Determining the Optimum Shape and Orientation of a Greenhouse on the Basis of Total Radiation availability

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Abstract

Greenhouse is a feasible option for sustainable crop production in the regions of adverse climatic conditions. For a successful greenhouse design, the selection of shape and orientation is of paramount importance.

In this study, three most commonly used single span shapes of greenhouses namely even-span, uneven-span and vinery type have been selected for comparison. The length, width and height (at the center) are kept same for all the selected shapes. The relevance of this paper was to develop a thermal model using MATLAB program for computing transmitted total solar radiation (beam, diffused and ground reflected) at each hour, for each month and at any latitude for the selected geometry greenhouses (through each wall, inclined surfaces and roofs) for both east-west and north-south orientation. The computed transmitted solar radiation is then introduced into another thermal model that is developed using MATLAB program to compute hourly inside air temperature for each shape and orientation. Statistical validation is carried out for the former model using solar radiation data for horizontal surface at (28^0 35'N and 77^0 12'E), New Delhi, India and (19^0 07'N and 72^0 51'E), Mumbai, India.

At 19^{o}N latitude, uneven-span shape greenhouse receives 10% more yearly average solar radiation as compared to even-span shape greenhouse whereas vinery shape to

receives 12% less yearly average solar radiation as compared to even-span shape. Similarly, at 28°N latitude, unevenspan shape to receives 8% more average radiation as compared to even-span shape whereas vinery shape receives 10% less yearly average solar radiation as compared to even-span shape. Results above show that east-west orientation of uneven-span solar greenhouse is the best suited during each month for both analyzed latitudes.

The developed model is very simple and has provided understanding to climate control process inside the greenhouse.

Keywords: Greenhouse; Solar energy; Solar radiation; Greenhouse shapes; Thermal modeling

Introduction

The main purpose of a greenhouse is to provide an environment conducive to plant production on a year-round basis or to extend the growing season. Greenhouses work by trapping heat from the sun. The glass panels of the greenhouse let in light but keep heat from escaping. This causes the greenhouse to heat up, much like the inside of a car parked in sunlight, and keeps the plants warm enough to live in the winter.

Greenhouses are used extensively by botanists, commercial plant growers, and dedicated gardeners. Particularly in cool climates, greenhouses are useful for growing and propagating plants because they both allow sunlight to enter and prevent heat from escaping. The transparent covering of the greenhouse allows visible light to enter unhindered, where it warms the interior as it is absorbed by the material within. The transparent covering also prevents the heat from leaving by reflecting the energy back into the interior and preventing outside winds from carrying it away.

The environment inside a greenhouse is dependent on many factors including the time of year, the amount and duration of natural sunlight, the relative humidity, the size and type of equipment and structure and the type of plants growing in the house. Total solar

radiation received by a greenhouse at a particular time and locations depends upon its shape as well as orientation, which ultimately determines the inside air temperature. Air temperature is one of the most dominant parameters affecting the plant growth. It is already established that inside air temperature of a passive greenhouse directly depends upon the ambient air temperature, the solar radiation intensity, the overall heat transfer coefficient, the cover material and the wind velocity (Sethi, 2009)

The selection of optimum shape and orientation of a greenhouse can lower the heating and cooling loads of the installed systems thereby saving a lot of operating cost. Hence, in this study, an attempt has been made to select the most suitable shape and orientation of a greenhouse on the basis of total solar radiation availability for different latitudes in the northern hemisphere.

The main objective of this project is to carry out a study on the three most commonly used single span shapes of greenhouses (even span, uneven span and vinery) keeping their length, width and height the same.

Materials and Methods

A mathematical model for computing transmitted total solar radiation (beam, diffuse and ground reflected) at each hour, for each month and at any latitude for the selected geometry greenhouses (through each all, inclined surfaces and roofs) is developed using MATLAB program for both east-west and north-south orientation. Experimental validation is carried out for the former model using solar radiation data for horizontal surface at (28^0 35'N and 77^0 12'E), New Delhi, India and (19^0 07'N and 72^0 51'E), Mumbai, India.

Practical relevance of the project

Greenhouses are primarily used for increasing crop production during off-season. Air temperature is one of the most dominant parameters affecting the plant growth. It is already established that air inside temperature of a passive greenhouse directly depends upon the ambient air temperature, the solar radiation intensity, the overall heat

transfer coefficient, the cover material and the wind velocity. Total solar radiation received by a greenhouse at a particular time and location also depends upon its shape as well as orientation, which ultimately determines the inside air temperature.

The project finds practical application in the selection of optimum shape and orientation of a greenhouse thus lowering the heating and cooling loads of the installed systems and saving a lot of operating cost.

