MATHEMATICAL MODELING OF SOLAR RADIATION AVAILABILITY ON A GREENHOUSE IN COMPOSITE CLIMATIC REGIONS
3.1 INTRODUCTION

Knowledge of exact amount of solar radiation availability and transmission is essential for selecting the shape and orientation of a greenhouse for better solar energy utilization in a composite climate. Edwards and Lake (1965) measured solar radiation transmission in a large span east-west oriented greenhouse. Obstruction to diffuse radiation caused by various components of the structure was determined by making measurements on overcast days of various stages of construction and mean daily transmissivity of the diffuse component was found to be 64-69 %, that of the direct component, 57% in summer and 68% in winter. They pointed out that changes in shape rather than structure could lead to improvements in transmission particularly that of direct radiation. Manbeck and Aldrich (1967) attempted to generalize direct visible solar radiation transmission in a semi-cylindrical greenhouse using an analytical procedure. Studies have been conducted by Coulson and Tempo (1977) regarding the availability of solar radiation upon slopes of different orientation buildings for poultry houses. A correlation equation has been developed by Orgill (1977) for hourly direct and diffuse radiation on a horizontal surface. Kozai (1977) developed a computer model to predict the effects of orientation and latitude on the overall transmission of a free standing conventional glasshouse. Ben-Abdallah (1983) analyzed solar radiation input to conventional and shed-type glasshouse by means of the total transmission factor. Coffin et al. (1988) built and tested scale models of conventional and insulated multispan greenhouses at Montreal. The east-west (E-W) models were found to have higher overall light levels than the north-south (N-S) ones during the winter months, though no apparent difference was observed for the rest of the year. Solar radiation transmission and capture in single span greenhouses were evaluated by Lau (1988) by means of computer modeling and simulations. It was shown that the quantity of solar radiation incident on an inside surface is governed by the geometry of the greenhouse through the interception factor for direct radiation and configuration factor of diffuse radiation. Simulated results were found to agree well with actual data obtained from a shed-type and a conventional glass house. Elaborated models of total radiation for a semi-cylindrical greenhouse have been described by Tiwari, (1998).

No such study has been conducted for finding the total solar radiation availability on even-span and semi-cylindrical greenhouse for both E-W and N-S oriented greenhouses in composite climates for selecting the shape and orientation of the greenhouse. In this study, a mathematical model for the hourly availability of solar radiation on even-span and semi-cylindrical greenhouse canopy cover for E-W and N-S orientation for the complete year has
been presented. From the theoretical results of solar radiation availability and transmission factor, selection of the greenhouse shape and orientation has been made for ideal solar input efficiency.

### 3.2 ANALYTICAL APPROACH OF THE MODEL

In order to formulate the computational procedures some assumptions have been made. These are: (i) internal reflection with in the greenhouse is assumed negligible (ii) a clear polyethylene sheet with parallel surfaces does not diffuse light.

#### 3.2.1 Hourly Solar Radiation on an Inclined Surface

Hourly solar radiation incident on the greenhouse cover depends on the time of the day i.e. the hour angle \( \omega \) (zero at noon, negative in the morning and positive in afternoon, varies by 15° after each hour), \( n \)th day of the year (starts from January 1) i.e. declination angle \( \delta \), solar altitude angle i.e. \( \alpha_s \) with horizontal or \( \theta_z \) with vertical and solar azimuth angle \( \gamma \) (zero for south facing surfaces, 180° for North facing surfaces, -90° for east facing and +90 for west facing surfaces), latitude angle \( \phi \) of a place and inclination angle \( \beta \) of the surface with horizontal. Different solar angles using an inclined surface have been shown in Fig. 3.1.

