

ESTIMATION OF SOLAR RADIATION: AN EMPIRICAL MODEL FOR BANGLADESH

MOHAMMAD ARIF SOBHAN BHUIYAN

*Department of Electronic and Communication Engineering,
Faculty of Science and Engineering, Southern University Bangladesh,
Chittagong-4000, Bangladesh.*

arif_apece@hotmail.com, arifsobhan@southern.edu.bd

ABSTRACT: This study is carried out to compute empirically global, diffuse and direct solar radiation on a horizontal surface for the ten districts equally distributed all over Bangladesh ($20^{\circ}34'$ and $26^{\circ}34'$ north latitude, $88^{\circ}01'$ and $92^{\circ}41'$ east longitude) as well as to predict correlations among them. For this study, meteorological data for 28 years (between 1980 and 2007) are used which are collected from Bangladesh Meteorological Department. The global radiation in Bangladesh is found to be maximum in the month of April/May and minimum in the month of November/December in all the districts. The values of the correlation coefficients a, b, c, d, c', d', e, f, e' and f' for ten stations of Bangladesh are also evaluated. It is evident that, the values of the coefficient "a" vary from 0.2296 to 0.2569, while the coefficient "b" varies from 0.5112 to 0.5560. The overall mean deviations of the ten values of both a and b are 0.2432 ± 0.0136 and 0.5336 ± 0.0224 , respectively. The maximum and minimum values of the other correlation coefficients c, d, c', d', e, f, e' and f' are (1.5695 and 1.4357), (-1.7210 and -1.9986), (0.4011 and 0.376), (-0.2072 and -0.2510), (-0.3811 and -0.5464), (1.946 and 1.6456), (-0.1206 and -0.1684) and (0.7984 and 0.7000) respectively. Their maximum variations due to location are (1.5022 ± 0.0672), (-1.8598 ± 0.1388), (0.3885 ± 0.0125), (-0.2291 ± 0.0219), (-0.4637 ± 0.0826), (1.7958 ± 0.1502), (-0.1445 ± 0.0239) and (0.7492 ± 0.0492) respectively.

ABSTRAK: Kajian ini dibuat secara empirikal mengenai kadar penyebaran secara resapan, global dan langsung radiasi solar, keatas permukaan mendatar untuk sepuluh daerah di seluruh Bangladesh ($20^{\circ}34'$ dan $26^{\circ}34'$ utara latitud, $88^{\circ}01'$ dan longitud $92^{\circ}41'$ timur) dan meramal korelasi mereka. Kajian ini menggunakan data meteorologi selama 28 tahun (antara 1980 dan 2007) yang dikutip dari Jabatan Meteorologi Bangladesh. Radiasi global maksima di Bangladesh adalah pada bulan April / Mei dan minima pada bulan November / Disember di semua daerah. Kajian dibuat mengenai nilai pekali korelasi a, b, c, d, c', d', e, f, e' dan f' bagi sepuluh stesen di Bangladesh. Nilai pekali "a" adalah antara 0.2296 dan 0.2569, manakala pekali "b" adalah antara 0.5112 dan 0.5560. Sisihan min keseluruhan bagi sepuluh nilai a dan b adalah 0.2432 ± 0.0136 dan 0.5336 ± 0.0224 . Nilai maksima dan minima pekali korelasi lain c, d, c', d', e, f, e' dan f' adalah (1.5695 and 1.4357), (-1.7210 dan -1.9986), (0.4011 dan 0.376), (-0.2072 dan -0.2510), (-0.3811 dan -0.5464), (1.946 dan 1.6456), (-0.1206 dan -0.1684) dan (0.7984 dan 0.7000). Variasi maksima antara mereka disebabkan lokasi adalah (1.5022 ± 0.0672), (-1.8598 ± 0.1388), (0.3885 ± 0.0125), (-0.2291 ± 0.0219), (-0.4637 ± 0.0826), (1.7958 ± 0.1502), (-0.1445 ± 0.0239) dan (0.7492 ± 0.0492).

KEYWORDS: *Bangladesh; coefficient; correlation; radiation; solar*

1. INTRODUCTION

Energy certainly plays a vital role in development and welfare of human being. There exists a direct correlation between the development of a country and its consumption of energy. World reserve of conventional energy sources are limited and will be used up once. Therefore, the whole world is looking for non-exhaustible energy sources for their future. Among the all non-conventional energies, solar energy is the best option if it can be used in a cost effective manner. Moreover the technology is environmentally sound. As the solar energy intercepted by the earth in one year is ten times greater than the total fossil resources including undiscovered and unexplored non-recoverable reserves [1], it is expected that the present world wide research and development program on solar energy will help to solve the future energy crisis of the world.

The applications of solar energy require information of the availability of solar energy for its optimum use. Since solar radiation is not uniform over all places on the earth, any solar energy conversion installation at a certain place requires knowledge of the amount of solar radiation at that place which again varies from time to time. Bangladesh, being situated between 20°34' and 26°34' north latitude, 88°01' and 92°41' east longitude, is endowed with abundant sunshine for at least 8 months of the year. The prospect of utilization of solar energy is thus very bright. But solar radiation data, a prerequisite for the designing and sizing of solar energy systems, are not available in many locations of Bangladesh due to absence or malfunction of measuring instruments. However, the climatological data such as sunshine hour, temperature, humidity etc. are available at meteorological department for most districts of Bangladesh. These data can be used in empirical models to estimate the global solar radiation and its components at any location. We used these data to compute empirically the global, diffuse and direct solar radiation over ten districts distributed all over Bangladesh.

2. ESTIMATION OF RADIATION

The empirical models for determination of solar radiation can be roughly classified into three categories: a) sun-shine based models, b) cloud based models and c) meteorological data based model [2, 3]. A number of correlations that include meteorological parameters such as latitude, ambient temperature, the total precipitation, relative and specific humidity, the elevation, amount of cloud cover etc. have been developed by different researchers [4 - 17].