Analytical approach of the thermal model

Three different shapes of single span greenhouses (Figures 1a–c) have been selected for the study. For realistic comparison, length, width and height of each shape are kept same viz. 6 m, 4 m and 3 m. Each shape is further subdivided into various sections along E-W and N-S orientation. The details of each section are shown in **Table 1** (E-W orientation) and **Table 2** (N-S orientation).

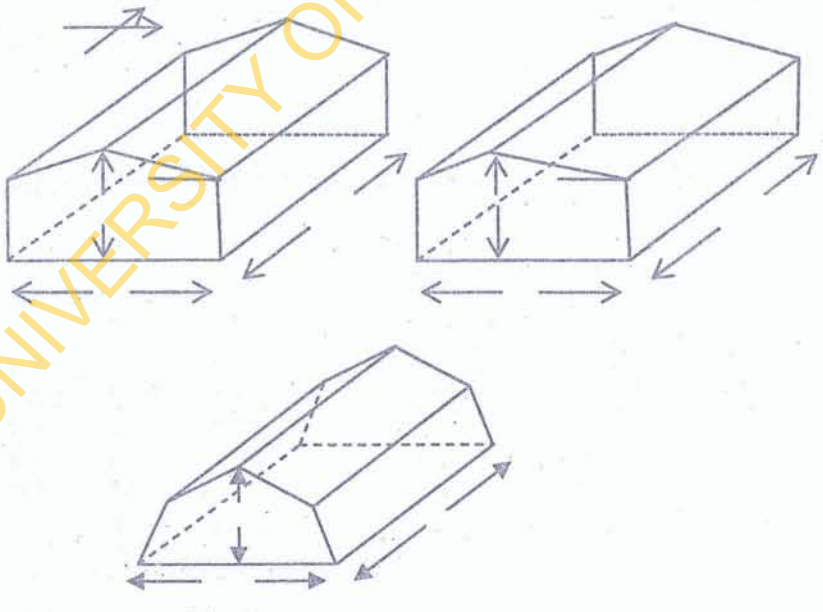

Figure 1: View of selected greenhouse shapes in E-W orientation.

Table 1: Sectional details of selected geometry greenhouses in E-W orientation

Shape (Area)	Sectional details SW-south wall, SR- south roof, NW- north wall, NR- north roof, EW- east wall, WW- west wall A= area of the ith section, where i is 1-6 for even-span, uneven- span, vinery shape, 1-10 for modified arch and 1-8 for quonset shape greenhouse					
Even span (70.82 m²)	SW(1) 12m² β=90⁰ γ =0⁰	SR(2) 13.41m² β=26.56⁰ γ =0⁰	NW(3) 12m² β=90⁰ γ =180⁰	NR(4) 13.41m² β=153.44⁰ γ =180⁰	EW(5) 10 m² β=90⁰ γ =-90⁰	WW(6) 10 m² β=90⁰ γ =+90⁰
Uneven-span (71.45 m²)	SW 12 m² β=90⁰ γ =0⁰	SR 18.97 m² β=18.48⁰ γ =0⁰	NW 12 m² β=90⁰ γ =180⁰	NR 8.48 m² β=135⁰ γ =180⁰	EW 10 m² β=90⁰ γ =-90⁰	WW 10 m² β=90⁰ γ =+90⁰
Vinery (59.64 m²)	SW 9.6 m² β=90⁰ γ =0⁰	SR 12.72 m² β=45⁰ γ =0⁰	NW 9.6 m² β=108.44⁰ γ =180⁰	NR 12.72 m² β=135⁰ γ =180⁰	EW 7.5 m² β=90⁰ γ =-90⁰	WW 7.5 m² β=90⁰ γ =+90⁰

Table 2: Sectional details of selected geometry greenhouses in N-S orientation

Shape (Area)	Sectional details					
Even span (70.82 m²)	EW 12m² β=90⁰ γ=-90⁰	ER 13.41 m² β=26.56⁰ γ =-90⁰	WW 12m² β=90⁰ γ =+90⁰	WR 13.41m² β=26.56⁰ γ =+90⁰	NR 10 m² β=90⁰ γ =180⁰	SW 10 m² β=90⁰ γ =0⁰
Uneven-	EW	ER	WW	WR	NR	SW

span (71.45 m²)	12 m² β=90⁰ γ =- 90⁰	18.97 m² β=18.48⁰ γ =- 90⁰	12 m² β=90⁰ γ =+90⁰	8.48 m² β=45⁰ γ =+90⁰	10 m² β=90⁰ γ =180⁰	10 m² β=90⁰ γ =0⁰
Vinery (59.64m²)	EW 9.6 m² β=71.56⁰ γ =- 90⁰	ER 12.72 m² β=45⁰ γ =- 90⁰	WW 9.6 m² β=71.56⁰ γ =+90⁰	WR 12.72 m² β=45⁰ γ =+90⁰	NR 7.5 m² β=90⁰ γ =180⁰	SW 7.5m² β=90⁰ γ =0⁰

