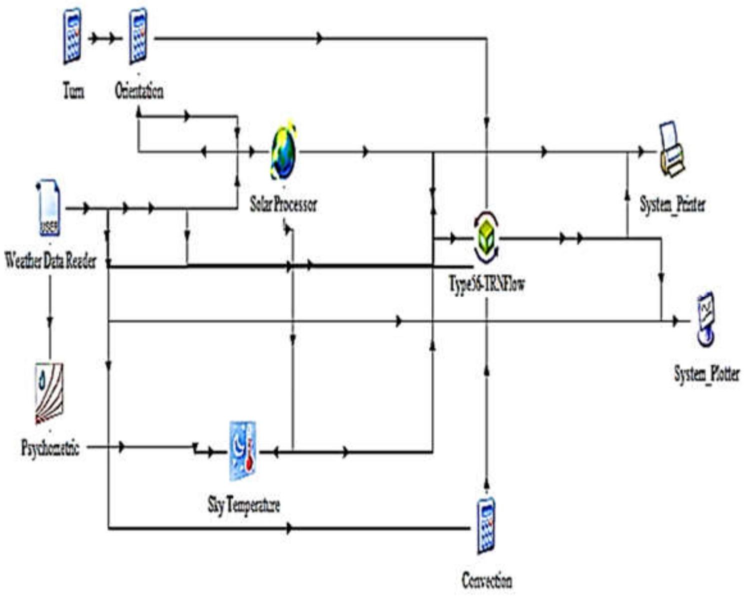

Figure 2: Transient system simulations (TRNSYS) studio of the greenhouse model.

Vapour pressure deficit (VPD)

The Vapour Pressure Deficit was calculated using the internal temperature and relative humidity values obtained in each of the greenhouses under each simulation condition specified. VPD was calculated using equations 1-3 (Akpenpuun *et al.,* 2021).

$$VPD = (e_s - e) \times 0.1 \qquad 1$$

$$e_s = 6.11 \times 10^{\frac{7.5\times T}{237.7+T}} \qquad 2$$

$$e = 6.11 \times 10^{\frac{7.5\times T_d}{237.7+T_d}} \qquad 3$$

$$T_d = T - \left(\frac{100 - RH}{5}\right) \qquad 4$$

where, VPD = Vapour Pressure Deficit (kPa); e_s = Saturated Vapour Pressure (mbar); e = Actual Vapour Pressure (mbar); T = Greenhouse Temperature (°C); T_d = Dew Point Temperature (°C); RH = Relative Humidity (%).

Table 3: Components of the greenhouse model in TRNSYS 18.

Component	**Type**	**Description**
Weather data reader	9e	This component reads data from a data file
Solar radiation processor	16c	Using the total solar radiation on a horizontal surface, this component calculates the total, beam, reflected, and diffused radiation on all greenhouse surfaces.
Sky temperature calculator	69b	Dew temperature, a horizontal beam, and diffuse radiation are used as inputs to calculate the sky temperature for long-wave radiation exchange.
Psychrometric chart	33e	Using inputs like dry bulk temperature and humidity ratio, this component calculates dew point temperature.
Greenhouse building model	56-a	This type is used to call TRNBUILD so that the actual 3D greenhouse model can be processed.
Printer	25d	Results were printed using this type on an external user-provided file.
Plotter	65c	This is an online result plotter

Cooling load determination

The cooling load was determined using the following equations:

$$Hw = U \times Ac \times (T_0 - T_i) \qquad 5$$

$$Hv = \rho i \times cp \times N \times V \times \ (T_0 - T_i) \qquad 6$$

$$Hs = F \times Ls \times (\Delta T - \theta) \qquad 7$$

$$Ht = (Hw + Hv + Hs) \times fw \qquad 8$$

where, Ht = Greenhouse cooling load(W); Hw = Through-flow heat load (W)

Hv = Interstitial ventilation heat transfer load (W); Hs = Underground heat transfer load (W)

