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Optimum Collector Tilt Angles For Low Latitudes

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Abstract: Determination of the optimum collector tilt angles for low latitudes is the main subject of this paper. The monthly, seasonal and yearly average daily values of insolation were calculated for tilt angles ranging from 0-40°. Microsoft Excel was used to fit equations on monthly, seasonal and yearly average daily insolation with respect to tilt angles. The calculus method of optimization was employed to establish the optimum tilt angle for low latitudes, 4.86-13.02 °N, spanning the territory of Nigeria. Expressions for the optimum tilt angles with respect to the low latitudes were also obtained. The results obtained compare favourable with those in literature and are useful for designing solar equipment in the range of the low latitudes considered in this study.

Keywords: Solar radiation, flat-plate solar collector, optimum tilt angles, low latitudes, solar energy.

1. INTRODUCTION

The intensity of extraterrestrial solar radiation on earth's horizontal and tilted surfaces is reduced by clouds, dusts and shades. Thus, the insolation reaching the earth's surface which is made up of the beam (or direct), diffuse (or scatter) and ground reflected radiations, depends on the cloudiness or clearness of the sky, which in turn depends on the season of the year [1-5]. However, harnessing the insolation to optimum level is of primary interest to solar design engineers in designing solar equipment.

Several factors affect the performance of the flat plate solar collectors: the angle of latitude, the declination angle, the slope angle, the sunrise or sunset hour angle and the azimuth angle [6]. However, the angle of latitude, the declination angle, the sunrise or sunset angle and the sunrise or sunset hour are controlled by nature whereas man controls the tilt and azimuth angles [7-9]. It has been established that the optimum performance of flat-plate solar collector occurs at azimuth angle of zero for south facing flat-plate solar collector [1]. Proper determination of tilt angle is essential in order to maximize: the insolation on the absorber plate, the working fluid temperature, and the collector and thermal efficiencies of solar equipment [10].

Solar trackers have been developed for tracking the solar path and adjusting the collector tilt angle accordingly for the purpose of maximizing solar energy from the sun. Although, tracking is the most efficient means of solar radiation energy collection, it is costly, energy demanding for its operation and does not suit all solar equipment [11]. Thus, emphasis is laid on the collector optimal tilt angle to achieve maximum insolation on tilted surfaces. This collector tilt angle may be permanently fixed, or adjusted monthly or seasonally [12].

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Several propositions for the optimum tilt angle exist in the literature. For example, Wenger and Oliveira [13] proposed that the optimum tilt angle should commensurate with the latitude of the location; Fagbenle [14] proposed that for latitudes below 8.5°, the optimum tilt angle should be the latitude plus 10°, otherwise, the latitude plus 5°; Qiu and Riffat [15] proposed that the optimum tilt angle should be the latitude plus 10°. It is therefore necessary to find out which tilt angles are the optimal for the low latitudes of Nigeria, 4.86 – 13.02 [°N].

This paper, therefore, aims to establish the true optimum tilt angle for the low latitudes of Nigeria, 4.86 – 13.02 [°N], which maximizes the insolation on a tilted surface, and to provide expressions for predicting monthly, seasonal and yearly optimum tilt angles for the range of latitude considered.

2. THE GOVERNING EQUATIONS

The relevant equations are as follows [1, 6]:

The declination (i.e. the angular position of the earth-sun at solar noon with respect to the plane of equator), δ, is given as

$$\delta = 23.45\sin\left(360\left(\frac{284+n}{365}\right)\right) \quad (1)$$

where n is number of days starting from 1st January to the given date.

The tilt angle (i.e. the angle between the horizontal and the tilted surface), s, is given by Wenger and Oliveira [13] and Fagbenle [14], respectively, as

$$s = \phi \quad (2a)$$

or, $s = \phi + 10^o$, for $0^o < \phi < 8.5^o$, or $s = \phi + 5^o$, for $\phi > 8.5^o$ (2b)

The sunrise hour angle, ω_s, is given as

$$\omega_s = \cos^{-1}\left(-\tan\delta\tan\left(\phi - s\right)\right),\ \text{sign}\left(\delta\right) = \text{sign}\left(\phi\right) \tag{3a}$$

$$\text{or, } \omega_s = \cos^{-1}\left(-\tan\delta\tan\phi\right),\ \text{sign}\left(\delta\right) \neq \text{sign}\left(\phi\right) \tag{3b}$$

where $\text{sign}\left(x\right)$ is the sign of *x*.

