Optimization of Tilt Angles for Solar Devices to Gain Maximum Solar Energy in Indian Climate

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Chapter 16
Optimization of Tilt Angles for Solar Devices to Gain Maximum Solar Energy in Indian Climate

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Abstract Availability of maximum solar radiation can be ensured by optimizing the tilt angles for a given location. Most of the optimization techniques are based on the available theoretical models. Keeping this in view, tilt angles were optimized for composite climate (Nagpur and Delhi) and hot and dry climate (Jodhpur), India, using actual solar radiation data of India Meteorological Department (IMD). The optimization of tilt angle is done by establishing a polynomial relation between tilt angle and solar radiation data for annual, bi-annual, seasonal, bi-monthly, and monthly tilts. The optimum tilt angles for New Delhi and Nagpur were found as $\Phi - 5°$ and $\Phi + 4°$, respectively, while for Jodhpur it was $\Phi + 4°$ for south facing. The highest solar radiation was predicted for monthly tilt. However, total solar radiation for bi-annual tilt was also found very close to that of monthly optimum. According to the analysis carried out, it is recommended to have bi-annual tilt (zero tilt from April to September and 42°–49° degree tilt from October to March).

Keywords Latitude (Φ) · Solar radiation · South facing · Optimum tilt angles · Composite · Hot and dry climate

16.1 Introduction

The energy demand is going up with the time in agriculture, domestic, rural, and industrial sectors. It is also well known that increased use of conventional energy sources is leading to the release of a high amount of pollutants. In such a situation, solar energy can be used as an optional energy source. India has abundant solar radiation due to being located near the equator. It is a prerequisite for researchers to estimate the exact values of solar radiation on the surface with different tilt angles and also the Optimum Tilt Angle (OPTA) for a particular location. During summer,

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about 90% of India receives 3.5–6.0 kWh m^{-2} day^{-1} of radiation, and the northern part may go up to 7.5 kWh $m^{'2}$ day^{-1} [1]. The mean daily global solar radiation of 5 kWh m^{-2} day^{-1} is available on about 58% part of India, having the potential for solar energy applications [2]. The Government of India launched the Jawaharlal Nehru National Solar Mission (JNNSM) targeting to harvest as much as 175,000 MW of energy by the end of 2022, in order to make India a leader in solar power [3]. When solar radiation is captured on an optimally inclined surface, it can ensure maximum radiation, which could be used for desalination, drying, cooking, and rooftop PV plants, etc. The optimum tilt can improve the performance of solar devices to a great extent. Solar Radiation (SR) is directly converted into electricity by the PV system, which can be easily used. The system is a useful choice for both rural and urban locations, including building integrated and attached applications.

The SR depends on locations, orientations, and the tilt angle of the solar devices like Stand-Alone Photovoltaic (SAPV). Therefore, the Optimum Tilt Angle (OPTA) needs to be determined to ensure the gain of maximum SR [4]. The monthly average daily SR on the horizontal plane of Indian cities was calculated by the authors [5]. Thakur and Chandel [6] optimized the angle of tilt for a 190 kWp plant located at Khatkar-Kalan in India. They found that the annual, seasonal, and monthly tilts gave 25, 28, and 29% higher energy as compared to fixed tilt (25°). Yadav and Chandel [7] tried out the various models of diffuse SR to calculate OPTA for Hamirpur, Himachal Pradesh, India. It was observed that Liu and Jordan model is found the best with only a 4.5% error in predicted and observed SR values. Maximum insolation is ensured by setting the azimuthal angle between 10° and 20° and fixing the solar device at latitude. A number of thumb rules were followed as concrete information on tilt angle was not available [8–11]. Pandey and Katiyar [12, 13] tried different models for predicting diffuse radiation on the various tilted surfaces for Lucknow, India (26° 0.75′ N, 80° 0.50′ E). From the analysis, it was observed that Kulcher's model gave the best prediction. Agrawal et al. [14] used the Liu and Jordan model to calculate radiation on a tilted surface and found that daily optimum tilt has only 4.5% more radiation than monthly tilt. Jamil et al. [15] optimized the tilt angle of Aligarh, India (27° 0.89′ N, 78° 0.08′ E) and compared it with that of New Delhi (capital of India, 28° 0.61′ N, 77° 0.20′ E) and found that monthly and seasonal optimum tilts provided substantial gain in radiation over annual optimum. Herrera-Romero et al. [16] estimated the optimum tilt angles requiring minimum adjustment only. It was observed that the monthly adjustment has only 0.15% energy loss as compared to daily adjustment. The authors [17] observed that the gain in annual solar energy harvest was about 4.28 7.06%, and 8.42 higher than latitude when inclined according to bi-annual, tri-monthly, and monthly tilts, respectively.