![Fig. 3.1 Schematic of different solar angles on an inclined plane](image)

The required values of these parameters have been calculated using Eqns. 3.1 to 3.6 as suggested by Duffie and Beckman (1991).

\[
\delta = 23.45 \times \sin \left( \frac{360 \times 284 + n}{365} \right) 
\]

\[
\omega = 15 \left( t_{solar} - 12 \right) 
\]

\[
\alpha_s = \sin^{-1}(\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) 
\]

\[
\theta_z = \cos^{-1}(\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) 
\]
Zenith angle of sun on inclined surface is calculated as given by Eqn. 3.5
\[ \theta_i = \cos^{-1}[\sin \phi (\sin \delta \cos \beta + \cos \delta \cos \gamma \cos \omega \sin \beta) + \cos \phi (\cos \delta \cos \omega \cos \beta - \sin \delta \cos \gamma \sin \omega \sin \beta)] \]  
3.5

Solar azimuth angle \( \gamma \) is given by Eqn. 3.6
\[ \gamma = \cos^{-1}[(\cos \theta_i \sin \phi - \sin \delta)/(\sin \theta_i \cos \phi)] \]  
3.6

Intensity of extra terrestrial radiation measured on a plane normal to the radiation on the \( n \)th day of the year is given in terms of solar constant \( I_{se} \) which is 1367 W/m\(^2\) as given by Duffie and Beckman (1991).
\[ I_{ext} = I_{se} \left[ 1 + 0.034 \cos \left( \frac{360n}{365} \right) \right] \]  
3.7

Value of direct solar radiation in terrestrial region depends upon turbidity factor of atmosphere as given by Tiwari (1998).
\[ I_n = I_{ext} \times \exp[-T_r/(0.9 + 9.4 \sin \alpha)] \]  
3.8

Where \( T_r \) is the turbidity factor known for different months and for different regions as given by Tiwari (1998). Beam radiation \( I_b \) and diffuse radiation \( I_d \) on a horizontal surface and beam radiation on inclined surface \( I_b' \) is given by Eqn. 3.9, 3.10 and 3.11.
\[ I_b = I_n \cos \theta_z \]  
3.9
\[ I_d = \frac{1}{3} [I_{ext} - I_n] \cos \theta_z \]  
3.10
\[ I_b' = I_n \cos \theta_i \]  
3.11

Total solar radiation \( I_g \) incident on horizontal surface at any time is calculated from Eqn. 3.12
\[ I_g = I_b + I_d \]  
3.12

Therefore, total solar radiation \( I_i \) incident on an inclined surface at any time is the sum of the beam radiation \( I_b \) and diffuse radiation \( I_d \) transmitted at the glazing level through the roof and the walls. The latter originates from \( I_b \) the sky diffuse irradiance and ground reflected irradiance.

An expression for total solar radiation falling on an inclined surface as given by Liu and Jordon (1960) is;
\[ I_i = I_b (R_b) + I_d (R_d) + r (R_s) (I_b + I_d) \]  
3.13

\( R_b \) (conversion factors for beam radiation) is the ratio of flux of beam radiation incident on an inclined surface \( (I_b') \) to that on a horizontal surface \( (I_b) \). Therefore, Eqn. 3.11 and 3.9 gives
\[ R_b = \cos \theta_i / \cos \theta_z \]  
3.14

Depending upon the orientation of the inclined surface, expressions for \( \cos \theta_i \) (Eqn 3.5) and \( \cos \theta_z \) (Eqn 3.4) have been computed.
$R_d$ (conversion factor for diffuse radiation) is the ratio of flux of diffuse radiation incident on an inclined surface ($\sigma_i$) to that on a horizontal surface ($\sigma_i$) and is

$$R_d = \frac{(1 + \cos \beta)}{2} \quad 3.15$$

$R_e$ is the reflected component and $r$ is the reflection coefficient of the ground (taken as 0.2 for ordinary ground).

$$R_e = \frac{(1 - \cos \beta)}{2} \quad 3.16$$

$I_i$ has been computed for each month of the day for semi-cylindrical (Appendix A, Tables A1-A12) and even-span (Appendix B, Tables B1-B12) greenhouses for east-west and north-south orientations (Appendix C, Tables C1 and C2). In order to validate the developed model, hourly variation of beam, diffuse and total radiation on a horizontal surface at 31°N latitude on May 12, 2005 is computed with the help of Eqns 3.9, 3.10 and 3.12 and given below in Table 1. Using this data, total radiation on an inclined surface (south wall of east-west oriented greenhouse, inclined at 26.56° with horizontal) is computed and compared with the measured total radiation on the same inclined surface for the validation of the model. The comparison is shown in the results part.