The monthly average daily extraterrestrial radiation incident on a horizontal surface, H_0, is given as

$$H_0 = \frac{24}{\pi} I_{sc}\left(\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\left[\cos\phi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\phi\sin\delta\right]\right) \tag{4}$$

where I_{sc}, is the solar constant.

The hourly cloudiness index, K_T, is given as

$$K_T = a + b\left(\frac{n}{N}\right) \tag{5}$$

where *a* and *b* are the cloudiness constants whose values depend on the locality; *n/N* is the relative sunshine; and N = 365 days.

The monthly average daily total global insolation on a horizontal surface, H , is given as

$$H = K_T H_0 \tag{6}$$

The monthly average daily diffused insolation on the horizontal surface, H_d, according to Liu and Jordan [16] is correlated as

$$\frac{H_d}{H} = 1.271 - 2.7604\frac{H}{H_0} + 1.8036\left(\frac{H}{H_0}\right)^2 \tag{7}$$

The monthly average daily solar beam contribution to the global insolation on a horizontal surface, H_b, is

$$H_b = H - H_d \tag{8}$$

The overall correction factor, *R*, is

$$R = \left(1 - \frac{H_d}{H}\right)R_b + \frac{H_d}{H}R_d + \rho_{gr}R_r \tag{9}$$

where ρ_{gr} is the effective ground reflectance and R_b is the ratio of the beam insolation on tilted surface to that on horizontal surface and is given as

$$R_b = \frac{\cos\left(\phi - s\right)\cos(\delta)\cos(\omega) + \sin(\phi - s)\sin(\delta)}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \tag{10}$$

s and ω are the tilt angle and hour angle, respectively; and R_d is the ratio of the diffuse insolation on a tilted surface to that on a horizontal surface and is given as

$$R_d = \cos^2\left(\frac{s}{2}\right) \tag{11}$$

and R_r is the radiative configuration factor from the ground and surroundings to the tilted surface:

$$R_r = \sin^2\left(\frac{s}{2}\right) \tag{12}$$

The monthly average daily global insolation on tilted surface, H_T, is

$$H_T = H\,R \tag{13}$$

The insolation reaching the absorber plate, q_s, is given as

$$q_s = H_T\,\tau_c\alpha \tag{14}$$

where τ_c and α are the transmittance and absorptance, respectively, and their product is given as

$$\tau_c\alpha = \frac{2\alpha\ r e^{-k_c \ell_c}}{\left(r^2 + 1\right)\left[1 - \left(1 - \alpha\right)\rho_{gr}\right]} \tag{15}$$

where r, k_c, *and* l_c are the refractive index of the cover plate, the extinction coefficient for the cover glass and the thickness of glass cover, respectively.

3. THE OPTIMUM TILT ANGLE

The data for the insolation reaching the absorber plate, q_s, is expressed as a quadratic function of the tilt angle, s, so that its optimum value q_s^* is obtained at the stationary point:

$$\frac{dq_s}{ds} = 0 \tag{16}$$

where

$$q_s = c_0 + c_1 s + c_2 s^2 \tag{17}$$

c_i, $i = 0,1,2$, are constant coefficients.

Differentiating Equation (17) and substituting into Equation (16), the optimum tilt angle, *s**, is found to be

$$s^* = \frac{c_1}{2c_2} \tag{18}$$

and the optimum insolation, q_s^*, becomes

$$q_s^* = c_0 + c_1 s^* + c_2\left(s^*\right)^2 \tag{19}$$

4. RESULTS AND DISCUSSION

The following input parameters are specified:

i. The solar constant, $I_{SC} = 1353$ [W/m^2].

ii. The hour angles, ω, are tabulated in Table **1**.

iii. The azimuth angle, $\gamma = 0$ for south facing flat plate collectors.

iv. Number of days (*n*) starting from 1st January to 15th February, $n = 45$ days.

v. The values for cloudiness constants, *a* and *b*, and the relative sunshine, *n/N*, for the latitudes considered here are given by Fagbenle [14].