Total solar radiation availability on greenhouse cover

Hourly solar radiation incident on an inclined surface of a greenhouse depends upon the time of the day, i.e. the hour angle ω, nth day of the year (starts from January 1), i.e. declination angle δ, solar altitude angle, i.e. α_s with horizontal or θ_z with vertical and surface azimuth angle γ, latitude angle ϕ of a place and angle β of the surface with horizontal. The required values of these parameters have been computed (Sethi, 2009).

- Variation of extraterrestrial radiation

$$I_{ext} = I_{sc}\left[1 + 0.034\cos\left(\frac{360n}{365}\right)\right] \quad (1)$$

where I_{ext} is the radiation measured on the plane normal to the radiation on the nth day of the year.

- Value of direct solar radiation in terrestrial region depends upon turbidity factor Tr of atmosphere (Sethi, 2009).

$$I_n = I_{ext}\, x \exp[-Tr/(0.9 + 9.4\sin\alpha_s)] \quad (2)$$

- Beam Radiation

R_b denotes the ratio of the average daily beam radiation on an inclined surface to that on a horizontal surface, and then the direct beam radiation on an inclined surface can be written as

$$I_b' = I_b R_b \tag{3}$$

R_b is a pure geometric parameter, dependent on the horizontal tilt, surface azimuth, declination angle and latitude. For surface facing directly towards the equator in the Northern Hemisphere, is given by the following equation

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos w + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos w + \sin\phi\sin\delta} \tag{4}$$

- Diffuse radiation

Assuming an isotropic distribution of the diffuse radiation over the hemisphere, the diffuse part is only dependent on the horizontal inclined angle β and the diffuse radiation of the horizontal surface. Diffuse radiation on inclined surface is

$$I_d' = I_d \frac{(1 + \cos(\beta))}{2} \tag{5}$$

This takes into account that the inclined slope sees only a portion of the hemisphere. The value of β for various sections is given in Tables 2 and 3 below.

- Reflected Light

The reflected component of total radiation is then computed as

$$I_R' = rI_g((1 - \cos(\beta)) / 2) \tag{6}$$

The value of r, a property that is expressed by the albedo factor ρ is given for some ground covers in Table 1 below.

Table 3: Typical reflectivity values for some ground covers

	Albedo
Lawn	0.205
Untilted Field	0.26
Naked Ground	0.17
Weather-beaten concrete	0.3
Asphalt	0.15
Fresh snow	0.85
Old snow	0.58

The energy of the reflected light is dependent on the ground's ability to reflect, a property which is expressed by the albedo factor ρ. The albedo ranges from 0.1 (asphalt paved road) to 0.9 (snow).

- Radiation on an inclined surface

Expression for total solar radiation falling on an inclined surface of the greenhouse is given by the equation below and represented in Fig. 2.

$$I_i = I_b^{'} + I_d^{'} + I_R^{'} \quad (7)$$

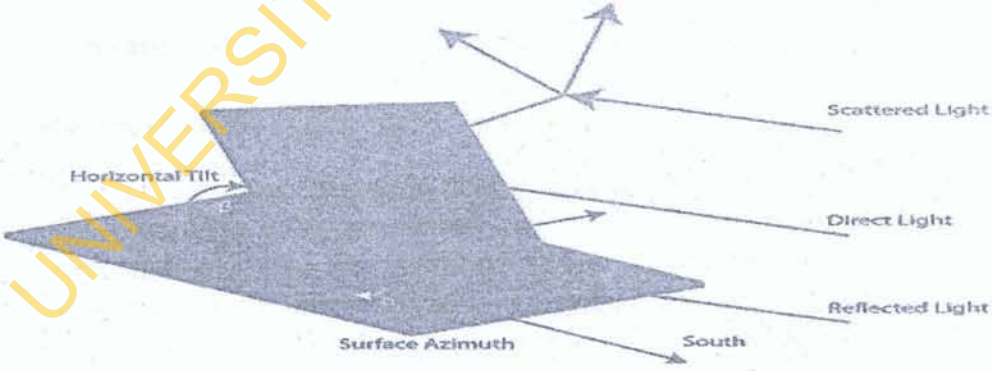

Figure 2: Showing the three components of radiation on an inclined surface.Source:(http://www.greenrhinoenergy.com /solar /radiation /tiltedsurface.php)