**Table 1. Total, diffuse and beam radiation on a horizontal surface at 31°N latitude on 12th May, 2005.**

<table>
<thead>
<tr>
<th>Time of day</th>
<th>Total radiation (W/m²)</th>
<th>Diffuse radiation (W/m²)</th>
<th>Beam radiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6am</td>
<td>108.45</td>
<td>68.51</td>
<td>39.94</td>
</tr>
<tr>
<td>7am</td>
<td>312.16</td>
<td>96.71</td>
<td>215.45</td>
</tr>
<tr>
<td>8am</td>
<td>510.08</td>
<td>120.16</td>
<td>389.92</td>
</tr>
<tr>
<td>9am</td>
<td>712.14</td>
<td>133.32</td>
<td>578.82</td>
</tr>
<tr>
<td>10am</td>
<td>876.38</td>
<td>140.51</td>
<td>735.87</td>
</tr>
<tr>
<td>11am</td>
<td>975.74</td>
<td>144.68</td>
<td>831.06</td>
</tr>
<tr>
<td>12 noon</td>
<td>1016.65</td>
<td>145.20</td>
<td>871.45</td>
</tr>
<tr>
<td>1pm</td>
<td>975.74</td>
<td>144.65</td>
<td>831.06</td>
</tr>
<tr>
<td>2pm</td>
<td>876.38</td>
<td>140.51</td>
<td>735.87</td>
</tr>
<tr>
<td>3pm</td>
<td>712.64</td>
<td>133.32</td>
<td>578.82</td>
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<tr>
<td>4pm</td>
<td>510.08</td>
<td>120.16</td>
<td>389.92</td>
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<tr>
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<tr>
<td>6pm</td>
<td>108.45</td>
<td>68.51</td>
<td>39.94</td>
</tr>
</tbody>
</table>
3.3 SOLAR RADIATION ON GREENHOUSE COVER

Using Eqns 3.1 to 3.16 a computer program has been developed in C for computing the hourly total solar radiation incident on different inclined and vertical surfaces (imaginary) of semi-cylindrical greenhouse (Fig. 3.2a) such as AB inclined at 75° with horizontal and facing south (area 1-a-b-2), BC inclined at 45° with horizontal and facing south (area 2-b-c-3), CD inclined at 15° with horizontal and facing south (area 3-c-d-4), DE inclined at 165° with horizontal and facing north (area 4-d-e-5), EF inclined at 135° with horizontal and facing north (area 5-e-f-6), FG inclined at 105° with horizontal and facing north (area 6-f-g-7), EW inclined at 90° with horizontal and facing east (area a-b-c-d-e-f-g) and WW inclined at 90° with horizontal and facing west (area 1-2-3-4-5-6-7). Although these surfaces are curved but for computation purpose these are considered as flat. Similarly for different inclined surfaces of even-span greenhouse (Fig. 3.2 b) such as SW inclined at 90° with horizontal (area 1-a-b-2), SR inclined at 26.56° with horizontal (area 2-b-c-3), NW inclined at 90° with horizontal (area 4-d-e-5), NR inclined at 153.44° with horizontal (area 3-4-d-c), EW inclined at 90° with horizontal (area a-b-c-d-e) and WW inclined at 90° with horizontal (area 1-2-3-4-5). The ratio of greenhouse cover \( A_c \) to the greenhouse floor area \( A_g \) has been kept as 2.10 for both the selected geometry greenhouses for solar radiation comparison purposes. The solar radiation values have been obtained for typical days of each month of the year as suggested by Duffie and Beckman, (1991).

The obtained values have been compared for each month for the selected geometry greenhouses in order to find the more suitable shape of commonly used greenhouse for E-W and N-S orientation in composite climates. Total solar radiation is thus given by

\[
S_t = \sum A_i I_i
\]

3.17

Where \( i \) is 1 to 8 for semi-cylindrical and 1 to 6 for even-span greenhouse and \( A_i \) and \( I_i \) are the area of \( i^{th} \) section and total solar radiation available on \( i^{th} \) section. \( \sum A_i I_i \) has been computed by using the Eqn 3.13 and multiplying it with the respective area \( A_i \) of the \( i^{th} \) section of the greenhouse. Using the developed computer program variation of \( \cos \phi, \cos \phi, R_b, R_d, R_v, I_g, I_d, I_l \) and \( I_i \) for each section of the greenhouse with time of the day have been computed for semi-cylindrical and for even-span greenhouse respectively. Total Insolation \( \sum A_i I_i \) has thus been computed for each month of the day for semi-cylindrical (Tables A1 to A12) and even-span (Tables B1 to B12) east-west and north-south (Tables C1 and C2) oriented greenhouse and shown in Appendices A, B and C respectively.
Month wise annual variation of total insolation i.e. sum of solar radiation on each wall and roof of an even span greenhouse for east-west and north-south orientation has been computed and compared as shown in Fig. 3.4. Annual variation of total solar radiation for each month (of a typical day) falling on semi-cylindrical and even-span greenhouse (both east-west oriented) is also shown in Fig. 3.4.