For estimation of global solar radiation G , the formula proposed by H.P. Garg and S.N. Garg [18] is used given by eq (1).

$$G = G_o (0.414 + 0.400 n/N - 0.0055 W_{at}) \quad (1)$$

Where G_o is the extraterrestrial radiation, n/N is the ratio of sun shine hour and day length and W_{at} is the atmospheric water content per unit volume described in eq (5). From geometrical consideration extraterrestrial daily global solar radiation (G_o) on a horizontal surface for each station is given by eq. (2):

$$G_o = 0.01163 \times \{(24 \times F)/\pi\} (\cos\phi \cos\delta \cos W_s + W_s \sin\phi \sin\delta) \quad (2)$$

Where F is a unit of conversion factor given in eq (3), ϕ is the latitude in radians, δ is the solar declination given in eq (6) and W_s is the sunset angle given in eq (4).

$$F = 1.95 \times 60.0 (1 + 0.033 \cos 360 \times d/365) \quad (3)$$

$$W_s = \cos^{-1}(-\tan\phi \tan\delta) \text{ in radians} \quad (4)$$

$$W_{at} = H_{rel} \times (4.7923 + 0.3647 T + 0.0055 T^2 + 0.0003 T^3) \quad (5)$$

$$\delta = \left[23 + \left(\frac{27}{60} \right) \right] \sin \left(360 \times \frac{d}{365} \right) \quad (6)$$

Where T is the ambient temperature in °C for the fractional sunshine duration n/N, H_{rel} is the relative humidity and d being the number of days after spring equinox (21st march).

For estimation of diffuse radiation (D), the formula proposed by M. Hussain [19] is used given by eq (7).

$$D = G_o \left\{ 0.306 - \left(0.165 \times \frac{n}{N} \right) + 0.0025 W_{at} \right\} \quad (7)$$

For estimation of direct or beam radiation (I), the subtraction method is used given by eq (8).

$$I = G - D \quad (8)$$

Hence it should be noted that all the radiation data are estimated in the unit of $\text{Kwh/m}^2\text{-day}$.

3. DETERMINATION OF REGRESSION COEFFICIENTS

Angstrom correlation [4] modified by Prescott [5], given in eq (9), for estimation of global radiation is generally employed all over the world. So, firstly the values of the Regression coefficients (a and b) are determined.

$$\frac{G}{G_o} = a + b \left(\frac{n}{N} \right) \quad (9)$$

Secondly, from Page correlation [6], given in eq (10), for diffuse radiation, the values of the correlation coefficients (c and d) for these stations are determined.

$$\frac{D}{G} = c + d \left(\frac{G}{G_o} \right) \quad (10)$$

From Angstrom like correlation [7], given in eq (11), for predicting diffuse radiation all over Bangladesh, the values of the coefficients c' and d' are determined.

$$\frac{D}{G_o} = c' + d' \left(\frac{n}{N} \right) \quad (11)$$

Thirdly, from both Page like and Angstrom like correlations [8], given in eqn. (12) and (13), for estimation of direct solar radiation, the values of the correlation coefficients e, f, e' and f' are also determined.

$$\frac{I}{G} = e + f \left(\frac{G}{G_o} \right) \quad (12)$$

$$\frac{I}{G_o} = e' + f' \left(\frac{n}{N} \right) \quad (13)$$

To estimate diffuse and direct solar radiation directly from global solar radiation [8], presented in eqn. (14) and (15) the values of the coefficients c_o , d_o , e_o and f_o are determined for the ten districts of Bangladesh.

$$\frac{D}{G} = c_o + d_o \left(\frac{n}{N} \right) \quad (14)$$

$$\frac{I}{G} = e_o + f_o \left(\frac{n}{N} \right) \quad (15)$$

4. RESULTS

The estimated values of monthly averaged global, diffuse and direct solar radiation for Khulna are given in tabular form below:

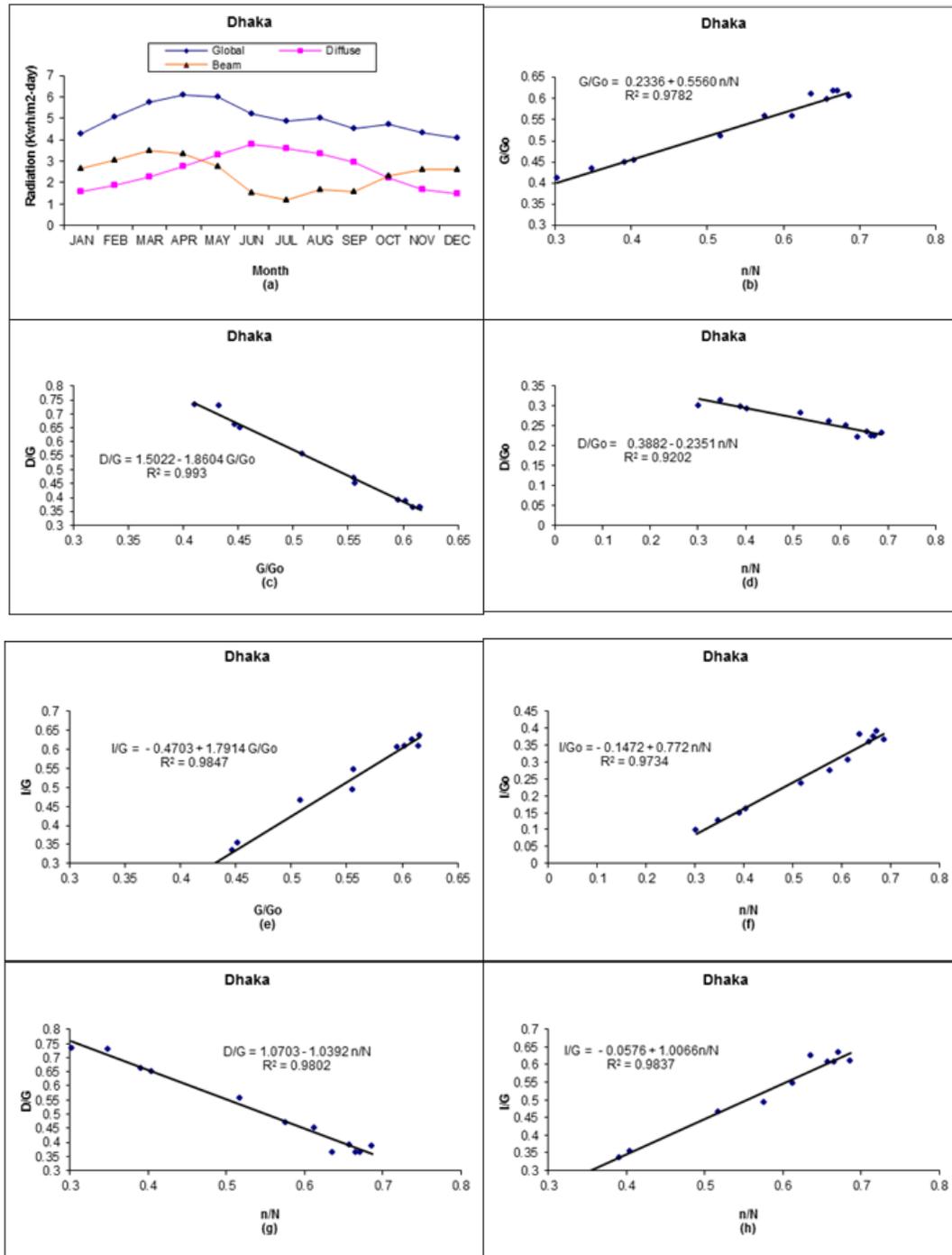


Fig. 1: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Dhaka (b) Correlation between n/N and G/G₀ (c) Correlation between G/G₀ and D/G (d) Correlation between n/N and D/G₀ (e) Correlation between G/G₀ and I/G (f) Correlation between n/N and I/G₀ (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G.

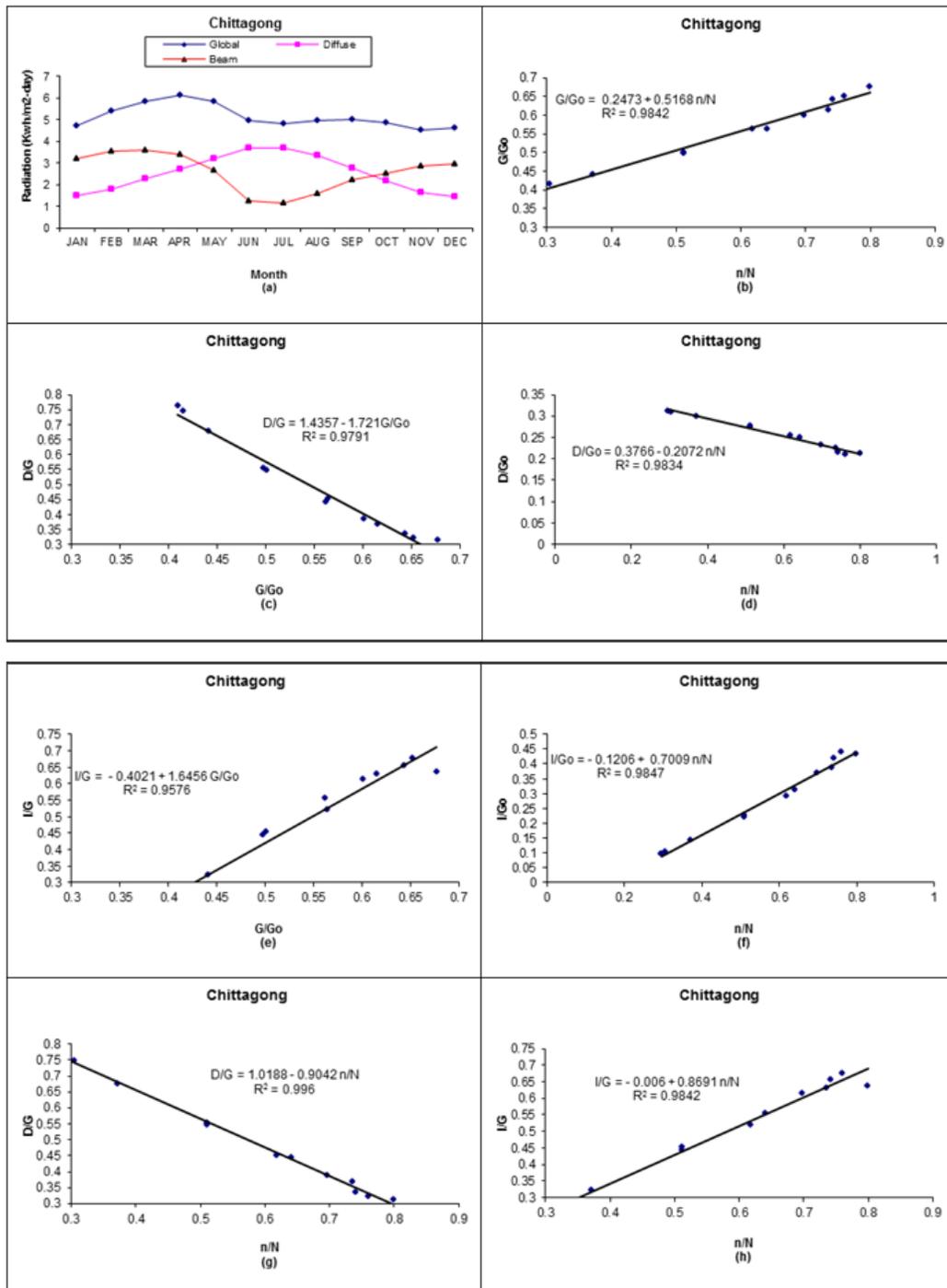


Fig. 2: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Chittagong (b) Correlation between n/N and G/G_0 (c) Correlation between G/G_0 and D/G (d) Correlation between n/N and D/G_0 (e) Correlation between G/G_0 and I/G (f) Correlation between n/N and I/G_0 (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G .