In this paper, the optimization of the tilt angle for maximum SR has been estimated for New Delhi, Nagpur, and Jodhpur. For the estimation, global SR data of the Indian Meteorological Department (IMD) have been used at different tilt angle to develop a polynomial relationship between the SR and tilt angle. The obtained tilt angles are compared with those given by others. Also, the losses in SR at monthly, seasonal,

Table 16.1 Criteria for the classification of climatic [19]

Climate	Temperature (°C)	Relative humidity (%)	Number of clear days
Hot and dry	>30	<55.5	>20
Warm and humid	>30	>55.5	<20
Moderate	25–30	<75.5	<20
Cold and cloudy	<25	>55.5	<20
Cold and sunny	<25	<55.5	>20
Composite	This applies when six months or more do not fall within any of the categories		

bi-annual, and annual OPTA's in comparison to a surface at bi-monthly OPTA have been calculated.

Locations Under the Study

New Delhi (28° 0.61′ N, 77° 0.20′ E, and msl 227 m) and Nagpur (21° 0.08′ N, 79° 0.05′ E, and msl 319 m), both fall under composite climate, while Jodhpur (6° 0.23′ N, 73° 0.02′ E, and msl 231 m) falls under hot and dry climate (Table 16.1). All the locations receive substantial amount of solar radiation.

16.2 Methodology

16.2.1 Solar Radiation

The incident SR reaching on the surface of the earth without any absorption is known as direct or beam radiation (H_{b}). A part of SR is scattered to the atmosphere before reaching the earth surface known as diffuse radiation (H_{d}), when some of the radiation (H_{b}) gets reflected back from the surface, then it is called as reflected radiation (H_{r}) [18]. The total solar energy received on an inclined surface can be determined by adding the beam radiation, diffused radiation, and reflected radiation reaching on a surface. The total monthly average daily SR on an inclined surface can be given as $H_{\mathrm{t}} = H_{\mathrm{b}} + H_{\mathrm{d}} + H_{\mathrm{r}}$. The solar radiation data (direct, diffuse, and reflected radiation, MJ/m^2 day^{-1}) were taken from IMD observations for New Delhi, Nagpur, and Jodhpur, India. Average monthly daily data were added for 12 months, 6 months, 3 months, and 2 months in order to optimize the tilt annually, bi-annually, seasonally, and bi-monthly, respectively. The angle made by the solar devices from the horizontal surface is known as tilt angle (β). The optimum tilt angle (β_{opt}) is determined by using the SR data of IMD for various inclinations from 0° to 90° at a step of 10° to achieve maximum SR. The relation between incident solar radiation and tilt was established by a second-order polynomial equation ($H_{\mathrm{t}} = a\beta^2 + b\beta + c$) for three tilts having the highest total global solar radiation. By equating $\frac{dH_{\mathrm{T}}}{d\beta} = 0$, β was determined for which $\frac{d^2H_{\mathrm{T}}}{d\beta^2}$ = negative, where $H_{\mathrm{t}} = H_{\mathrm{f}} + H_{\mathrm{Diff}} + H_{\mathrm{R}}$