![Fig. 3.2 Schematic view of (a) semi-cylindrical and (b) even-span greenhouse](image)

3.4 SOLAR RADIATION TRANSMISSION INSIDE THE GREENHOUSE

The most important requirement for computing the transmitted solar radiation through the greenhouse cover is the transmittance of the cover material of known refractive index ‘n’ and extinction coefficient $K$. Solar radiation transmission through each wall and roof of the selected geometry greenhouse canopy cover after reflection and absorption at the interface has been computed by means of Fresnel and Bouguer’s law of attenuation respectively.

For smooth surfaces, Fresnel has derived expressions for the refraction of unpolarized radiation on passing from a medium 1 with a refractive index, $n_1$ taken as 1 for air, to medium 2 with refractive index, $n_2$ taken as 1.37 for polyethylene sheet (Duffie, 1991).

$$ r_1 = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} $$

3.18
\[ r_p = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \]  
\[ r = \frac{1}{2} [r_\perp + r_p] \]

Where, \( \theta_1 \) and \( \theta_2 \) are the angles of incidence & angle of refraction respectively. Eqn 3.18 and 3.19 represent the perpendicular and parallel components of unpolarized radiation. Eqn 3.20 gives the average of the two components. The angles \( \theta_1 \) and \( \theta_2 \) are related to the indices of refraction by Snell’s law,

\[ \frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} \]

If perpendicular and parallel components are not equal (except at normal incidence) then the transmittance of initially unpolarized solar radiation is the average transmittance of the two components through single cover as given below;

\[ \tau_r = \frac{1}{2} \left[ \frac{1 - r_p}{1 + r_p} + \frac{1 - r_\perp}{1 + r_\perp} \right] \]

The absorption of radiation in a partially transparent medium is described by Bouguer’s law, which is based on the assumption that the absorbed radiation is proportional to the local intensity in the medium and the distance the radiation travels in the medium \( x \);

\[ dI = I K dx \]

\[ \tau_a = e^{-KL/cos\theta} \]

where, \( K \) for polyethylene sheet is taken as 400m\(^{-1}\) (Godbey, 1979) and \( L \) as 0.1mm.

Finally with the simplification, transmittance of a single cover is computed with the relationship;

\[ \tau = \tau_a \tau_r \]

Using Eqns. 3.18 to 3.25, transmittance \( \tau \) of solar radiation through each wall and roof of the selected geometry (even-span and semi-cylindrical) greenhouses for each hour of the day and for each typical day of each month has been computed. Angle of incidence \( \theta_i \) on each wall and roof of the greenhouse for each hour of the day and for each month of the year has also been computed. Using \( \theta_i \), angle of refraction \( \theta_r \), perpendicular and parallel components of unpolarized radiation, absorbance \( \tau_a \) and transmittance \( \tau_r \) have been computed. Using the computed transmittance for each month, total energy transmitted on the floor of the greenhouse has been computed and presented in Fig. 3.12 for each month (typical day).
Transmission factor as suggested by Lau (1988) is used to compare solar input efficiency of even-span and semi-cylindrical shape as well as for east-west and north-south orientation greenhouse. Transmission factor (TF) for even-span and semi-cylindrical (Appendix D1) greenhouse for E-W orientation at 31°N is shown in Fig. 3.14 and for east-west and north-south oriented even-span greenhouse at 31°N is also shown in Fig. 3.14 for the same greenhouse cover to floor ratio. TF for E-W and N-S greenhouse at other latitudes is shown in Appendix D2. The concept behind the TF is important in that the transmitted solar radiation at the glazing level is an essential quantity that leads to the computation of quantities such as solar radiation falling on to plant canopy and floor levels. TF is given by the following expression;

\[ TF = \frac{\sum_{i=1}^{n} (A_i I_i) \tau}{A_g I_g} \]  

3.26

The numerator represents the sum of total radiation transmitted through all glazing surfaces \((i = 1 \text{ to } 6 \text{ for even span and } i = 1 \text{ to } 8 \text{ for semi cylindrical})\) while the denominator is global solar radiation incident on an outside horizontal surface. The total energy input \(I_i\) from Eqn. 3.13 has been computed and multiplying it with the respective area of the surface & transmissivity at that hour gives the transmitted solar radiation.