The hourly total solar radiation available on the greenhouse cover of a selected shape is total sum of solar radiation falling on

The hourly total solar radiation available on the greenhouse cover of a selected shape is total sum of solar radiation falling on different surfaces (each wall and roof) of the greenhouse. Total solar radiation available on the greenhouse cover is thus given by:

$$S_t = \sum_{i=1}^{6} A_i I_i \tag{8}$$

where A_i and I_i are the surface area of the ith section and total solar radiation available on ith section i.e. For E-W the hourly total solar radiation is given by:

$$S_t = A_{SW} I_{SW} + A_{SR} I_{SR} + A_{NW} I_{NW} + A_{NR} I_{NR} + A_{EW} I_{EW} + A_{WW} I_{WW} \tag{9}$$

For N-S orientation the hourly total solar radiation is given by:

$$S_t = A_{EW} I_{EW} + A_{ER} I_{ER} + A_{WW} I_{WW} + A_{WR} I_{WR} + A_{NW} I_{NW} + A_{SW} I_{SW} \tag{10}$$

Total solar radiation falling on inclined surface of the selected greenhouse has been computed (using the computer program written in MATLAB) on an hourly basis for all the sections of each shape of the greenhouse in both E-W and N-S orientations, using the above equations and values in Tables 1, 2 and 3.

Main program flow

The developed mathematical model has been solved with the help of computer program based on MATLAB software 7.4. The program makes use of the MATLAB graphic user interphase (GUI). The graphical user interface is a graphical display that contains components that enable a user to perform interactive tasks.

The GUI components of this model contain:

- Two push buttons that provides the reset and calculate mode.
- Editable text field boxes which enable the users to enter or modify text values.

- Static text boxes to label the push buttons and the editable text field boxes

Figure 3 below shows the GUI layout of the model

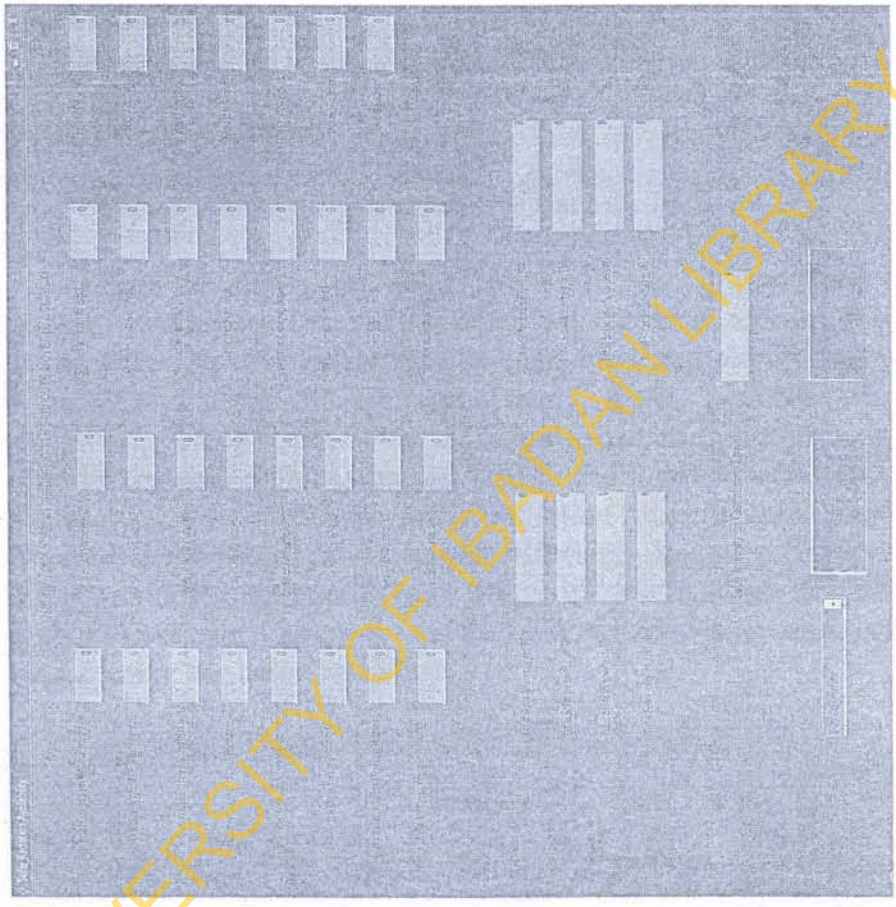

Figure 3: The GUI layout of the model

Experimental validation

The data used for the experimental validation was collected from Handbook of Solar Radiation Data for India [26]. It consists of monthly average hourly global radiation, daily global radiation and sunshine hours for New Delhi, India (28^0 35'N and 77^0 12'E) and Mumbai, India (19^0 07'N and 72^0 51'E).