Table 1. The Hour Angle, ω, as a Function of the Hour of the Day

Hour	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
ω [°]	+60	+45	+30	+15	0	-15	-30	-45	-60

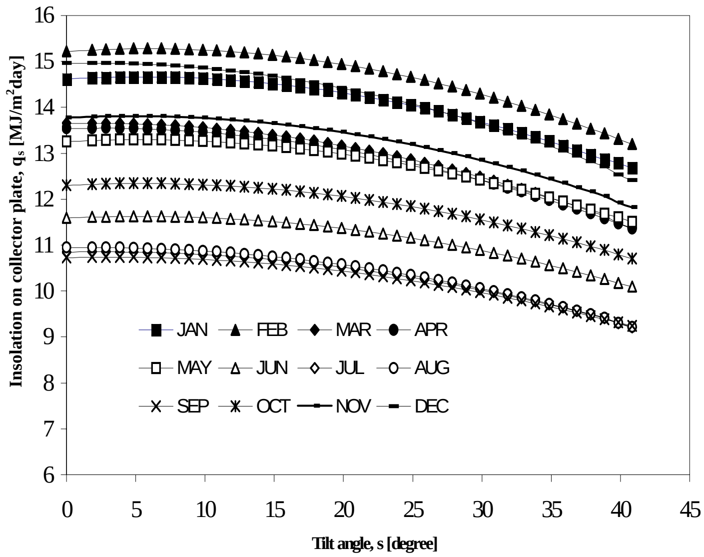

Fig. (1). Monthly average daily insolation on a south facing collector for Port Harcourt (latitude of 4.858 °N).

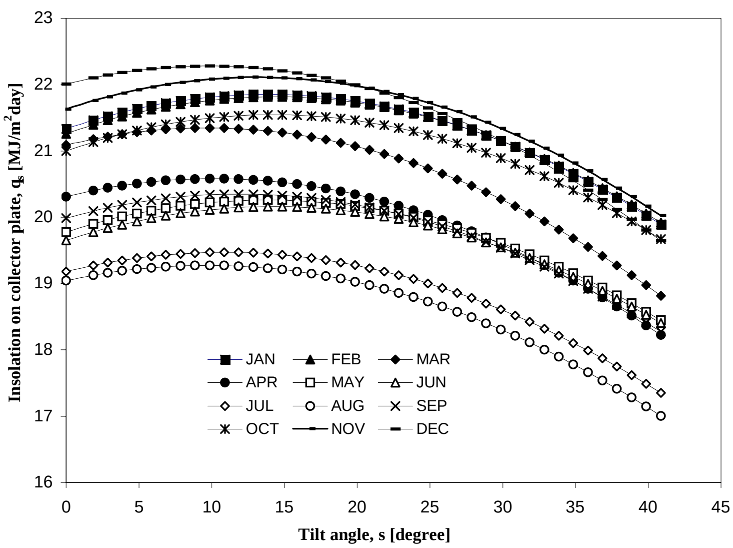

Fig. (2). Monthly average daily insolation on a south facing collector for Sokoto (latitude of 13.017 °N).

vi. The ground reflectance, $\rho_{gr} = 0.2$, according to Liu and Jordan [16].

vii. The refractive index of the cover plate, $r = 1.52$ for glass.

viii. The absorptance of the absorber, $\alpha = 0.95$ for smooth aluminium.

ix. The thickness of the cover glass, $\ell_c = 0.004$ [m].

x. The extinction coefficient for the cover glass, $k_c = 20$ [m^{-1}].

xi. The cities considered are: Port Harcourt, Enugu, Makurdi, Lokoja, Minna, Bauchi, Maiduguri and Sokoto, which are located in the latitudes of 4.858, 6.467, 7.700, 8.800, 9.617, 10.333, 11.850 and 13.017 [°N], respectively.