3.5 RESULTS AND DISCUSSION

3.5.1 Model validation

The representation of computed and measured values of total radiation on a south facing inclined roof of even-span greenhouse for different hours of the day is shown in Fig. 3.3. It is observed that both the set of values are closely matched indicating that the developed model is validated. The slight difference during some values is due to the cloudy patches in the sky or measuring or instrumental errors.

3.5.2 Greenhouse Orientation

A comparative analysis of the computed data of E-W and N-S oriented even-span greenhouse shows that for the same greenhouse cover to greenhouse floor ratio \((A_i/A_g = 2.10)\), E-W oriented greenhouse receives higher total insolation during winter months and lesser during summer months as compared to N-S oriented greenhouse at 31°N latitude as shown in Fig. 3.4.
Fig. 3.3 Predicted and measured values of total radiation on inclined roof of even-span E-W oriented greenhouse on 12-05-05 at 31 °N latitude.

It is observed that total insolation on E-W oriented greenhouse is 1.00, 1.78, 2.48, 3.00, 1.98 and 1.49 percent higher as compared to N-S oriented greenhouse in October, November, December, January, February and March respectively. Similarly, total insolation for E-W
orientation is 0.95, 4.03, 7.34, 6.29, 4.37 and 2.12 percent lower in April, May, June, July, August and September respectively as compared to N-S oriented greenhouse. It is due to the fact that N-S oriented greenhouse receives greater solar radiation through its east and west roof during the summer months with maximum reaches at 70.82% of the total as compared to south and north roofs (63.12%) of E-W oriented greenhouse on June 11. On the contrary E-W oriented greenhouse receives greater solar radiation through south and north roof during the winter months with maximum reaches at 57.2% of total as compared to east and west roofs (56.32%) of N-S oriented greenhouse on December 10 at 31°N latitude as shown in Fig. 3.5.

It is clear from the results that there is an advantage of selecting E-W oriented greenhouse at 31°N latitude for year round use as this orientation would put lesser load on the cooling system during summer. Also due to more sunshine hours and mild winter, greenhouse temperature in even-span greenhouse is not much less as compared to N-S oriented greenhouse for taking the maximum advantage of greenhouse effect.

Studies have also been conducted for total insolation over E-W and N-S oriented greenhouse for other latitudes as shown in Fig. 3.6 and Fig. 3.7. It is clear from Fig. 3.6 that for the month of December (10th), E-W oriented greenhouse receives greater solar radiation as compared to N-S oriented greenhouse for all the latitudes. The difference in total insolation received by E-W and N-S oriented greenhouse increases with the increase in
latitude angle. This increase is observed as 4.4, 5.3, 6.8, 10.5, 14.8, 19.3 and 24.5 percent at 20°, 25°, 30°, 35°, 40°, 45° and 50° N latitude as compared to N-S oriented greenhouse. However in summer, for the month of June (11th), E-W oriented greenhouse receives lesser solar radiation as compared to N-S oriented greenhouse for all the latitudes as shown in Fig. 3.7. The difference in total solar radiation received by N-S and E-W oriented greenhouse also increases with the increase in latitude angle but at a smaller rate than that in December. This increase is observed as 1.3, 2.2, 3.3, 5.2, 7.6, 9.4 and 11.5 percent at 20°, 25°, 30°, 35°, 40°, 45° and 50° N latitude as compared to E-W oriented greenhouse. Hence in summer at lower latitudes (<35° N) the effect of orientation is small but at higher latitudes (>35° N) the effect is significant in summer but not as much significant in winter for E-W oriented greenhouse.