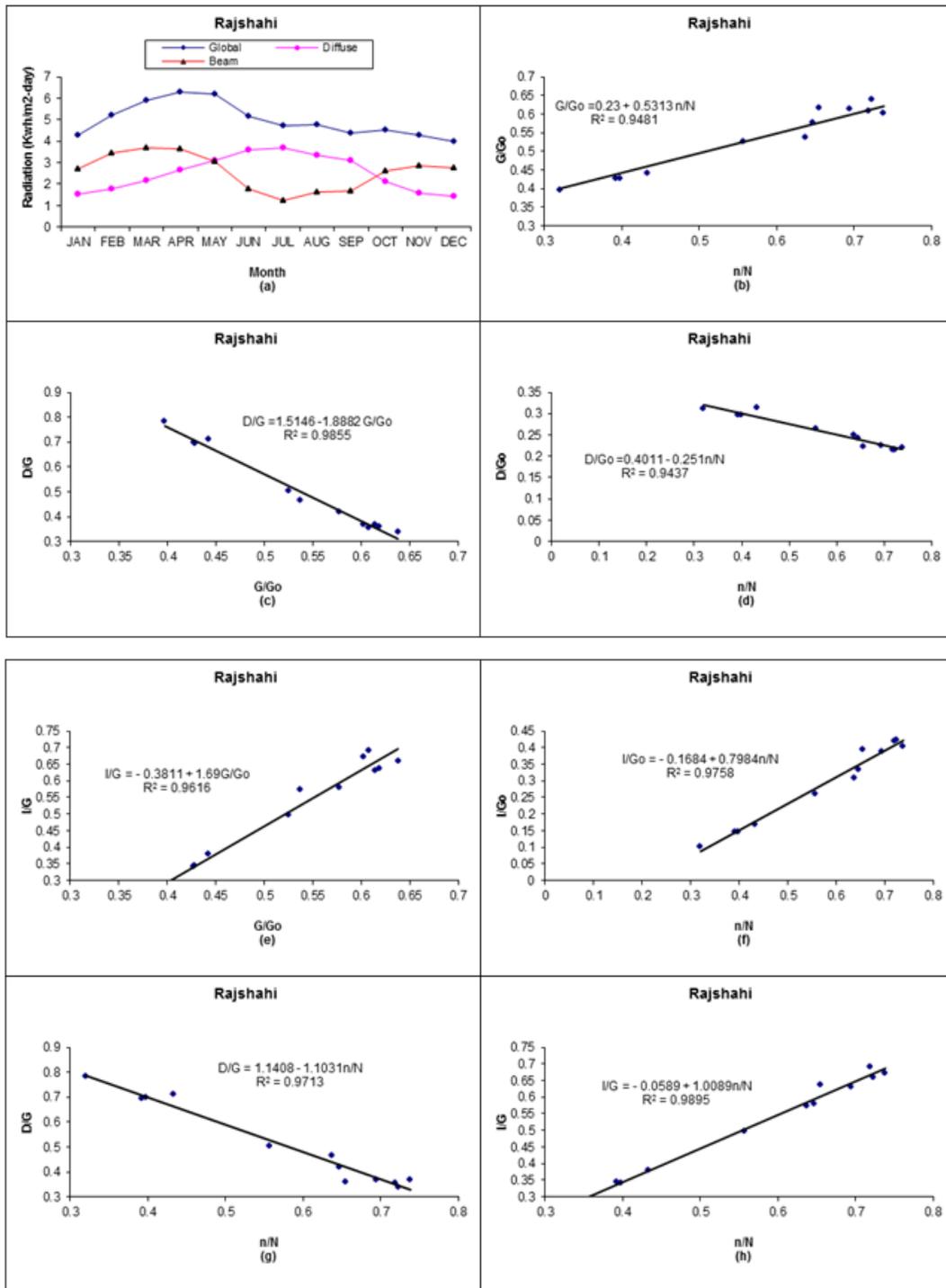


Fig. 3: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Rajshahi (b) Correlation between n/N and G/G_0 (c) Correlation between G/G_0 and D/G (d) Correlation between n/N and D/G_0 (e) Correlation between G/G_0 and I/G (f) Correlation between n/N and I/G_0 (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G .