The hourly total solar radiation incident on different inclined and vertical surface of the greenhouse for the selected greenhouse shapes in both E-W and N-S orientation is calculated and substituted in the model. The obtained values have been compared for each month (typical days of each month) in order to determine the more suitable shape and orientation of the selected greenhouse.

Results and discussion

- ***Effect of shape on solar radiation availability***

Effect of shape on solar radiation availability Total solar radiation availability (on the selected day of each month) for each selected shape in E-W orientation is computed and shown in Figures 4–6, as 19 and 28^{0}N latitude, respectively. It was observed that the uneven-span shape receives the maximum solar radiation during each month of the year in all latitudes; due to the largest south wall (SW) that receives the maximum solar radiation during each month as compared to the SW of other shapes. Although the uneven-span shape has the smallest north roof (NR), the reduction in solar radiation on this roof is not much as compared to the other shapes as north sections do not receive the beam radiation.

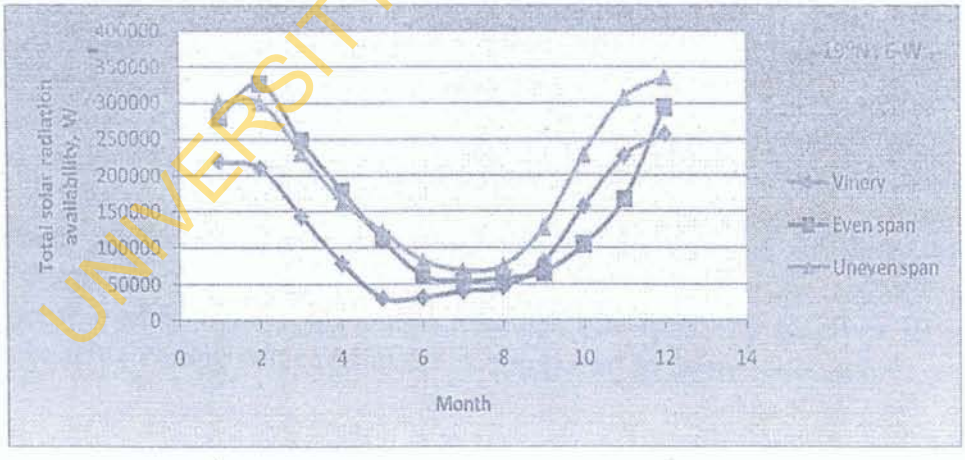

Figure 4: Annual variation of total solar radiation availability for different greenhouse shapes in E-W orientation at 19 ^{o}N latitude

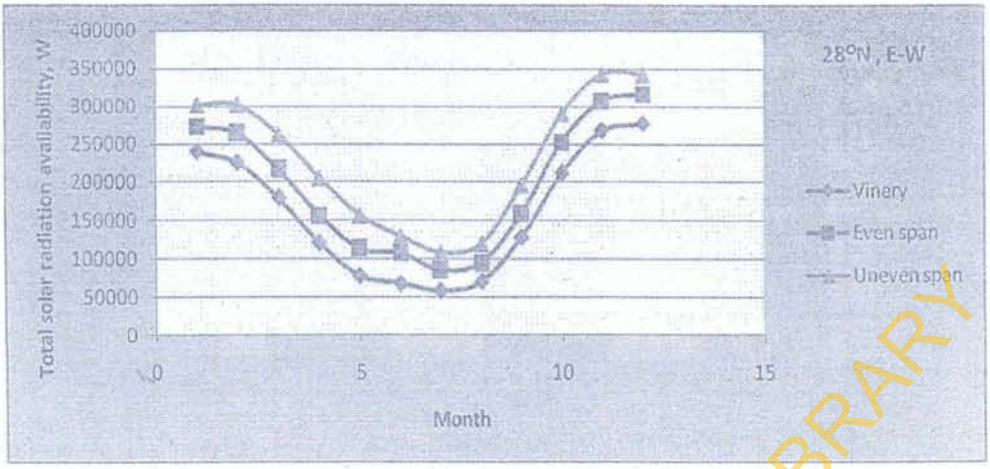

Figure 5: Annual variation of total solar radiation availability for different greenhouse shapes in E-W orientation at 28 °N latitude

At 19°N latitude, all greenhouse shapes receive greater amount of solar radiation in winter months but less in summer months (Figure 4). It is due to highest altitude angle of the sun during the summer months, which does not allow much radiation from the sidewalls. This difference further increases at 28°N latitude and the solar radiation received in winter months is slightly less as compared to the previous (Figure 5).