![Graph showing variation of total solar radiation with latitude angle for E-W and N-S oriented even-span greenhouse.](image)

**Fig. 3.6 Variation of total solar radiation with latitude angle for E-W and N-S oriented even-span greenhouse.**
Fig. 3.7 Variation of total solar radiation with latitude for E-W and N-S oriented even-span greenhouse.

3.5.3 Greenhouse Shape

Variation of total insolation on semi-cylindrical and even-span greenhouse (both east-west oriented) for a typical day of each month is also shown in Fig. 3.4. A comparative analysis of the data shows that for the same ratio of greenhouse cover to floor ratio, even-span greenhouse receives lesser total insolation from January to April and from August to December as compared to semi-cylindrical greenhouse at 3.5°N latitude. It is observed that total insolation on even-span greenhouse is lower by 0.72, 1.58, 1.65, 0.72, 0.52, 0.64, 1.57, 2.25 and 1.53 percent in January, February, March, April, August, September, October, November and December. It is because even span greenhouse has one vertical wall and one roof inclined at 26.56° towards south facing which receives lesser solar radiation on these surfaces as compared to the inclined surfaces of semi-cylindrical shape (as shown in Fig. 3.8) which is divided into three imaginary inclined plane surfaces (assumed) AB (75° inclined towards south), BC, (45° inclined towards south) and CD (15° inclined towards south) as shown in Fig. 3.2a and Fig. 3.2b. It is due to the fact that solar altitude angle is almost normal during noon hours on surfaces AB and BC as compared to vertical wall and inclined roof of even-span greenhouse. However, solar radiation received by even-span greenhouse is higher by 0.20, 2.4 and 0.23 percent in May, June and July as compared to semi-cylindrical greenhouse. It is because of the higher solar altitude angle during these months due to which
south roof of even span greenhouse receives greater solar radiation as compared to the south facing inclined surfaces of semi-cylindrical greenhouse as shown in Fig. 3.8. It is also seen from the Tables A1 to A24 (Appendix A) that the annual variation of solar radiation on north facing surfaces of semi-cylindrical and even-span greenhouse is very small due to diffuse radiation falling on these surfaces. It is also observed that there is a uniform variation in the solar radiation received by east and west walls of both the greenhouses. As the greenhouse is mostly used from October to April months and even-span greenhouse receives lesser radiation during these months as compared to semi-cylindrical shape, thereby putting lesser cooling load on the greenhouse cooling system. Hence even span geometry should be preferred in composite climates.

Fig. 3.8 Annual variation of solar radiation for south facing surfaces of even-span and semi-cylindrical greenhouse at 31 °N latitude.

3.5.4 Transmission Factor for Greenhouse

3.5.4.1 Solar radiation transmittance

Solar radiation transmittance through the greenhouse cover (roof and all walls) for different hours of the day for a typical day of each month has been computed and the average transmittance for each month is shown in Fig. 3.9.
Fig. 3.9 Annual variation of solar radiation transmittance for selected geometry greenhouses at 31 °N latitude.

It is observed from Fig. 3.9 that there is a small difference in the average solar radiation transmittance for even-span (0.644 in Jan. and 0.735 in June) and semi-cylindrical (0.649 in Jan. and 0.725 in June) shapes of east-west oriented greenhouse. Examination of Fig. 3.9 reveals that even-span greenhouse has a slightly higher transmittance from August to April except for May, June and July. However, transmittance of north-south oriented even-span greenhouse varies from 0.626 in Jan. (lowest) to 0.738 in June (highest) indicating that north-south oriented greenhouse captures lesser solar radiation in winter and higher in summer as compared to east-west oriented greenhouse at 31°N latitude. A detailed depiction of solar energy transmittance for each hour of the day during winter and summer months is shown Fig. 3.10 and Fig. 3.11 which show that solar radiation transmittance is more in summer months as compared to winter months for even-span, east-west oriented greenhouse. Total available and transmitted solar energy (MJ/m²) and total available and transmitted solar radiation (W/m²) on horizontal surface and inside greenhouse floor for even-span, east-west oriented greenhouse is shown in Fig. 3.12. It is observed that only 60 to 78 percent of the available total solar energy is transmitted inside the greenhouse during different months of the year.
Fig. 3.10 Variation of solar radiation transmittance at each hour of day during winter months for even-span, east-west oriented greenhouse at 31 °N latitude.