These input data were used to compute the monthly, seasonal and yearly average daily insolation on a tilted surface, Equation (14), for latitudes ranging from 4.858 to 13.017 °N. Figs. (**1**, **3** and **5**) show the monthly, seasonal and yearly dependence of the insolation reaching the tilted surface for Port Harcourt, the least latitude; and Figs. (**2**, **4** and **6**) show the monthly, seasonal and yearly dependence of the insolation reaching the tilted surface for Sokoto, the highest latitude. It is seen from these plots that the insolation increases from tilt angle of zero to the latitude plus or minus 2°, and then decreases with further increase in the tilt angle. Fig. (**7**), the monthly optimum insolation, for the cities considered,

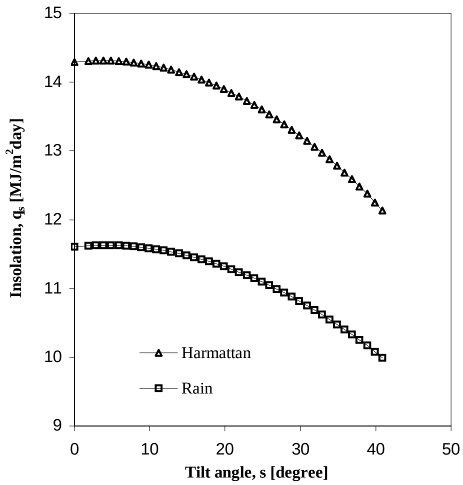

Fig. (3). Seasonal average daily insolation on tilted surface for Port Harcourt (latitude = 4.858 °N).

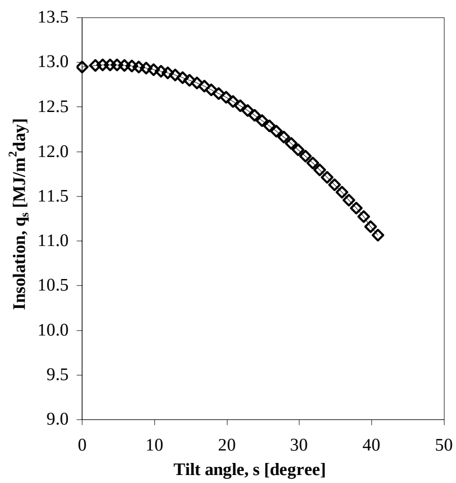

Fig. (4). Seasonal average daily insolation on tilted surface for Sokoto (latitude = 13.017 °N).

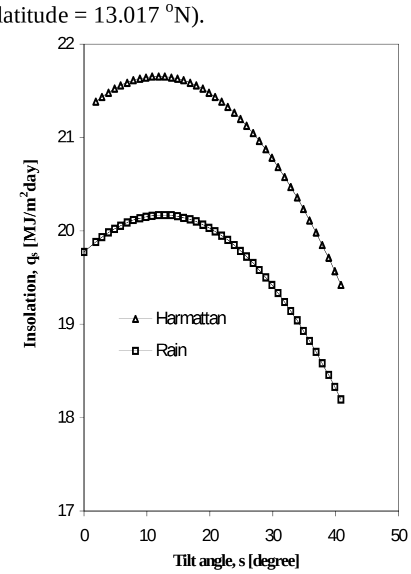

Fig. (5). Yearly average daily insolation on tilted surface for Port Harcourt (latitude = 4.858 °N).

shows that the solar insolation in June, July and August is at its lowest value. Thus, these months will not favour collection of solar energy because of poor climatic conditions (low

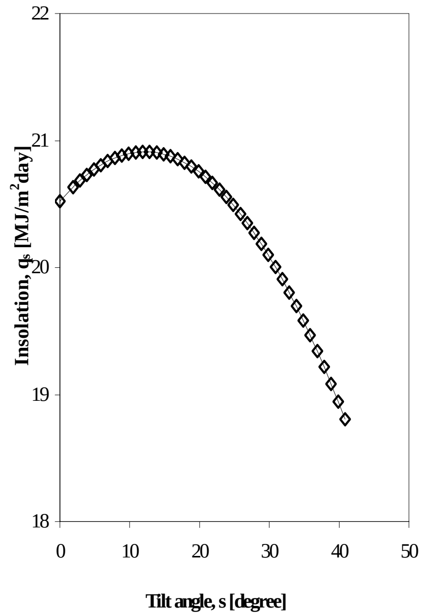

Fig. (6). Yearly average daily insolation on tilted surface for Sokoto (latitude = 13.017 °N).

relative sunshine). Therefore, solar drying of agricultural products will not be favoured in this period of the year because it is the peak of the rain season.