Yearly total solar radiation availability for all shapes at the selected latitudes in E-W orientation is shown in Figure 6. The comparison is made with reference to the even-span shape greenhouse. At 19°N latitude, uneven-span shape greenhouse receives 10% more yearly average solar radiation as compared to even-span shape greenhouse whereas vinery shape receives 12% less yearly average solar radiation as compared to even-span shape. Similarly, at 28°N latitude, unevenspan shape receives 8% more average radiation as compared to even-span shape whereas vinery shape receives 10% less yearly average solar radiation as compared to even-span shape.

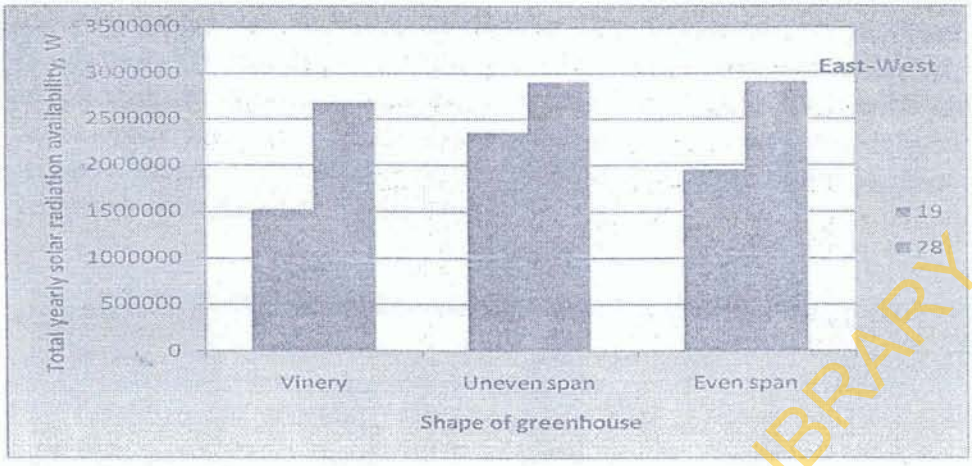

Figure 6: Availability of total solar radiation for all the shapes at different latitudes in E-W orientation

Although the length, width and height for all the greenhouse shapes is the same (6 m, 4 m and 3 m, respectively), due to the difference in the ratio of the cover to the floor area (Ac/Ag) of each shape, the total amount of solar radiation received from the whole greenhouse would automatically be different for each shape and the solar radiation availability should be a linear function of the cover area, but this is not true. A comparison between Ac/Ag ratio and yearly solar radiation availability for the selected shapes shows that an uneven-span shape has 0.88% more Ac/Ag ratio as compared to even-span shape but it receives 8.68% and 7.6% more radiation at 19 and 28°N latitudes, respectively. Vinery shape has 15.8% less Ac/Ag ratio but it receives 3.96% and 1.2% less solar radiation at 19 and 28°N latitudes. It can thus be concluded that shape of the greenhouse definitely affects the total solar radiation availability on it.

The maximum variation in total solar radiation availability amongst different shapes occurs in June (for summer) and in December (for winter) as shown in Figs. 7 & 8 at 19°N and 28°N latitudes, respectively.

At 19°N latitude, in June, an uneven-span shape receives 14.02% more radiation as compared to even-span shape (Figure 7) whereas vinery shape receive 32.26% less radiation as compared to an even-span shape. Similarly, in December, an uneven-span shape

receives 6.6% more radiation as compared to even-span shape (Figure 7) whereas vinery shape receive 6.9% less radiation as compared to an even-span shape. It can be concluded that due to hot climate throughout the year at 19°N latitude, a greenhouse shape, which receives minimum solar radiation would be more suitable. Hence vinery shapes should be preferred.