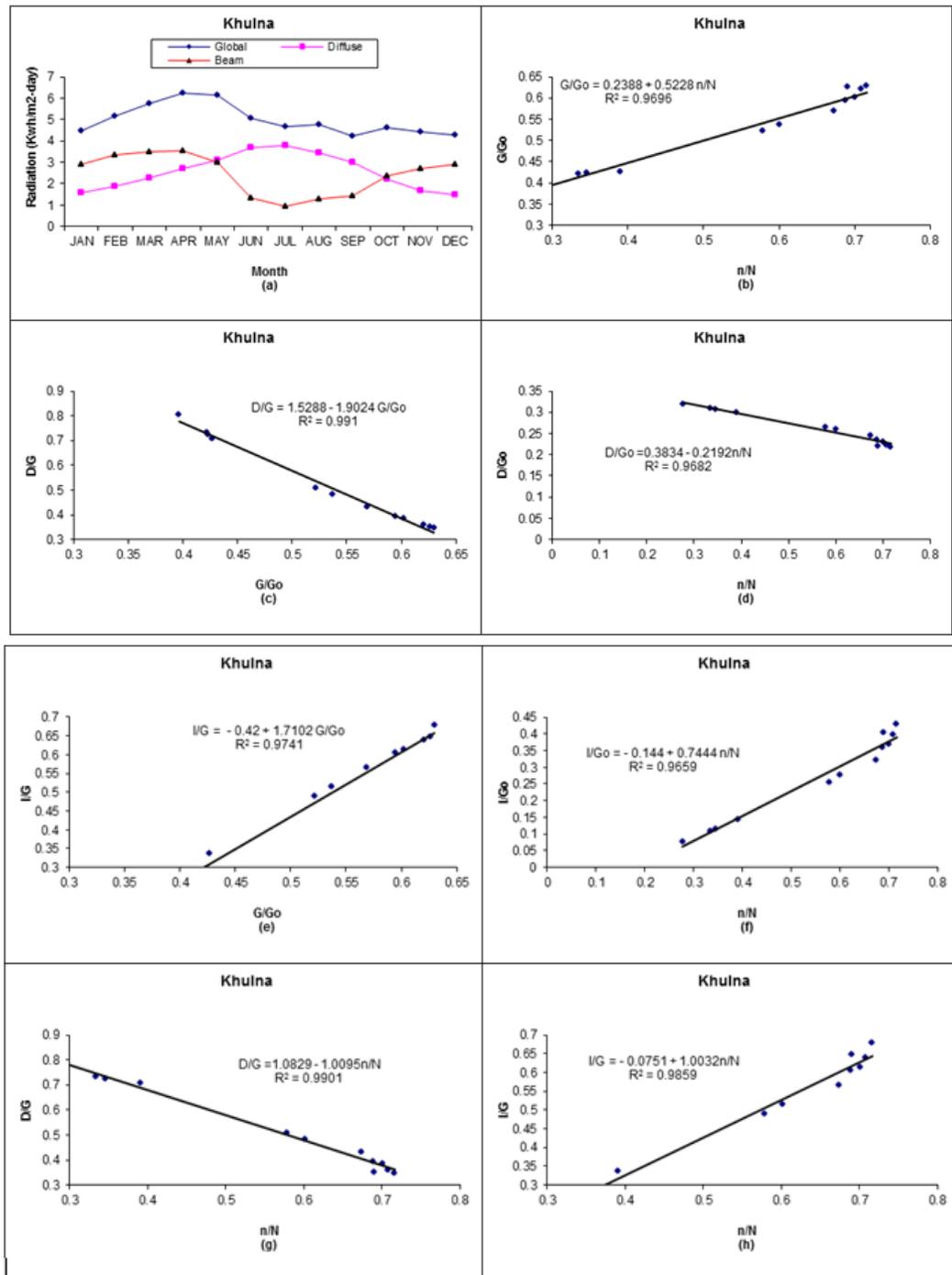


Fig 4: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Khulna (b) Correlation between n/N and G/G₀ (c) Correlation between G/G₀ and D/G (d) Correlation between n/N and D/G₀ (e) Correlation between G/G₀ and I/G (f) Correlation between n/N and I/G₀ (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G.

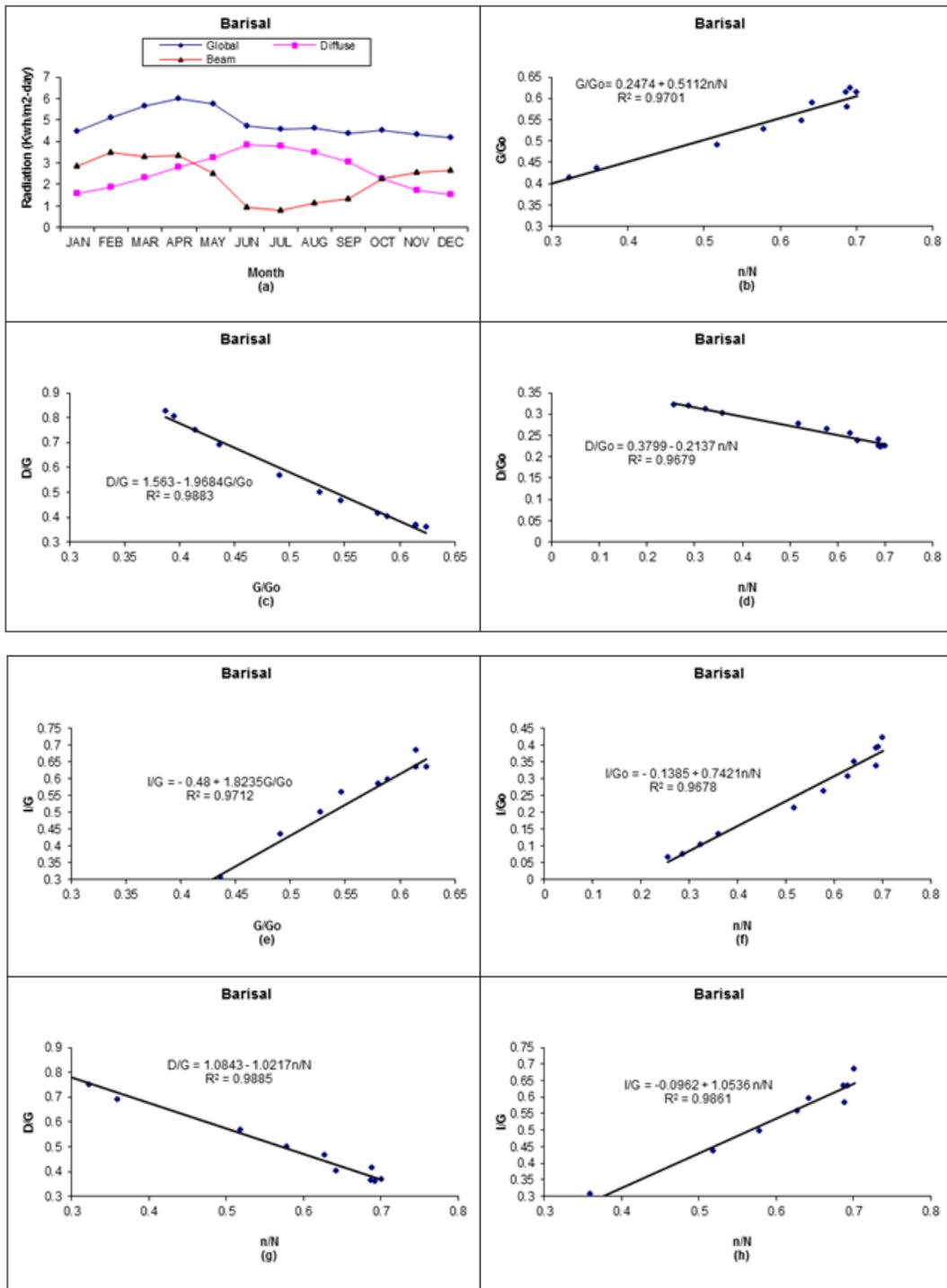


Fig. 5: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Barisal (b) Correlation between n/N and G/G_0 (c) Correlation between G/G_0 and D/G (d) Correlation between n/N and D/G_0 (e) Correlation between G/G_0 and I/G (f) Correlation between n/N and I/G_0 (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G .