on different inclinations. Based on this approach, annual, bi-annual, seasonal, bi-monthly, and monthly optimum tilts were determined. H_T values were calculated by adding monthly daily average radiation for the 12 months, 6 months, 3 months, 2 months, and 1 month. Relationships were established between inclination and total solar radiation by a second-order polynomial equation, whereby optimum tilt values were determined. In addition, percentage gain and loss of solar radiation were estimated using following relationships

$$\%\text{gain} = \left(\frac{H_{T\beta_{opt}}}{H_{T\beta_0}} - 1 \right) \times 100 \tag{16.1}$$

$$\%\text{loss} = \left(1 - \frac{H_{T\beta_{opt}}}{H_{T\beta_{bi\text{ - }monthly}}} \right) \times 100 \tag{16.2}$$

16.3 Result and Discussion

For every month of the year, values of monthly daily average SR were taken for various tilt angles and plotted in Fig. 16.1 for New Delhi, and similar trends were also found for the other two locations. From Table 16.2 and Fig. 16.1, it is evident that total solar radiation is a function of tilt angle which increases initially with tilt angle, and after certain tilt angle, it starts decreasing. And it is clear that tilt angle increases during winter and decreases during summer for a south facing surface.

As discussed in the methodology section, the OPTA (monthly, bi-monthly, seasonal, bi-annual, and annual) has been determined. The radiation data for Delhi, Jodhpur, and Nagpur have been taken from IMD data on various inclinations (0°–90°).The relationship between total of monthly daily average of solar radiation (each month for monthly, two months for bi-monthly, three months for seasonal, six months for bi-annual, and twelve months for annual) and inclination was established by considering three best inclinations, and a second-order polynomial equation was fitted the best ($R^2 = 1$) ($H_T = a\beta^2 + b\beta + c$). The OPTA was estimated by differentiating the equation and equating to zero which led to $2\alpha\beta + b = 0$ and β being equal to $-b/2a$. (Fig. 2a–c).

The seasonal optimum tilt was maximum for winter (NDJ: 59.8–55.5) and minimum for summer (MJJ: 0–11). However, for spring, it was (FMA: 25–32.5) and for autumn (ASO: 19.0–26.6) (see in Table 16.3). It was found that the OPTA was 0° (April, May, June, July, August, and September) for Delhi, Jodhpur, and Nagpur and 48.75, 48.45, and 42.6 during (October–March) for New Delhi, Jodhpur, and Nagpur, respectively, for bi-annual optimum (Table 16.4).

The optimum angle of tilt of the solar devices (Table 16.5) in January is optimized as 55.1°, 48.0°, and 55.0° with monthly daily global solar radiations as 22.16, 24.54, and 26.18 MJ/m^2 for Delhi, Nagpur, and Jodhpur, respectively. The OPTA is 0° in (July–August for Delhi, June–July–August for Jodhpur, and April–August for