Fig. 3.11 Variation of solar radiation transmittance at each hour of day during summer months for even-span, east-west oriented greenhouse at 31 °N latitude.
Fig. 3.12 Annual variation of available and transmitted total solar energy for even-span, east-west oriented greenhouse on outside horizontal surface and inside greenhouse floor at 31°N latitude.

Fig. 3.13 Hourly variation of global outside and transmitted solar irradiance at horizontal surface for even-span, east-west oriented greenhouse at 31°N latitude (June-11 and December-10).
Hourly variations of global solar radiation (W/m\(^2\)) on a horizontal surface and transmitted solar radiation inside greenhouse floor for E-W oriented greenhouse in June and December is shown in Fig. 3.13. The figure shows that although a maximum of 1022.5 W/m\(^2\) is available on a horizontal surface during 12 noon on June 11, only 712.3 W/m\(^2\) is transmitted inside the greenhouse which is used to estimate the quantity of heat to be actually removed from the greenhouse in order to maintain the desired room air temperature in extreme summer. Similarly, on December 10, maximum of 667.7 W/m\(^2\) is available on outside horizontal surface, out of which 408.3 W/m\(^2\) is captured by the greenhouse which is used to find the additional heat requirements (if any) to raise the greenhouse air temperature up to desirable value.

3.5.4.2 Transmission factor variation with shape and orientation of greenhouse

Variation of transmission factor (TF) for each month (typical day) of the year for selected shapes and orientations (appendix D1) for the same ratio of greenhouse cover to floor area (A\(_c\)/A\(_f\) = 2.10), is shown in Fig. 3.14. It is clear from the Fig. that there is a small effect of the shape of the greenhouse on the transmission factor at 31 °N latitude as both the curves for even-span and for semi-cylindrical shape run neck and neck for all the months of the year. However, close examination of the Fig. 3.14 reveals that TF for even-span greenhouse is slightly lesser from August to April with lowest in December (3.21 percent) as compared to semi-cylindrical greenhouse. It is because even span greenhouse has lower solar energy transmittance as compared to the semi-cylindrical shape as shown in Fig. 3.9. However, TF for even-span greenhouse is slightly higher in May, June and July with highest in June (1.36 percent) as compared to semi-cylindrical greenhouse. It is due to higher solar energy transmittance through even-span greenhouse as shown in Fig. 3.9. On the contrary annual TF comparison between E-W and N-S oriented even-span greenhouse reveals that E-W oriented greenhouse has 8.78, 4.07, 2.37, 1.61, 3.09, 6.70 and 10.28 percent higher TF in January, February, March, September, October, November and December months as compared to N-S oriented even-span greenhouse. However, it is lower by 0.9, 4.7, 5.70, 5.75 and 4.16 percent in April, May, June, July and August for even-span greenhouse as compared to N-S oriented greenhouse as observed from Fig. 3.14. It can thus be concluded that E-W oriented greenhouse should be preferred over N-S oriented due to greater solar energy input efficiency during winter and lesser in summer months. Daily average of TF for each month has also been computed for E-W oriented even-span greenhouse during winter months (October - March) and for summer months (April - September) and is presented in Fig. 3.15 and Fig. 3.16.
Fig. 3.14 Annual variation of transmission factor for selected greenhouses at 31°N latitude.

Fig. 3.15 Hourly variation of transmission factor during winter months for even-span, east-west greenhouse at 31°N latitude.
Study is also extended for other latitudes for even-span as well as for semi-cylindrical shape greenhouse of east-west orientation as shown in Table D2 (appendix D) and for east-west as well as for north-south orientation greenhouses of even-span shape. It is clear from Figs. 3.17 to 3.21 that there is almost no difference in annual variation of TF between even-span and semi-cylindrical greenhouse for 10° and 20°N latitudes. However at 31°N, 40°N and 50 °N latitude this effect is marginal with maximum at 50°N, which means semi-cylindrical greenhouse should be preferred for cold temperate climates.

Fig. 3.16 Hourly variation of transmission factor during summer months for even-span, east-west greenhouse at 31°N latitude.
Fig. 3.17 Annual variation of transmission factor for selected geometry, east-west oriented greenhouses.