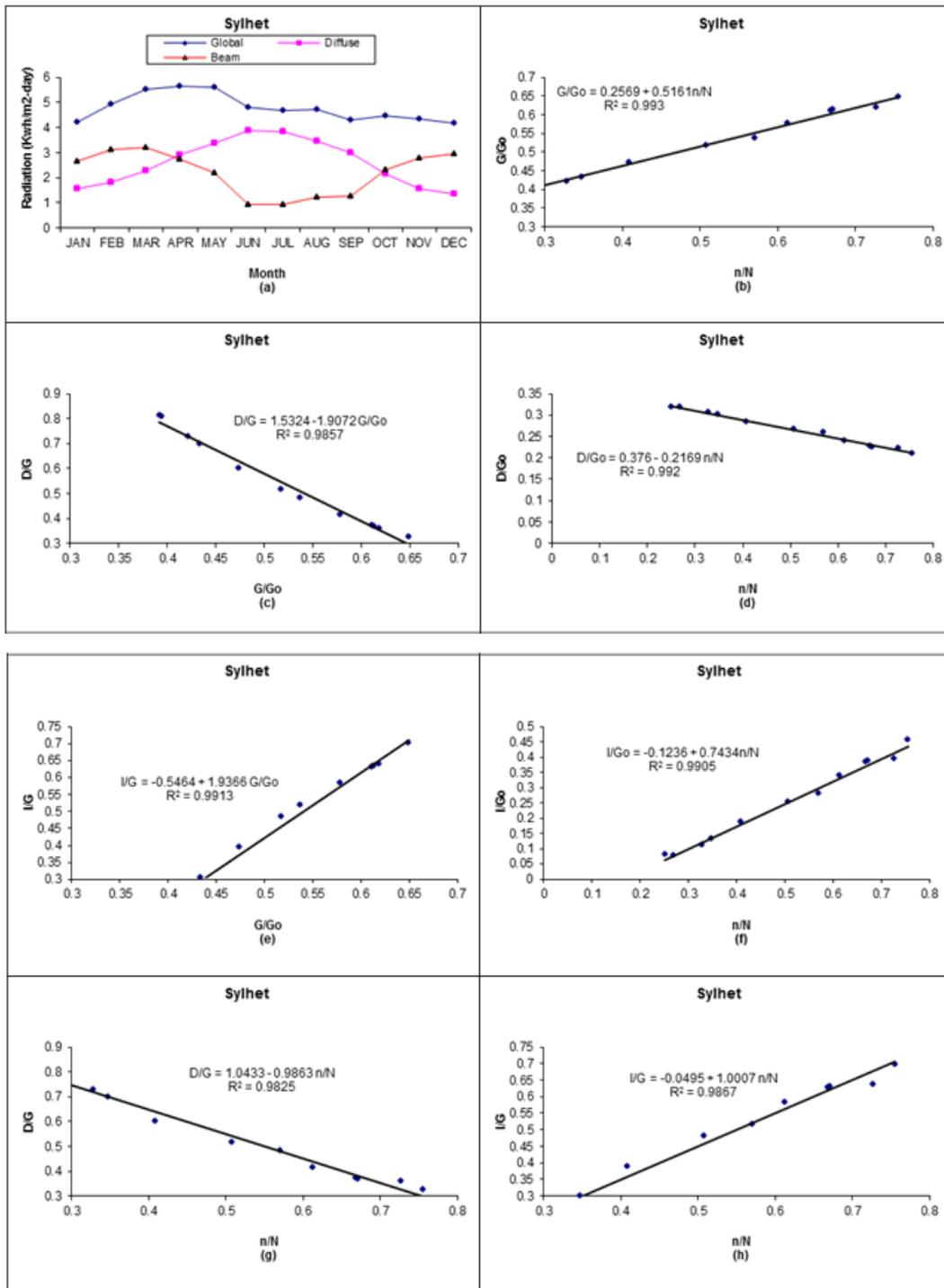


Fig. 6: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Sylhet (b) Correlation between n/N and G/G_0 (c) Correlation between G/G_0 and D/G (d) Correlation between n/N and D/G_0 (e) Correlation between G/G_0 and I/G (f) Correlation between n/N and I/G_0 (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G .