Fw = Correction factor according to wind speed; F = Heat loss coefficient per unit length of outer periphery(W/m.°C); Ls = Greenhouse (m); ΔT = Indoor and outdoor temperature difference (°C); θ = Load reduction reference temperature difference (°C); ρi = Indoor air density (kg/m^3); cp = Specific heat of indoor air (J/kg°C); N = Interstitial ventilation rate (times/s)

V = Greenhouse volume (m^3); U = Greenhouse heat transmission rate (W/m^2 °C)

A cost-benefit analysis was performed to compare the costs of cooling between the greenhouse designs with the lowest and highest cooling loads for one year. For this analysis, the Nigerian naira (a tropical country in West Africa) is used for the energy-cost conversion.

$$E = P \ \times t \qquad 9$$

Where: E = Energy (kWh)

P = Power (kW)

T = time (h)

Statistical Analysis

The data collected from the TRNSYS simulation was analysed using statistical tools namely descriptive statistics, analysis of variance (ANOVA), and the Tukey HSD test. was used to make pairwise comparisons between groups after they have been deemed statistically significant.

Results

The descriptive statistics of the greenhouse air temperature distribution within the different greenhouse designs at orientations 0^o, 45^{o,} and 90^o when the ventilation was switched on and off are presented in Table 4.

Table 4: Descriptive statistics of temperature

	0^{o}_Vent-Off			0^{o}_Vent-On		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	29.59	24.12	30.10	26.19	25.45	26.36
SD	8.91	3.39	8.44	4.47	3.77	4.53
Min	13.60	13.59	14.00	14.35	14.35	14.37
Max	53.23	35.64	52.41	40.36	37.71	40.83
Sum	259191.97	211315.96	263673.21	229412.73	222949.87	230926.85

	45^{o}_Vent-Off			45^{o}_Vent-On		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	29.88	24.12	30.37	26.22	25.45	26.40
SD	9.02	3.39	8.54	4.48	3.77	4.54
Min	13.60	13.59	14.00	14.35	14.35	14.37
Max	53.11	35.64	52.46	40.40	37.71	40.87
Sum	261715.68	211315.96	266079.80	229710.96	222949.87	231268.84

	90^{o}_Vent-Off			90^{o}_Vent-On		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	30.52	24.12	30.57	26.25	25.45	26.43
SD	9.71	3.39	8.69	4.49	3.77	4.56
Min	13.56	13.59	14.00	14.35	14.35	14.37
Max	54.86	35.64	52.63	40.41	37.71	40.88
Sum	267340.60	211315.96	267765.78	229933.93	222949.87	231516.29

The descriptive statistics of the relative humidity of the different greenhouse designs at orientations 0^{o}, 45^{o}, and 90^{o} when the ventilation was off and on are shown in Table 5. The ANOVA result showed significant differences in the distribution of the relative humidity within the greenhouses.

Table 5: Descriptive statistics of relative humidity

	0^{o}_Vent-Off			0^{o}_Vent-On		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	32.07	39.77	30.78	73.46	75.91	72.78
SD	13.62	7.83	12.70	22.11	21.06	22.10
Min	8.08	20.06	14.00	10.06	11.53	9.84
Max	75.05	75.14	52.41	100.00	100.00	100.00
Sum	280939.54	348411.16	263673.21	643537.41	664965.00	637549.33

	45^{o}_Vent-Off			45^{o}_Vent-On		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	31.68	39.77	30.41	73.31	75.91	72.61
SD	13.78	7.83	12.84	22.08	21.06	22.07
Min	8.13	20.06	8.39	10.07	11.53	9.84
Max	75.05	75.14	73.15	100.00	100.00	100.00
Sum	277518.79	348411.16	266430.60	642176.72	664965.00	636035.77

	90^{o}_Vent-Off			90^{o}_Vent-On		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	31.46	39.77	30.20	73.23	75.91	72.52
SD	13.90	7.83	12.94	22.12	21.06	22.11
Min	7.95	20.06	8.32	10.07	11.53	9.83
Max	75.05	75.14	73.15	100.00	100.00	100.00
Sum	275571.62	348411.16	264525.34	641471.63	664965.00	635258.08