The dependence of the insolation on a tilted surface for these cities is fitted as a quadratic function, Equation 17, using Microsoft Excel. The values of the coefficients, c_i, of Equation (17), are tabulated in Tables (**A1**) and (**A2**) of the Appendix; they are useful for determining the monthly, seasonal and yearly optimum tilt angles, s^*, Equation (18) by the calculus method (using Equation 16). The results obtained from the monthly, seasonal and yearly analysis for the eight Nigerian cities considered showed that the optimum tilt angle varies with latitude of the location, Tables (**2**) and (**3**). The monthly optimum tilt angles, Table (**2**), produce the largest annual cumulative insulation; this is followed by the seasonal optimum tilt angles, Table (**3**). That is, by varying the tilt angle of the fixed flat plate collector every month to their monthly optimum angle, the solar energy collected per year will be more than that collected per year when the tilt angle of the collector is changed twice (seasonally) a year to their seasonal optimum. Of course, the least solar energy harvest is realised when the collector tilt angle is permanently fixed to their yearly optimum angle.

Table (**3**) also compares the seasonal and yearly optimum tilt angles and their corresponding values of insolation obtained in this work with those of Wenger and Oliveira [13], and Fagbenle [14]. It is seen that the results obtained in this work are better, and thus, the optimum tilt angle for a specified low latitude is neither equal to the latitude of the location nor equal to the latitude plus 10^o as suggested by Wenger and Oliveira [13], and Fagbenle [14], respectively, Equations (2a) and (2b). However, the deviation of the optimum tilt angles from the latitudes of the locations considered in the present work is approximately ±2^o.

Mathematical expressions correlating the optimum tilt angle with latitude are presented in Tables (**4**) and (**5**) for the monthly, and seasonal and yearly cases, respectively.

APPENDIX A; Tabulated Data

Table A1. Coefficients in the Equation for the Monthly Insolation, Equation (17), q_s [MJ/m²day]

Location (Latitude)	Coefficient	Monthly											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port Harcourt	c_0	14.6250	15.2200	13.6510	13.5430	13.2630	11.5930	10.8440	10.9440	10.7280	12.3050	13.7760	14.9580
(4.858° N)	c_1	0.0157	0.0194	0.0050	0.0055	0.0136	0.0120	0.0056	0.0035	0.0058	0.0132	0.0138	0.0059
	c_2	-0.0016	-0.0017	-0.0015	-0.0014	-0.0014	-0.0012	-0.0011	-0.0011	-0.0010	-0.0013	-0.0015	-0.0017
Enugu	c_0	10.0660	16.3970	15.1170	14.9750	14.6290	13.3030	12.2430	11.7680	12.5070	14.4490	16.3440	16.9610
(6.467° N)	c_1	0.0249	0.0277	0.0097	0.0112	0.0220	0.0197	0.0095	0.0062	0.0119	0.0223	0.0229	0.0115
	c_2	-0.0018	-0.0019	-0.0017	-0.0017	-0.0016	-0.0014	-0.0013	-0.0012	-0.0013	-0.0016	-0.0019	-0.0019
Makurdi	c_0	18.1020	18.3440	17.3620	16.4250	16.1210	14.8280	14.1630	13.5850	14.6710	16.2730	17.3550	17.9640
(7.700° N)	c_1	0.0355	0.0386	0.0171	0.0175	0.0304	0.0279	0.0160	0.0115	0.0199	0.0319	0.0302	0.0176
	c_2	-0.0021	-0.0022	-0.0020	-0.0019	-0.0019	-0.0017	-0.0016	-0.0015	-0.0016	-0.0019	-0.0020	-0.0021
Lokoja	c_0	19.4270	19.4590	18.9180	17.9550	17.4690	16.7220	16.3450	15.9990	16.7700	17.9620	19.6590	19.9900
(8.800° N)	c_1	0.0488	0.0480	0.0223	0.0260	0.0429	0.0391	0.0209	0.0173	0.0329	0.0424	0.0387	0.0238
	c_2	-0.0024	-0.0024	-0.0022	-0.0020	-0.0021	-0.0020	-0.0019	-0.0018	-0.0020	-0.0021	-0.0024	-0.0024
Minna	c_0	21.2360	21.1970	21.0270	20.1900	19.5500	18.8270	18.0190	18.0930	18.9950	20.6550	21.5590	21.8400
(9.617° N)	c_1	0.0567	0.0556	0.0332	0.0372	0.0516	0.0478	0.0294	0.0271	0.0432	0.0535	0.0471	0.0342
	c_2	-0.0026	-0.0026	-0.0025	-0.0024	-0.0024	-0.0023	-0.0021	-0.0021	-0.0023	-0.0025	-0.0026	-0.0026
Bauchi	c_0	21.5100	21.5020	21.0680	20.2200	19.6740	19.2920	18.8010	18.6370	19.8950	20.7940	21.8010	22.1670
(10.333° N)	c_1	0.0599	0.0628	0.0363	0.0366	0.0543	0.0551	0.0375	0.0313	0.0454	0.0602	0.0566	0.0383
	c_2	-0.0027	-0.0027	-0.0026	-0.0024	-0.0024	-0.0024	-0.0023	-0.0022	-0.0024	-0.0026	-0.0027	-0.0027
Maiduguri	c_0	21.6120	21.5410	21.2200	20.5000	19.8820	19.5470	19.0450	18.9530	19.7460	20.3940	21.7410	22.0890
(11.850° N)	c_1	0.0688	0.0714	0.0447	0.0455	0.0629	0.0638	0.0453	0.0390	0.0524	0.0667	0.0650	0.0466
	c_2	-0.0027	-0.0027	-0.0026	-0.0025	-0.0025	-0.0024	-0.0023	-0.0023	-0.0024	-0.0026	-0.0027	-0.0027
Sokoto	c_0	21.3380	21.2640	21.0980	20.3210	19.7840	19.6580	19.1900	19.0560	19.9930	21.0030	21.6410	22.0200
(13.017° N)	c_1	0.0742	0.0768	0.0505	0.0509	0.0685	0.0703	0.0514	0.0448	0.0529	0.0757	0.0712	0.0529
	c_2	-0.0027	-0.0027	-0.0026	-0.0025	-0.0025	-0.0025	-0.0024	-0.0023	-0.0025	-0.0027	-0.0027	-0.0027