Fig. 3.18 Annual variation of transmission factor for selected geometry, east-west oriented greenhouses.
Fig. 3.19 Annual variation of transmission factor for selected geometry, east-west oriented greenhouses.

Fig. 3.20 Annual variation of transmission factor for selected geometry, east-west oriented greenhouses.
Fig. 3.21 Annual variation of transmission factor for selected geometry, east-west oriented greenhouses.

Fig. 3.22 Annual variation of transmission factor for east-west and north-south oriented even-span greenhouse.
Fig. 3.23 Annual variation of transmission factor for east-west and north-south oriented even-span greenhouse.

Fig. 3.24 Annual variation of transmission factor for east-west and north-south oriented even-span greenhouse.
Fig. 3.25 Annual variation of transmission factor for east-west and north-south oriented even-span greenhouse at 40°N latitude.

Fig. 3.26 Annual variation of transmission factor for east-west and north-south oriented even-span greenhouse at 50°N latitude.
Fig. 3.27 Variation of transmission factor for east-west and north-south oriented even-span greenhouse at different latitudes on Dec. 10.

Fig. 3.28 Variation of transmission factor for east-west and north-south oriented even-span greenhouse at different latitudes on June 11.

Figs. 3.22 to 3.26 show that with the increase in the latitude angle the effect of orientation increases significantly. An E-W oriented greenhouse shows a small year round
advantage over N-S greenhouse at 10° and 20°N latitudes due to higher TF in winter months and lower TF in summer months. This advantage becomes more significant at 40° and 50°N latitudes where due to lower ambient air temperatures in winter, E-W oriented greenhouse would provide maximum solar energy utilization efficiency. However, it is observed that during summer months of northern hemisphere, N-S greenhouse has greater TF as compared to E-W oriented greenhouse, which means N-S greenhouse has greater solar energy utilization in summer months which is not at all required at lower latitudes where due to higher solar radiation levels ambient temperatures remain quite high so an E-W oriented greenhouse should be preferred for less than 31°N latitudes. Also for higher latitudes greater than 31°N, the percent variation of TF for E-W orientation is more in winter as compared to N-S orientation in summer, therefore E-W orientation greenhouse may be preferred. A comparative analysis shown in Fig. 3.27 and Fig. 3.28 for the months of December and June show that E-W oriented greenhouse has 4.09 percent higher TF in December as compared to N-S oriented greenhouse which has 2.23 percent higher TF in June. This variation increases with the increases in latitudes for both December and June. At 50°N latitude in December, E-W oriented greenhouse shows a maximum TF (15.18 percent greater) as compared to N-S oriented greenhouse. Whereas, N-S oriented greenhouse has a maximum TF (10.32 percent greater) as compared to E-W oriented greenhouse in June. So overall it can be concluded that an E-W oriented greenhouse may be preferred for year round use of the greenhouse at any location up to 50°N latitudes.

3.6. CONCLUSIONS
From the present study following conclusions can be drawn

1. Total solar radiation on E-W greenhouse remains higher in winter months (highest in December as 2.48 percent) as compared to N-S oriented greenhouse. Similarly, total solar radiation on E-W greenhouse remains lower in summer months (lowest in June as 7.34 percent) as compared to N-S oriented greenhouse at 31°N latitude. So N-S oriented greenhouse captures lesser solar radiation in winter and higher in summer as compared to E-W oriented greenhouse at 31°N latitude.

2. At other latitudes the difference in total insolation received by E-W and N-S oriented greenhouse increases with the increase in latitude angle (maximum 24.5 percent at 50° N latitude).

3. Only 60 to 78 percent of the available total solar energy is transmitted inside the greenhouse during different months of the year. Transmittance is more in summer months as compared to winter months for E-W oriented greenhouse as compared to N-S oriented
greenhouse. There is a small difference in the average solar radiation transmittance for even-span and for semi-cylindrical greenhouse (E-W oriented).

4. The effect of shape of the greenhouse is very small on solar radiation and transmission factor at 31°N latitude. However, the slight difference shows that even-span greenhouse receives a little smaller amount of total solar radiation in summer and a little more in winter as compared to semi-cylindrical greenhouse.

5. Finally, it can be concluded that an even-span, E-W oriented greenhouse should be preferred due to greater solar energy input efficiency during winter and lesser in summer months in composite climates.