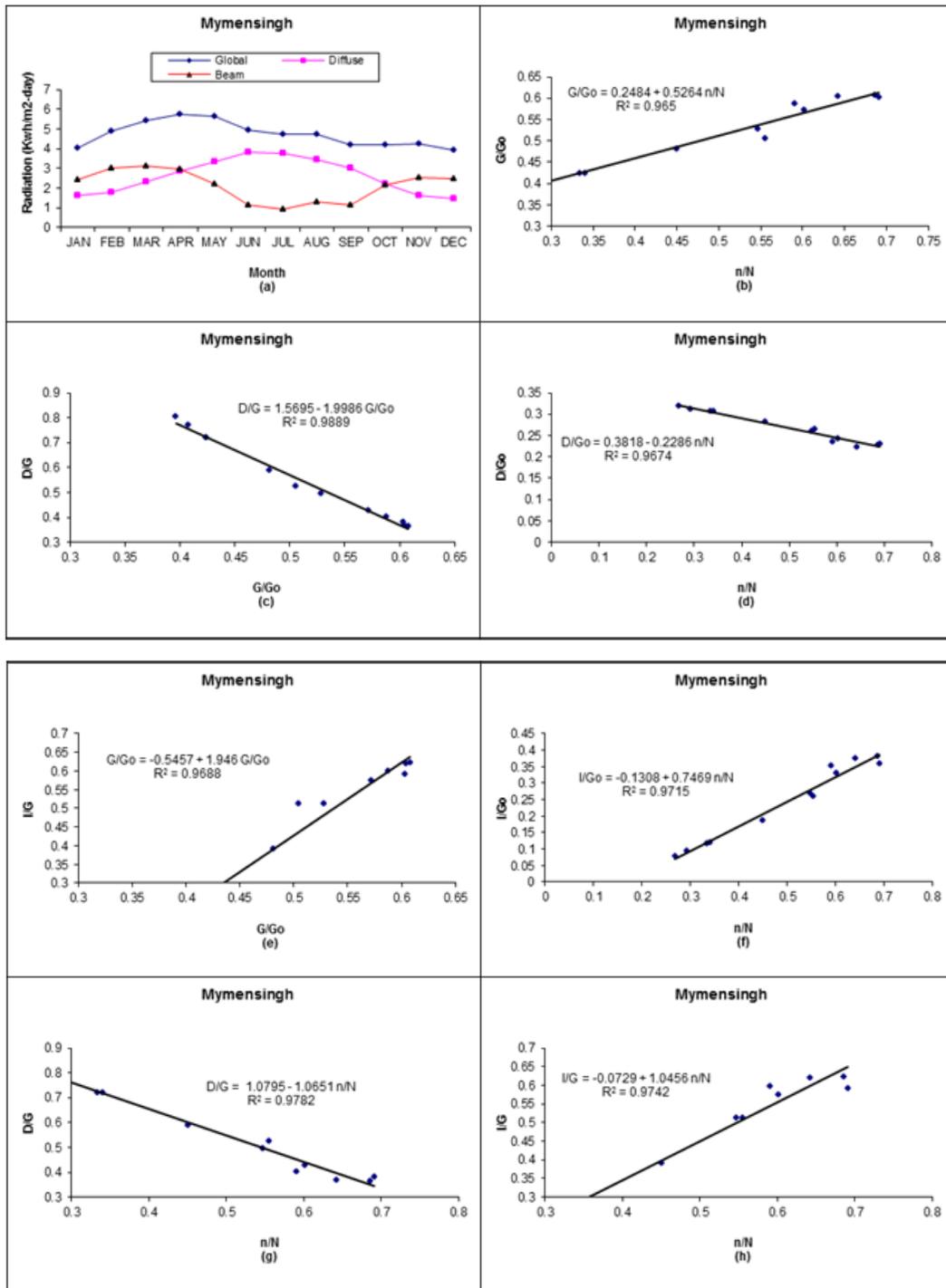


Fig. 8: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Mymensingh (b) Correlation between n/N and G/G₀ (c) Correlation between G/G₀ and D/G (d) Correlation between n/N and D/G₀ (e) Correlation between G/G₀ and I/G (f) Correlation between n/N and I/G₀ (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G.

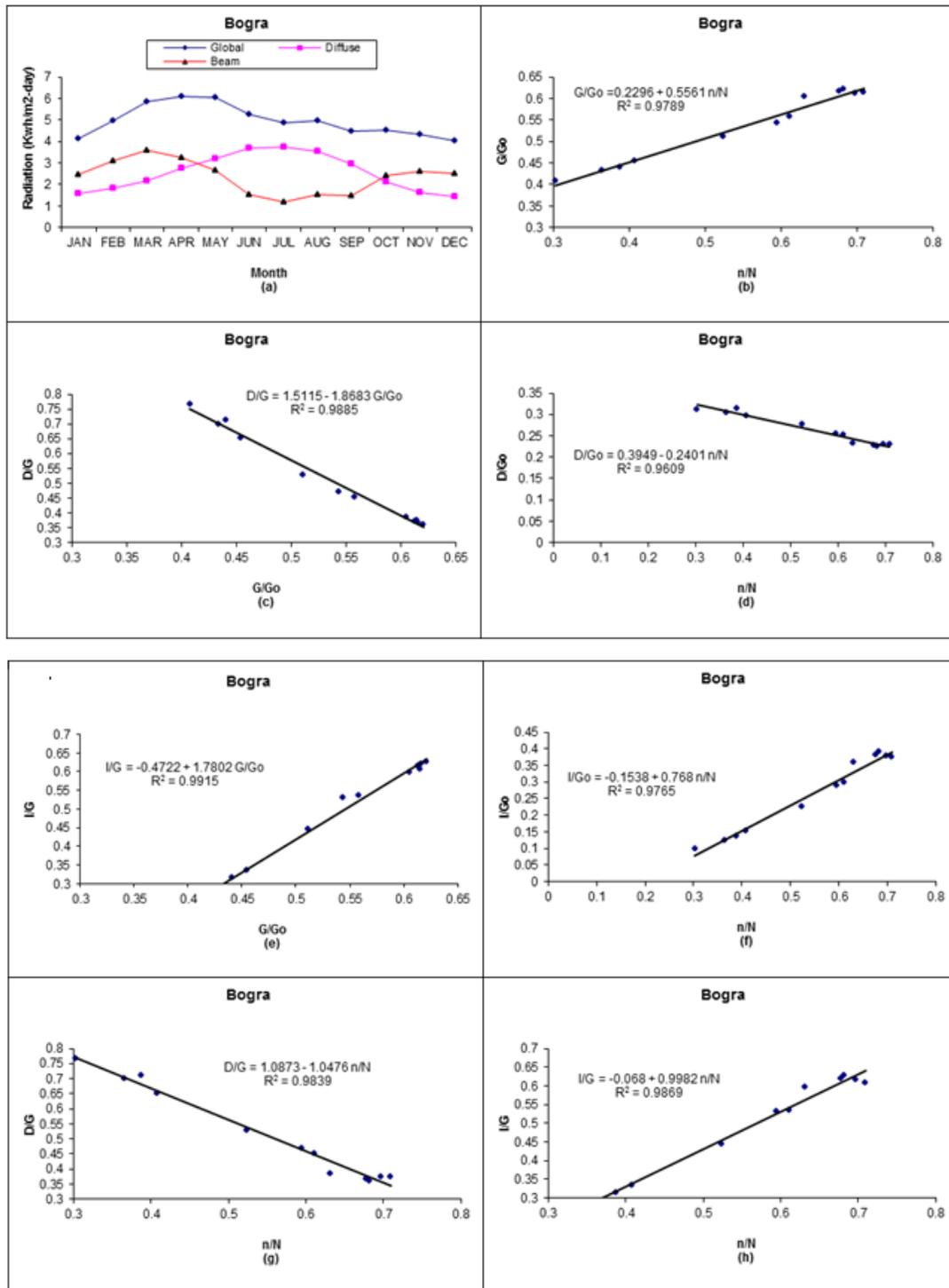


Fig. 9: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Bogra (b) Correlation between n/N and G/G₀ (c) Correlation between G/G₀ and D/G (d) Correlation between n/N and D/G₀ (e) Correlation between G/G₀ and I/G (f) Correlation between n/N and I/G₀ (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G.