The descriptive statistics of the VPD of the gable, split-gable, and tunnel greenhouses at orientations 0^{o}, 45^{o}, and 90^{o} when the ventilation was switched off or on are shown in Table 6. The descriptive statistics show that the mean VPD of the greenhouses ranged from 1.64 kPa to 2.81 kPa when the ventilation was switched off and 0.86 to 1.05 kPa when the ventilation was switched on.

Table 6: Descriptive statistics of VPD.

	0º_Vent-Off			**0º_Vent-On**		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	2.70	1.64	2.75	1.00	0.86	1.04
SD	1.74	0.46	1.64	0.95	0.82	0.96
Min	0.44	0.44	0.48	0.00	0.00	0.00
Max	8.84	3.52	8.5	4.7	4.07	4.83
Sum	23615.98	14339.49	24112.44	8787.18	7540.51	9080.34
	45º_Vent-Off			**45º_Vent-On**		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	2.75	1.64	2.81	1.01	0.86	1.04
SD	1.76	0.46	1.67	0.95	0.82	0.96
Min	0.44	0.44	0.48	0.00	0.00	0.00
Max	8.79	3.52	8.52	4.72	4.07	4.84
Sum	24106.64	14339.49	24584.86	8844.94	7540.51	9147.35
	90º_Vent-Off			**90º_Vent-On**		
Description	**Gable**	**Split-gable**	**Tunnel**	**Gable**	**Split-gable**	**Tunnel**
Mean	2.80	1.64	2.85	1.01	0.86	1.05
SD	1.81	0.46	1.71	0.95	0.82	0.97
Min	0.44	0.44	0.48	0.00	0.00	0.00
Max	8.98	3.52	8.592	4.72	4.07	4.84
Sum	24535.54	14339.49	24969.78	8885.47	7540.51	9192.84

The ANOVA results showed significant differences in the distribution of the air temperature within the greenhouses. The p-value corresponding to the F-statistic of one-way ANOVA is less than 0.01, indicating that the treatments are significantly different. The Tukey-Kramer HSD critical values of Q were 4.4032 and 3.6333 for $\alpha = 0.01$ and 0.05, respectively using 4 and 3506 as degrees of freedom. The Tukey HSD test results showed that the comparison of the mean of all the greenhouse roof designs was significant at $p<0.01$ at the condition of vent off and vent on. However, the comparison between gable vs split-gable and gable vs tunnel at 90° orientation with the ventilation turned on and gable vs tunnel at 45° orientation with ventilation turned on were significant at $p<0.05$. Figure 3 to 5 depicts the ambient and internal greenhouse temperature variations with ventilation off and on at 90° orientations. Figures 3 to 5 show the trends of the ambient and greenhouse air temperature.

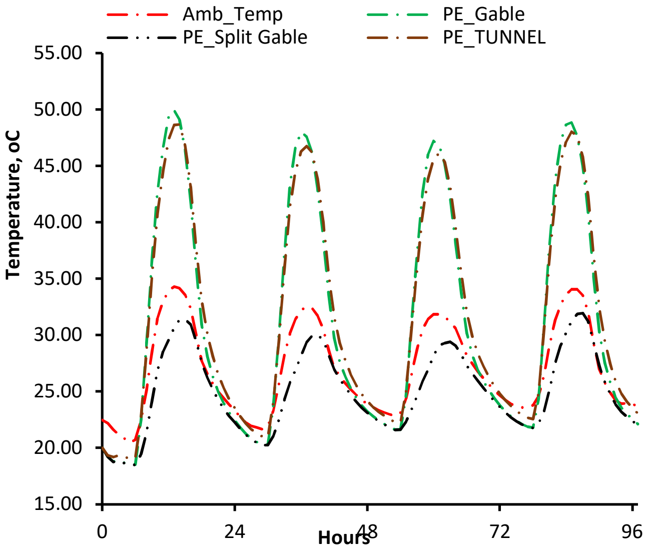

Figure 3: Ambient and internal greenhouse temperature variation with ventilation switched off at 0° orientation