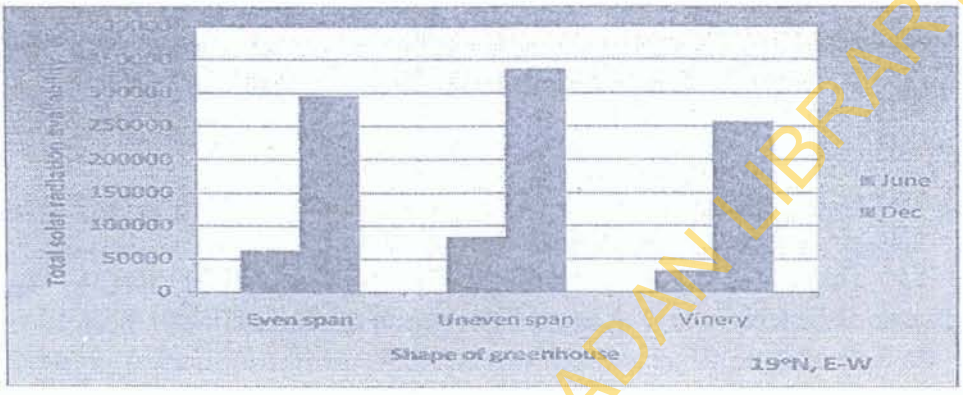

Figure 7: Variation in total solar radiation availability in June and December for all the shapes (E-W orientation) at 19°N latitude

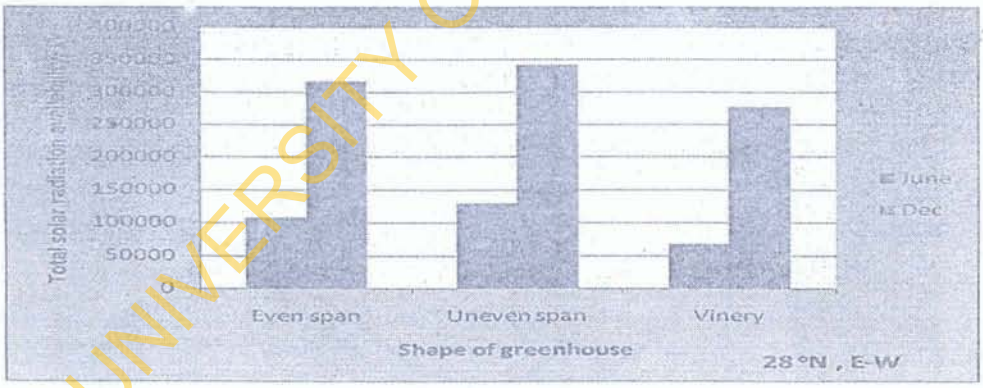

Figure 8: Variation in total solar radiation availability in June and December for all the shapes (E-W orientation) at 28°N latitude

At 28°N latitude, in June, an uneven-span shape receives 9.4% more radiation as compared to even-span shape (Figure 8) whereas vinery shape receive 22% less radiation as compared to an even-span shape. Similarly, in December, an uneven-span shape receives 4,02%

more radiation as compared to even-span shape (Figure 8) whereas vinery shape receive 6.6% less radiation as compared to an even-span shape. It can be concluded that due to hot climate throughout the year at 28°N latitude, a greenhouse shape, which receives minimum solar radiation would be more suitable. Hence vinery shapes should be preferred.

It can be concluded that due to hot climate throughout the year at 19°N and 28°N latitudes, a greenhouse shape, which receives minimum solar radiation would be more suitable. Hence vinery shapes should be preferred.

- *Effect of orientation on solar radiation availability*

A comparison of total solar radiation availability during each month of the year for even-span greenhouse in E-W and N-S orientation at 19°N latitude is shown in Figure 9. It is observed that on an average, N-S orientation receives more solar radiation during all months of the year as compared to E-W orientation. It is because in summer, eastern and western sections in N-S orientation receive more radiation as compared to northern and southern sections in E-W orientation. At this latitude ambient air temperatures are high throughout the year and E-W orientation which receives less solar radiation is more suited, as its application would be held lower inside air temperature during the year.

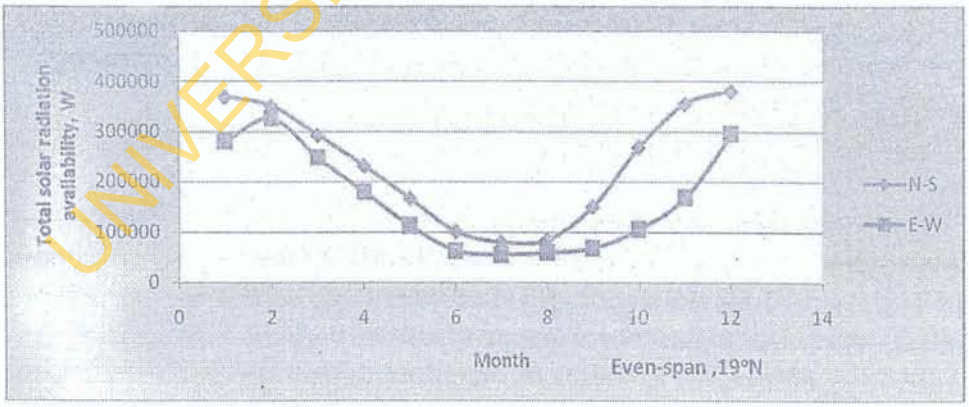

Figure 9: A comparison of annual variation in total solar radiation availability for even-span greenhouse in E-W and N-S orientation at 19°N latitude