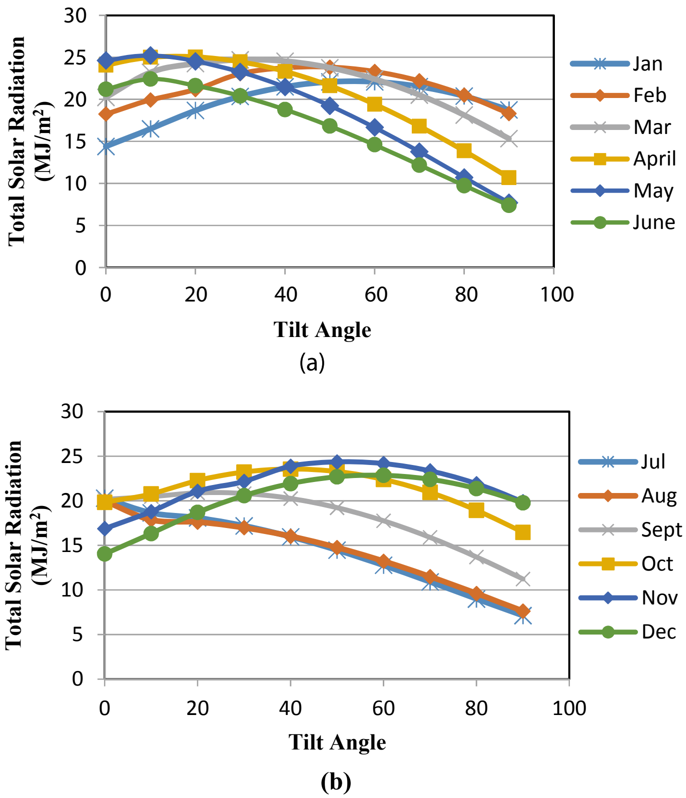

Fig. 16.1 **a** Monthly average total daily solar radiation (Delhi) with tilt angles (January–June). **b** Monthly average total daily solar radiation (Delhi) with tilt angles (July–December)

Table 16.2 Annual sum of monthly daily solar radiation (MJ/m^2) data on inclined planes

Tilt (°)	Delhi	Nagpur	Jodhpur
0	234.07	238.9	259.9
10	245.18	242.13	262.12
20	259.96	250.28	278.90
30	257.24	250.75	282.63
40	255.01	246.23	279.78
50	251.18	235.60	270.54
60	231.75	219.49	255.25
70	212.03	198.55	234.85
80	187.93	173.60	200.40
90	160.34	150.03	180.60