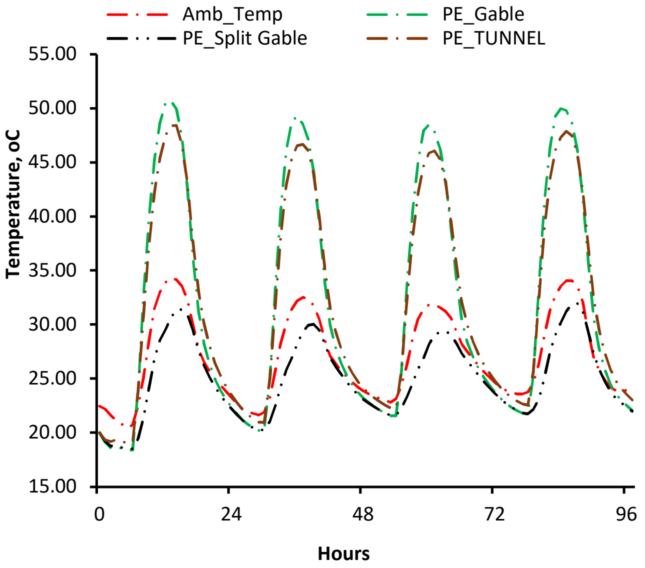

Figure 4: Ambient and internal greenhouse temperature variation with ventilation switched off at 90° orientation.

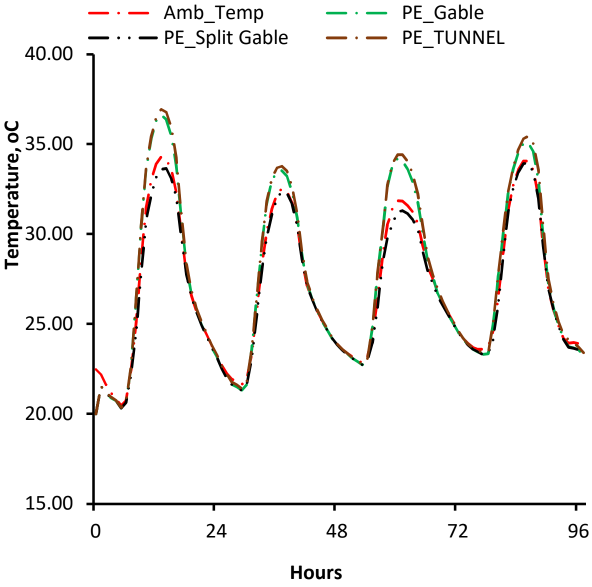

Figure 5: Ambient and internal greenhouse temperature variation with ventilation switched on at 90° orientation

The descriptive statistics show that the mean RH of the greenhouses ranged from 30% to 40% when the ventilation was switched off and 70% to 76% when the ventilation was switched on. The p-value corresponding to the F-statistic of one-way ANOVA is less than 0.01, indicated that the treatments (greenhouse shapes) were significantly different. The Tukey-Kramer HSD critical values of Q were 3.6432 and 2.7720 for α = 0.01 and 0.05, respectively, using 2 and 17518 as degrees of freedom. The results of the Tukey HSD analysis showed that all the comparisons were significantly different. Figures 6 to 8 are the relative humidity variation of the greenhouses at 90o orientation.