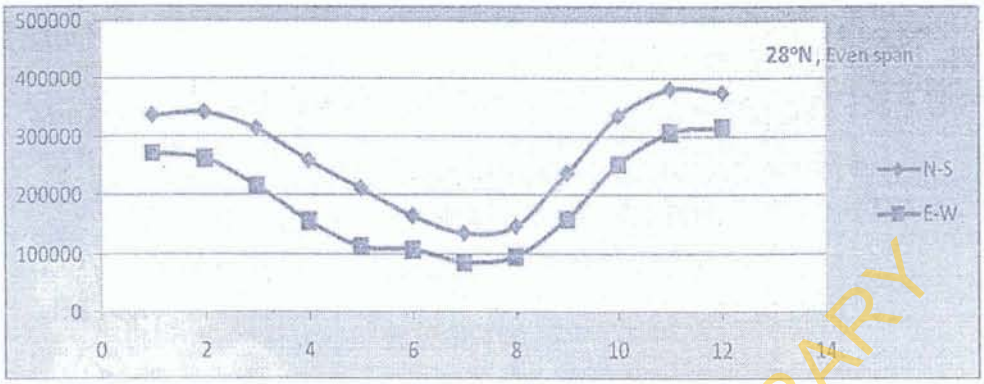

Figure 10: A comparison of annual variation in total solar radiation availability for even-span greenhouse in E-W and N-S orientation at 28°N latitude

A comparison of total solar radiation availability during each month of the year for even-span greenhouse in E-W and N-S orientation at 28°N latitude is shown in Fig. 10. It is also observed that on an average, N-S orientation receives more solar radiation during all months of the year as compared to E-W orientation. It is because in summer, eastern and western sections in N-S orientation receive more radiation as compared to northern and southern sections in E-W orientation. At this latitude also, ambient air temperatures are high throughout the year and E-W orientation which receives less solar radiation is more suited, as its application would be held lower inside air temperature during the year. For all other shapes like vinery and uneven span the trend of solar radiation availability is similar to even-span shape as discussed above.

Conclusion

Room temperature is one of the most important aspects of any greenhouse. In some areas, greenhouses shut down during certain months because the temperature is too hot or too cold to produce high-quality plants. It is therefore necessary to predict the solar radiation availability inside the greenhouse in order to determine the optimum shape and orientation of the greenhouse for a particular location and latitude. A model was developed for analyzing the orientation and shape of greenhouse which is most suitable for all year round applications.

The following conclusions are drawn from the present studies:

- The model developed is very simple and useful to predict the solar radiation availability inside the greenhouse.
- Air temperature remains the highest inside an uneven span shape and the lowest in a vinery shape as compared to other shapes during different months of the year.
- Uneven-span shape greenhouse receives the maximum solar radiation during each month of the year at all latitudes, whereas vinery shape receives the minimum solar radiation during each month of the year at all latitudes.
- At 19°N and 28°N, a vinery shape should be preferred as it receives minimum amount of solar radiation during all months of the year.
- At 19°N, east-west orientation should be preferred as it receives less solar radiation is summer with small differences in receive solar radiation in winter months. With increase of the latitude angle, the difference in the radiation received during winter month increase as compared to lower altitude. As winters are severe and longer at higher altitude angle, E-W orientation should be also preferred, as it would provide more radiation in winter and less in summer.

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Nomenclature

A - surface, [m^2]
I_{sc} - solar constant, [= 1367 Wm^{-2}]
I_t - hourly total radiation on a horizontal surface, [kWm^{-2}]
I_{ext} - daily extraterrestrial solar radiation on a horizontal surface, [kWm^{-2}]
I_b - hourly beam radiation, [kWm^{-2}]
I_d - hourly diffuse radiation, [kWm-2]
n - number of the day of the year starting from the first of January, [dimensionless]
R_b - the ratio of beam radiation on the tilted surface to that on a horizontal surface
S_t - total solar radiation available on the greenhouse cover, [kW]
Greek letters
δ - solar declination, [deg]
β - angle of the surface with horizontal, [deg]
φ - latitude of site, [deg]
r - ground reflectance factor [dimensionless]
ω - the sunset hour angle, [deg]
γ- surface azimuth angle