Table A2. Coefficients in the Equation for the Seasonal and Yearly Global Solar Radiation, Equations (17), q_s [MJ/m²day]

Location (Latitude)	Const	Seasonal		Yearly
		Harmattan	Rain	
Port Harcourt	c_0	14.2950	11.6120	12.9540
(4.858° N)	c_1	0.0109	0.0090	0.0100
	c_2	-0.0016	-0.0012	-0.0014
Enugu	c_0	15.9760	13.1490	14.5630
(6.467° N)	c_1	0.0181	0.0153	0.0167
	c_2	-0.0018	-0.0014	-0.0016
Makurdi	c_0	17.5910	14.9400	16.2650
(7.700° N)	c_1	0.0262	0.0230	0.0246

Table A2. cont…

Location (Latitude)	Const	Seasonal		Yearly
		Harmattan	Rain	
	c_2	-0.0020	-0.0017	-0.0019
Lokoja	c_0	19.2380	16.8780	18.0570
(8.800° N)	c_1	0.0344	0.0326	0.0336
	c_2	-0.0023	-0.0020	-0.0021
Minna	c_0	21.1770	19.0220	20.0980
(9.617° N)	c_1	0.0438	0.0422	0.0431
	c_2	-0.0026	-0.0023	-0.0024
Bauchi	c_0	21.3470	19.5150	20.4320
(10.333° N)	c_1	0.0483	0.0474	0.0477
	c_2	-0.0026	-0.0024	-0.0025
Maiduguri	c_0	21.4520	19.5940	20.5220
(11.850° N)	c_1	0.0568	0.0551	0.0561
	c_2	-0.0027	-0.0024	-0.0025
Sokoto	c_0	21.2820	19.7800	20.5320
(13.017° N)	c_1	0.0626	0.0617	0.0621
	c_2	-0.0027	-0.0025	-0.0026

Table 2. Monthly Average Optimum Tilt Angles [Degree]