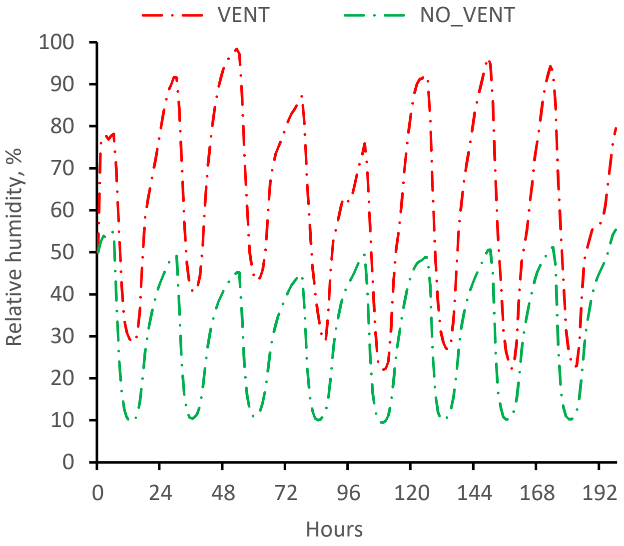

Figure 6: Gable greenhouse relative humidity variation at 90° orientation.

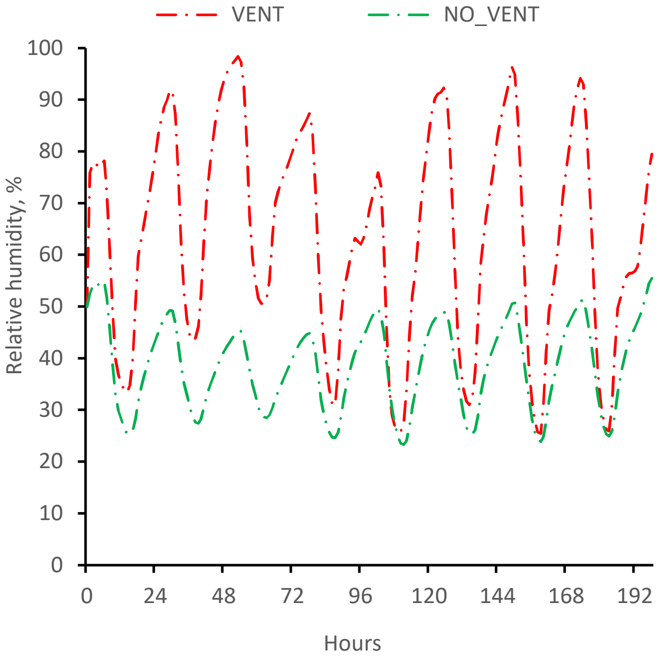

Figure 7: Split-gable greenhouse relative humidity variation at 90° orientation.

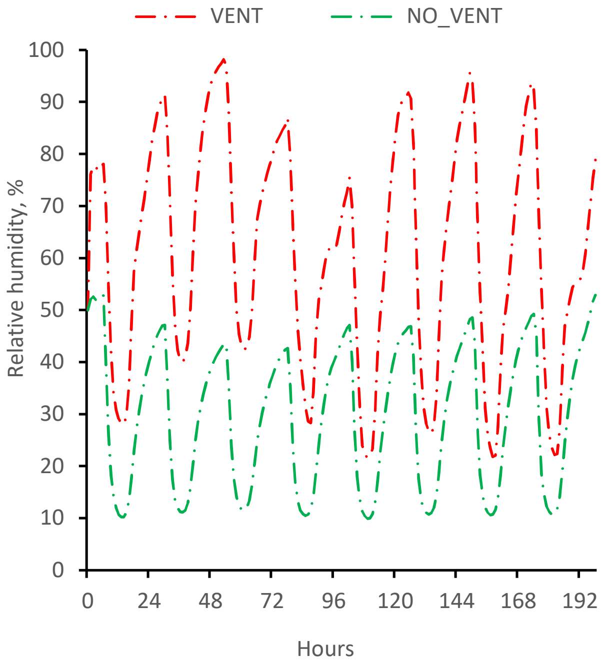

Figure 8: Tunnel greenhouse relative humidity variation at 90° orientation.