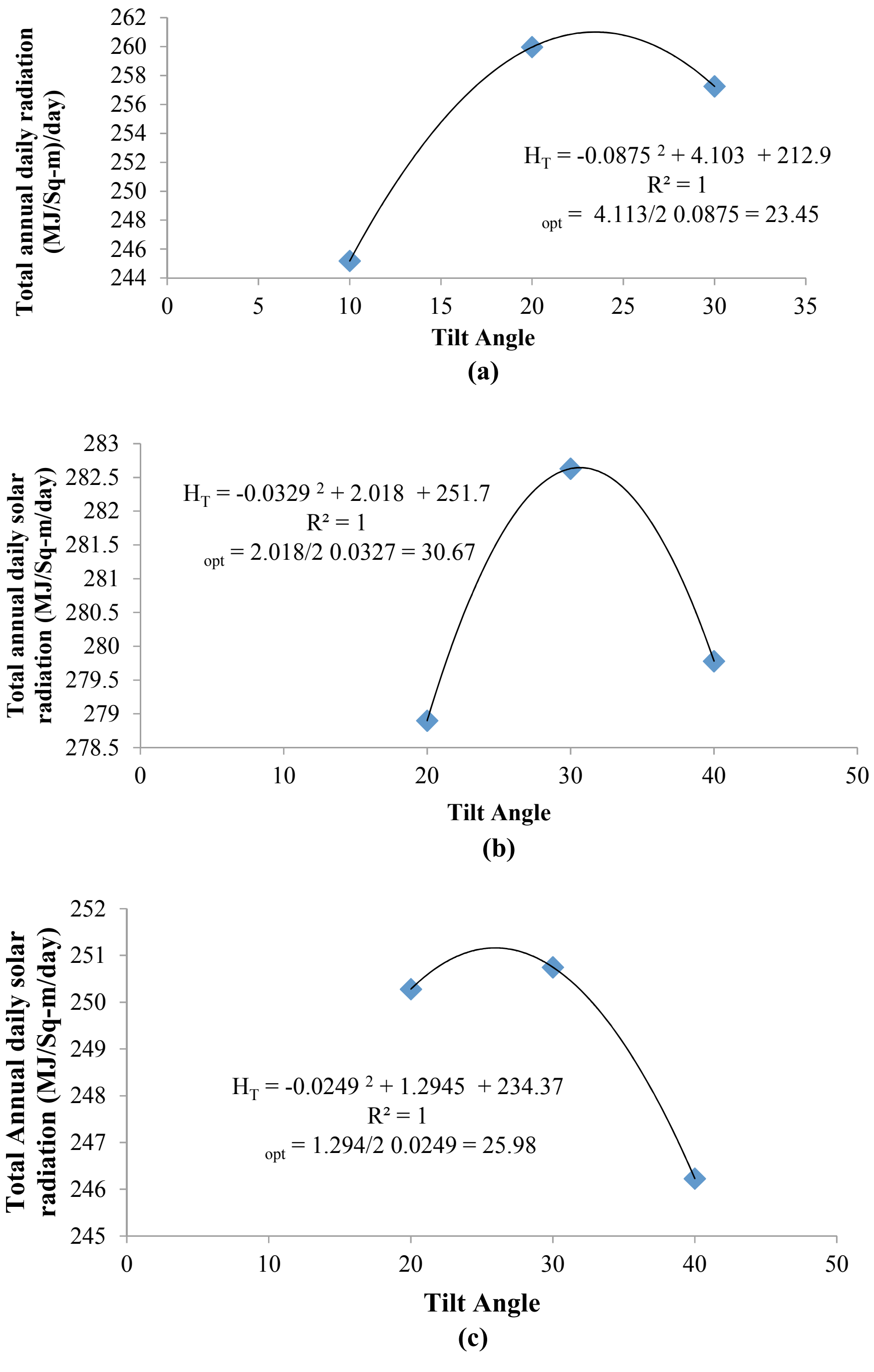

Fig. 16.2 **a** Relationship between total solar radiation and tilt angle for Delhi. **b** Relationship between total solar radiation and tilt angle for Jodhpur. **c** Relationship between total solar radiation and tilt angle for Nagpur

Table 16.3 Seasonal optimal tilt and total seasonal daily solar radiation (MJ m^{-2}) for all three cities

Seasons	Delhi		Nagpur		Jodhpur	
	Tilt (°)	Solar radiation	Tilt (°)	Solar radiation	Tilt (°)	Solar radiation
Spring (FMA)	32.1	72.30	25.0	71.73	32.5	77.94
Summer (MJJ)	11.6	66.40	0.0	63.22	0.0	77.18
Autumn (ASO)	25.3	62.04	19.0	54.77	26.6	67.39
Winter (NDJ)	55.5	69.33	50.8	78.50	55.1	78.50
Total		270.07		268.22		301.01

Table 16.4 Bi-annual optimal tilt and total seasonal daily solar radiation for all three cities

Seasons	Delhi		Nagpur		Jodhpur	
	Tilt (°)	Solar radiation	Tilt (°)	Solar radiation	Tilt (°)	Solar radiation
(April–September)	0.0	130.43	0.0	122.11	0.0	147.22
(October–March)	48.75	145.14	42.60	148.20	48.45	157.85
Total		275.75		270.31		305.07

Table 16.5 Monthly optimal tilt and total monthly daily solar radiation (MJ m^{-2}) for three cities

Months	Delhi		Nagpur		Jodhpur	
	Optimum tilt	Radiation (MJ m^{-2})	Optimum tilt	Radiation (MJ m^{-2})	Optimum tilt	Radiation (MJ m^{-2})
January	55.1	22.16	48	24.54	55.0	26.18
February	46.5	23.86	39.9	25.18	48.3	27.65
March	32.4	24.73	24.3	24.03	31.4	26.17
April	15.7	25.11	0.0	24.86	13.1	26.20
May	9.7	25.23	0.0	25,96	8.9	26.23
June	11.1	22.43	0.0	20.81	0.0	26.57
July	0	19.98	0.0	16.45	0.0	22.75
August	0	19.98	0.0	16.13	0.0	21.82
September	23.6	20.92	12.9	18.44	23.0	23.14
October	41.4	23.36	32.9	22.77	42.6	26.72
November	52.2	24.38	54.3	29.30	52.6	26.77
December	57.7	22.88	50.0	24.55	57.7	26.44
Total		276.02		273.02		306.64