Location	Latitude [°N]	Monthly											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port Harcourt	4.858	4.906	5.706	1.667	1.964	4.857	5.000	2.545	1.591	2.900	5.077	4.600	1.735
Enugu	6.467	6.917	7.289	2.853	3.294	6.875	7.036	3.654	2.583	4.577	6.969	6.026	3.026
Makurdi	7.700	8.452	8.773	4.275	4.605	8.000	8.206	5.000	3.833	6.180	8.395	7.550	4.190
Lokoja	8.800	10.167	10.000	5.068	6.500	10.214	9.775	5.500	4.806	8.225	10.095	8.063	4.958
Minna	9.617	10.904	10.692	6.640	7.750	10.750	10.391	7.000	6.452	9.391	10.700	9.058	6.577
Bauchi	10.333	11.093	11.630	6.981	7.625	11.313	11.479	8.152	7.114	9.458	11.577	10.481	7.093
Maiduguri	11.850	12.741	13.222	8.596	9.100	12.580	13.292	9.848	8.478	10.917	12.827	12.037	8.630
Sokoto	13.017	13.741	14.222	9.712	10.180	13.700	14.060	10.708	9.739	10.584	14.019	13.185	9.796

Table 3. Comparison of Seasonal and Yearly Optimum Tilt Angles, s^* [Degree], (and Insolation on Tilted Surface, q_s^* [MJ/m^{2}day])

Location	Latitude [°N]	Seasonal						Yearly		
		Present work		Wenger & Oliveira [13]		Fagbenle [14]		Present work	Wenger & Oliveira [13]	Fagbenle [14]
		Harmattan	Rain	Harmattan	Rain	Harmattan	Rain			
Port Harcourt	4.858	3.406 (14.314)	3.750 (11.629)	4.858 (14.310)	4.858 (11.627)	14.858 (14.104)	14.858 (11.481)	3.571 (12.7972)	4.858 (12.970)	14.858 (12.794)
Enugu	6.467	5.028 (16.022)	5.464 (13.191)	6.467 (16.018)	6.467 (13.189)	16.467 (15.786)	16.467 (13.021)	5.219 (14.607)	6.467 (14.604)	16.467 (14.404)
Makurdi	7.700	6.550 (17.677)	6.765 (15.018)	7.700 (17.674)	7.700 (15.016)	17.700 (17.428)	17.700 (14.815)	6.474 (16.345)	7.700 (16.342)	17.700 (16.105)

Table 3. cont….

Location	Latitude [°N]	Seasonal						Yearly		
		Present work		Wenger & Oliveira [13]		Fagbenle [14]		Present work	Wenger & Oliveira [13]	Fagbenle [14]
		Harmattan	Rain	Harmattan	Rain	Harmattan	Rain			
Lokoja	8.800	7.478 (19.364)	8.150 (17.011)	8.800 (19.366)	8.800 (17.010)	13.800 (19.275)	13.800 (16.878)	8.000 (18.191)	8.800 (18.190)	13.800 (18.121)
Minna	9.617	8.423 (21.301)	9.174 (19.216)	9.617 (21.298)	9.617 (19.215)	14.617 (21.202)	14.617 (19.147)	8.979 (20.292)	9.617 (20.291)	14.617 (20.215)
Bauchi	10.333	9.288 (21.571)	9.875 (19.749)	10.333 (21.568)	10.333 (19.749)	15.333 (21.476)	15.333 (19.678)	9.540 (20.660)	10.333 (20.658)	15.333 (20.576)
Maiduguri	11.850	10.519 (21.751)	11.479 (19.910)	11.850 (21.746)	11.850 (19.910)	16.850 (21.642)	16.850 (19.841)	11.220 (20.837)	11.850 (20.836)	16.850 (20.757)
Sokoto	13.017	11.593 (22.025)	12.340 (20.161)	13.017 (22.019)	13.017 (20.160)	18.017 (21.827)	18.017 (20.080)	11.942 (20.903)	13.017 (20.900)	18.017 (20.807)