The p-value corresponding to the F-statistic of one-way ANOVA is less than 0.01, indicating that the treatments are significantly different. The Tukey-Kramer HSD critical values of Q were 4.1208 and 3.3147 for α = 0.01 and 0.05 respectively using 3 and 26277 as degrees of freedom. The results of the Tukey HSD tests carried out and the results showed that gable vs split-gable at 0° orientation, split-gable vs tunnel at 0° orientation, and gable vs split-gable at 45° orientation and split-gable vs tunnel at 45° orientation, and gable-split-gable at 90° orientation, and split-gable vs tunnel at 90° orientation with the condition of ventilation both on and off were significantly different. Figures 9 to 10 show the comparisons between the VPD of the different greenhouse designs when the ventilation was off and on.

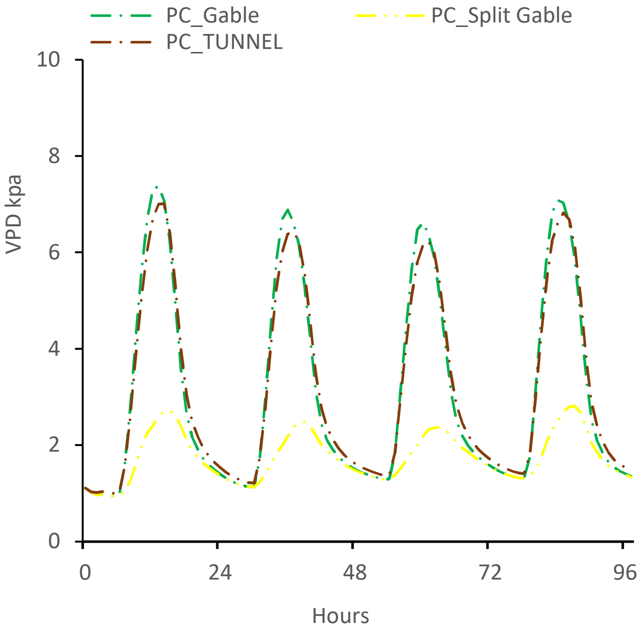

Figure 9: Greenhouses vapour pressure deficit variation with ventilation off at 90° orientation.

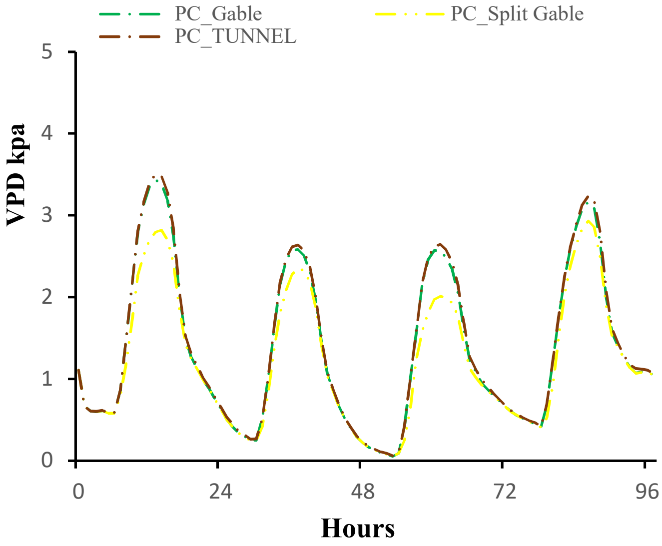

Figure 10: Greenhouses vapour pressure deficit variation with ventilation switched on at 90° orientation.