Nagpur). The tilt angle increases during the winter months and reaches a maximum of 57.7° in December for Delhi and Jodhpur, whereas it was 50° for Nagpur during December. The tilt angle β which causes the maximum value of H_T is determined by differentiating the polynomial equation of radiation and tilt relationship and equating it to zero. The values of bi-monthly tilt angles for Delhi, Jodhpur, and Nagpur have been given in Table 16.6. It is maximum in December and January 56.5°, 56.4°, and 49.33° for Delhi, Jodhpur, and Nagpur, respectively, and minimum (0°) in August and September.

In Tables 16.7 and 16.8, the comparison of monthly optimum and annual OPTA of Delhi and Jodhpur is estimated by other researchers, and present study has been made.

Table 16.6 Bi-monthly optimal tilt and total bi-monthly daily solar radiation (MJ m^{-2}) for three cities

Months	Delhi		Jodhpur		Nagpur	
	Optimum tilt	Radiation (MJ m^{-2})	Optimum tilt	Radiation (MJ m^{-2})	Optimum tilt	Radiation (MJ m^{-2})
FM	39.4	48.33	40.68	53.3	32.46	48.82
AM	11.2	50.23	0.0	53.71	0.0	48.71
JJ	13.23	47.82	0.0	49.32	0.0	41.58
AS	0.0	40.14	16.3	43.83	0.0	40.14
ON	44.23	47.86	47.0	52.55	45.44	51.31
DJ	56.5	45.02	56.4	52.61	49.33	49.08
Total		279.40		305.32		279.64

Table 16.7 Comparison of β_{opt} of the present study with [8, 15] for New Delhi

Months	Ahmed and Tiwari (monthly)	Basharat et al. (monthly)	Present study (monthly)	Ahmed and Tiwari (seasonal)	Basharat et al. (seasonal)	Present study (seasonal)
January	56	56	55.1	56	56	55.5
February	45	47	46.5	30	31	32.1
March	32	32	32.4	30	31	32.1
April	14	13	15.7	30	31	32.1
May	0	0	9.7	0	0	11.6
June	0	0	11.1	0	0	11.6
July	0	0	0	0	0	11.6
August	6	6	0	24	25	25.3
September	26	25	23.6	24	25	25.3
October	40	43	41.4	24	25	25.3
November	53	54	52.2	56	56	55.5
December	58	58	57.7	56	56	55.5

Table 16.8 Comparison of β_{opt}, seasonally adjusted tilt and yearly average tilt and monthly solar radiation on a tilted south facing plane at Jodhpur with [20]

Month	Maru and Vajpai (monthly)	Present study (monthly)	Maru and Vajpai (seasonal)	Present study (seasonal)	Maru and Vajpai (yearly)	Present study (yearly)
January	49.80	55.0	52.80	55.1	31.80	30.67
February	40.20	48.3	27.00	32.5	31.80	30.67
March	27	31.4	27.00	32.5	31.80	30.67
April	9	13.1	27.00	32.5	31.80	30.67
May	0	8.9	0.00	0.00	31.80	30.67
June	0	0.0	0.00	0.00	31.80	30.67
July	0	0.0	0.00	0.00	31.80	30.67
August	3.60	0.0	26.40	26.6	31.80	30.67
September	21.60	23.0	26.40	26.6	31.80	30.67
October	39.00	42.6	26.40	26.6	31.80	30.67
November	50.40	52.6	52.80	55.1	31.80	30.67
December	52.80	57.7	52.80	55.1	31.80	30.67

Previous researchers have determined seasonal and annual OPTA by calculating the average of the monthly optimum angles. Here, all the OPTA have been optimized separately.