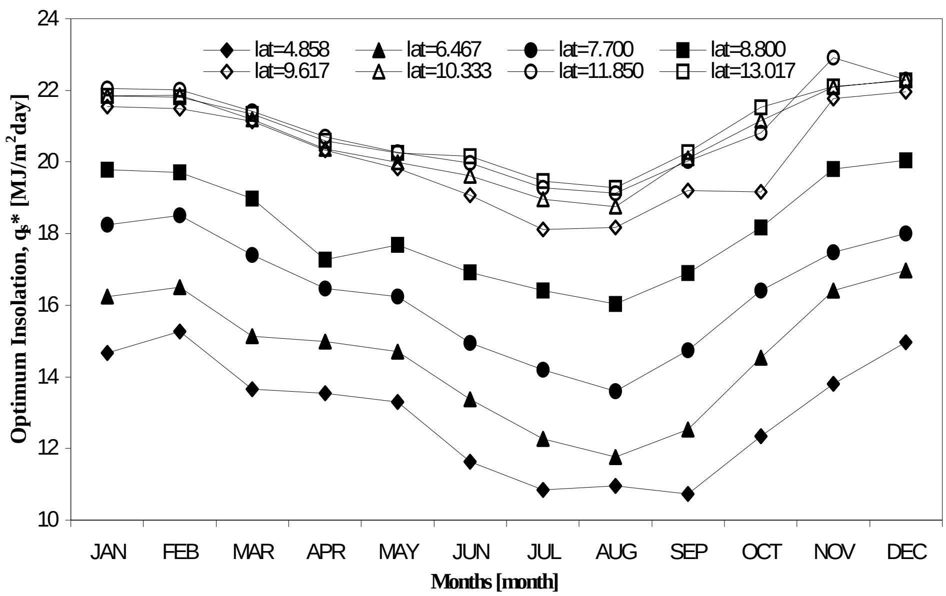

Fig. (7). Monthly average daily optimum insolation on a tilted surface for different latitudes [°N].

Table 4. Expression for the Monthly Optimum Tilt Angle Equation as a Function of the Latitude, ϕ [°N], 4.858 < ϕ < 13.017

Month	Equation	Regression Coefficient, R^2
January	$s^* = 3.1731 + 1.8629\,\phi - 0.04360\,\phi^2$	0.9952
February	$s^* = 0.0376 + 1.186\,\phi - 0.0069\,\phi^2$	0.9990
March	$s^* = 2.8649 + 0.8606\,\phi + 0.0087\,\phi^2$	0.9934
April	$s^* = 5.1027 + 1.5296\,\phi - 0.0271\,\phi^2$	0.9835
May	$s^* = 3.2078 + 1.8402\,\phi - 0.04148\,\phi^2$	0.9919
June	$s^* = 1.3594 + 1.3692\,\phi - 0.0131\,\phi^2$	0.9968
July	$s^* = 0.7960 + 0.5101\,\phi + 0.0305\,\phi^2$	0.9877
August	$s^* = 2.4705 + 0.6925\phi + 0.0198\,\phi^2$	0.9897
September	$s^* = 8.1841 + 2.6203\,\phi - 0.0881\,\phi^2$	0.9760
October	$s^* = 2.2886 + 1.6459\,\phi - 0.0304\,\phi^2$	0.9977

Table 4. cont….

Month	Equation	Regression Coefficient, R^2
November	$s^* = 0.8236 + 0.6640\ \phi + 0.0227\ \phi^2$	0.9925
December	$s^* = 2.2578 + 0.7214\ \phi + 0.0164\ \phi^2$	0.9932

Table 5. Expression for the Seasonal and Yearly Optimum Tilt Angle as a Function of the Latitude, ϕ [^{o}N], 4.858 < ϕ < 13.017

Month	Equation	Regression Coefficient, R^2
Harmattan	$s^* = 3.9743 + 1.6770\ \phi - 0.0374\ \phi^2$	0.9863
Rain	$s^* = 2.6136 + 1.3634\ \phi - 0.0156\ \phi^2$	0.9981
Yearly	$s^* = 2.9489 + 1.4050\ \phi - 0.0190\ \phi^2$	0.9965

This facilitates the prediction of the optimum tilt angles (monthly, seasonal and yearly) for any location within the range of low latitudes covered in this work.

CONCLUSION

The monthly, seasonal and yearly optimum flat plate solar collector tilt angles for low latitudes, 4.86-13.02 ^{o}N, have been presented in this work. Graphical and tabular data were generated, and polynomial expressions correlating the optimum tilt angle with the latitude were presented. The results, which have been shown to be better than those in the literature, will be particularly useful to the low-latitude solar equipment design engineers. Similar approach can be adopted for obtaining the optimum tilt angles for latitudes outside the range considered in this work.

CONFLICT OF INTEREST

None declared.

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None declared.

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