The cooling load is the amount of energy required to cool down the temperature build-up within the greenhouse. The climatic condition of the research location is such that there is a need to provide means of cooling down the greenhouse microclimate when maximum temperatures are exceeded. The cooling load of the greenhouse is shown in Figures 11 and 12 when the ventilation of each greenhouse design is turned on and off. The cooling load was maximum at 90° orientation, with 1521.522W, 454.5945W, and 3024.588 W for gable, split gable, and tunnel, respectively when the ventilation was switched on, and 15036.09W, 4531.922W, and 21299.03 W when the ventilation was switched off. The cooling load of the split-gable design was the lowest and consistently at 454.5945 W (ventilation switched on) and 4531.922 W (ventilation off) for the three greenhouse orientations (0°, 45°, and 90°). This result is consistent with Rasheed *et al.* (2020) who reported a 50% decrease in demand for cooling throughout the summer using natural ventilation. After the calculations, it would cost 3360 USD (#153, 437.00) to cool the split-gable greenhouse, which had the lowest cooling load of 0.45 kW per year, while cooling the tunnel greenhouse would cost as much as 17,200 USD (#7,188,898) with the highest cooling load of 21.30 kW per year.

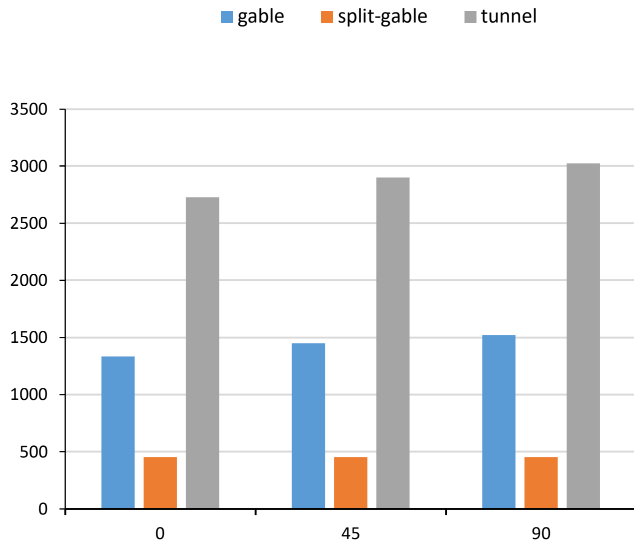

Figure 11: The cooling load of the greenhouses with ventilation switched on

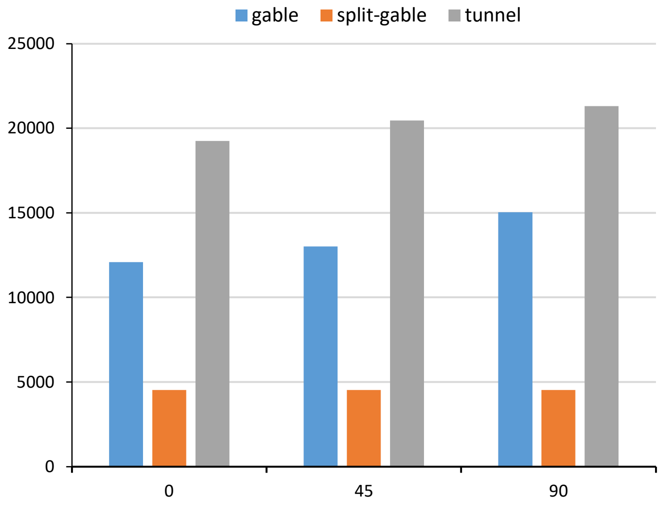

Figure 12: The cooling load of the greenhouses with ventilation off

Discussion

The tunnel greenhouse in the 90° (N-S) orientation with the ventilation system switched off had the highest internal temperature (40.88 °C) when compared to the gable and split-gable greenhouse shapes with internal temperatures of 40.41 °C and 37.71 °C, respectively. This is because the tunnel greenhouse has a larger surface area and internal volume than the gable and split-gable greenhouses, therefore, received more solar radiation which lead to higher temperatures within its micro-environment. The split-gable greenhouse, in contrast, had the lowest mean temperature of 24.12 °C in all the orientations investigated (0°, 45° and 90° (N-S)). This is due to the fact that the split-gable greenhouse has the smallest surface area and volume (147.33 m^2 and 168.75 m^3) when compared to the surface area and volume of the tunnel (186.24 m^2 and 287.62 m^3) and gable greenhouses (149.50 m^2 and 207.20 m^3). The large surface area of the gable and tunnel greenhouses allowed more solar radiation to be captured within their environments, and the large volume made available a larger volume air that was heated. This outcome made the split-gable greenhouse design preferred over the gable and tunnel greenhouse designs. The orientation with the preferred greenhouse environment was the 0º (E-W) orientation as this orientation reduces heat energy gained by the greenhouse. The findings in this study is similar to the finidings reported by Stanciu *et al.* (2016) who investigated the 90º (N-S) and 0º (E-W) greenhouse orientations in Romania and reported that the 0º E-W orientation resulted in a lower cooling demand during the summer than the 90º (N-S) orientation. This result is also consistent with Choab *et al.* (2020) who reported that the 0° (E-W) greenhouse orientation is the optimum orientation as it can save about 9.28% of the annual cost of air-conditioning of the greenhouse in Morocco compared to the North-South orientation.