The gain and loss of SR have also been determined as compared to H_T of the zero tilt and bi-monthly optimum, respectively (Table 16.9). The gain in SR for annual optimum varies from 7.19 to 11.54%, and for latitude, it varies from 5.66 to 9.66%, whereas loss for annual optimum varies from 6.55 to 8.43%, and for latitude, it varies from 8.24 to 9.73%. However, bi-annual tilt from April to September was 0° for all the three cities has been found suitable, and during October to March, optimum tilt of 48.75°, 48.45°, and 42.60° was estimated for Delhi, Jodhpur, and Nagpur, respectively, (Table 16.4) with (13–17%) gain over horizontal and 0.08–3.4% loss over bi-monthly optimum (Table 16.9). Further, in the bi-annually adjusted system, the losses of energy are 1.37%, 0.08%, and 3.34%, respectively, for Delhi, Jodhpur, and Nagpur as compared to that of bi-monthly optimum tilt. The losses in collected radiation for the annual optimum tilts are 6.55%, 7.36%, and 8.43% as compared with that of bi-monthly optimum tilt at Delhi, Jodhpur, and Nagpur, respectively (Table 16.9).

The bi-annual tilt is recommended for the solar devices for achieving maximum efficiency because it can capture a huge amount of solar radiation and needs only two adjustments during the year. However, for the fixed type of devices, an annual optimum tilt can be preferred.

Table 16.9 Gain and loss of global solar radiation on different tilts

	Gain (%)			Loss (%)		
	Delhi	Jodhpur	Nagpur	Delhi	Jodhpur	Nagpur
Annual zero tilt	234.07 (−0.0)	259.90 (−0.0)	238.90 (−0.0)	234.07 (16.20)	259.90 (14.80)	238.90 (14.59)
Bi-annual optimum	275.57 (17.73)	305.07 (17.37)	270.31 (13.14)	275.57 (1.37)	305.07 (0.08)	270.31 (3.34)
Annual opt	261.10 (11.54)	282.64 (10.87)	256.08 (7.19)	261.10 (6.55)	282.64 (7.36)	256.08 (8.43)
Latitude	256.68 (9.66)	278.28 (7.07)	252.43 (5.66)	256.68 (8.24)	278.28 (8.86)	252.43 (9.73)
Seasonal	270.07 (15.38)	301.01 (15.81)	268.22 (12.27)	270.07 (3.34)	301.01 (1.41)	268.22 (4.08)
Monthly	276.02 (17.92)	306.64 (17.97)	273.02 (14.29)	276.02 (1.21)	306.64 (−0.43)	273.02 (2.37)
Bi-monthly	279.40 (19.37)	305.32 (17.47)	279.64 (17.05)	279.40 (0.0)	305.32 (0.0)	279.64 (0.0)
Annual 90°	160.34 (−31.5)	180.06 (−30.7)	150.03 (−37.2)	160.34 (42.6)	180.06 (41.0)	150.03 (46.3)

16.4 Conclusion

As per the study conducted, the following conclusions are given:

- The value of optimum tilt angle changed between 0° (May, June, and July) and 57.7° (December) throughout the year, and the OPTA is maximum in December for all the three cities.
- For a bi-annual tilt, the months in which β_{opt} is 0° for three different locations in India are April, May, June, July, August, and September. From October to March, optimum tilts are 48.75°, 48.45°, and 42.6° for Delhi, Jodhpur, and Nagpur, respectively. The losses are minimum, 0.08, 1.37, and 3.34% with bi-annual tilt for Delhi, Jodhpur, and Nagpur, respectively, and hence, bi-annual tilt is suggested for all the three cities.
- For general applications, fixed annual tilt can be made use of which are approximately $\Phi + 4°$ for Jodhpur and Nagpur and $\Phi - 5°$ for Delhi

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