This RH in all the greenhouses investigated were not the same due to their roof configuration, volume and surface area of the covering material. The low relative humidity readings when the ventilation was switched off were less than the minimum acceptable RH range of 50%-75% recommended for successful crop production in greenhouses. Low humidity harms the growth and development of plants as low humidity causes an increase in the rate of evapotranspiration, which consequently causes a reduction in the rate of photosynthesis, leaf dryness, discolouration in fruits and ultimately stunted growth (Kittas *et al.*, 2005; Akpenpuun and Mijinyawa, 2020). The high relative humidity readings when the ventilation was switched on were within acceptable RH for successful crop production in greenhouses, this leads to enhanced vegetative growth and increased leaf area and length of petioles within the greenhouse (Lieten, 2000). Therefore, switching on the greenhouse ventilation system provided a better environment for crop production in comparison to switching off the ventilation system.

It was observed that the VPD of all the greenhouses in the 0 ° orientation with the ventilation system switched on were all within the recommended VPD range 0.8 and 1.1 kPa for greenhouse vegetables. Whereas, the VPD in all the greenhouse designs with the ventilation system switched off were all above the optimum VPD range. The lower and upper VPD limits in the greenhouse are 0.5 kPa and 1.3 kPa, respectively. Any value below or above the lower and upper limits would result in fungus attack, mineral deficiencies, wilting, and physiological abnormalities (Shamshiri *et al.*, 2018b). According to Speetjens *et al.* (2012), VPD values between 0.2 and 1.0 kPa are advised for pollination and the prevention of fungal diseases, while Iraqi *et al.* (1995), and Katsoulas and Kittas (2009) suggested an optimal day and night hours VPD of 0.8 kPa for the best photosynthetic rate, which would lead to high crop yield.

Conclusions

This study proposed three single-span greenhouse BES models cladded with polyethene created using the TRNSYS 18 program. The BES models were detailed for single-span greenhouses to simulate the thermal environment of the greenhouses under different greenhouse designs. The models were used to evaluate the effect of the structural parameters and orientation on the internal temperature, relative humidity, vapour pressure deficit and cooling load of the greenhouseThe statistical analysis of the simulated results showed that there were significant differeces between the greenhouse designs in terms of their microclimate parameters. The following are the study's primary conclusions: It was observed that

1. The tunnel greenhouse and gable greenhouses orientated in the 90º (N-S) direction with the ventilation switch off had the highest mean internal temperatures of 30.52 °C and 30.57 °C, respectively) while the 0º (E-W) orientation had the lowest mean internal temperature for all the greenhouses, thereby, making 0º (E-W) orientation the optimum.

2. The relative humidity readings when the ventilation was switched on were within the acceptable RH range of 50-75%,.
3. The VPD was between 0.86 to 1.05 kPa when the ventilation was switched on, which was within the optimum range of 0.8 and 1.1 kPa.
4. The split-gable greenhouse had the lowest cooling load and cost of 0.4546 kW and 153, 437 naira per annum, which makes it the preferred design, while the tunnel greenhouse had the highest cooling load cost of 7,188,898 naira per annum.

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