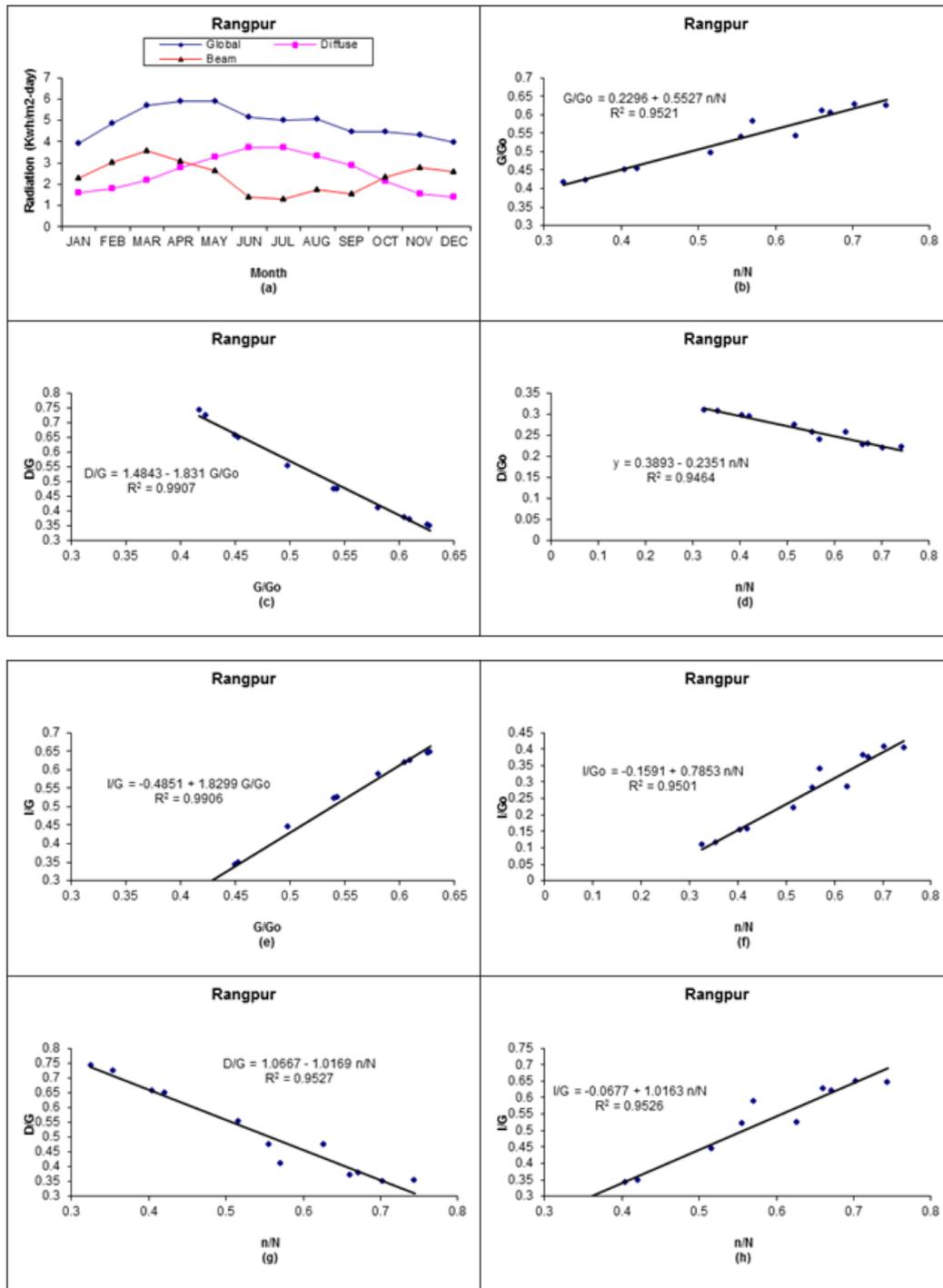


Fig. 10: (a) Monthly variation of Global, diffuse and beam solar radiation on a horizontal surface for Rangpur (b) Correlation between n/N and G/G_0 (c) Correlation between G/G_0 and D/G (d) Correlation between n/N and D/G_0 (e) Correlation between G/G_0 and I/G (f) Correlation between n/N and I/G_0 (g) Correlation between n/N and D/G (h) Correlation between n/N and I/G .

5. DISCUSSIONS

Figures 1 – 10 show the variation of monthly average global (G), diffuse (D), direct (I) solar radiation for ten stations. The dependence of global solar radiation on maximum temperature is intensified by sunshine hour. From all the curves, it is clear that the first peak in the global solar radiation occurs in April/May (summer). In this period, both sunshine hour and temperature are high. But the second peak occurs in August (autumn) which is not so prominent, due to high temperature but short sun shining period. Again, in November/December (winter), though there is enough sun shining period but the temperature is low. Therefore, it results in low global solar radiation.

The diffuse solar radiation depends on relative humidity and atmospheric water content. It increases with the decrease of sun shining hour and increase of atmospheric water content. Therefore, the diffuse radiation is maximum in June/July (rainy) and minimum in December/January (winter). Whereas the direct solar radiation is directly related to sunshine duration. The direct solar radiation is, therefore, maximum in March/April (summer) and minimum in July (rainy).

Table (1) shows the values of the correlation coefficients a, b, c, d, c', d', e, f, e' and f' (eq: 4-8) for ten stations of Bangladesh. It is evident that, the values of the coefficient “a” vary from 0.2296 to 0.2569, while the coefficient “b” varies from 0.5112 to 0.5560. The over all mean deviations of the ten values of a and b are 0.2432±0.0136 and 0.5336±0.0224, respectively.

Table 1: Station wise values of correlation coefficients.

Station	a	b	c	d	c'	d'	e	f	e'	f'
Dhaka (23°47'N)	0.2336	0.5560	1.5022	-1.8604	0.3882	-0.2351	-0.4703	1.7914	-0.1472	0.7720
Chittagong (22°21'N)	0.2473	0.5168	1.4357	-1.7210	0.3766	-0.2072	-0.4021	1.6456	-0.1206	0.7000
Rajshahi (24°22'N)	0.2300	0.5313	1.5146	-1.8882	0.4011	-0.251	-0.3811	1.6900	-0.1684	0.7984
Khulna (22°47'N)	0.2388	0.5228	1.5288	-1.9024	0.3830	-0.2192	-0.4200	1.7102	-0.1440	0.7444
Barisal (22°43'N)	0.2474	0.5112	1.5630	-1.9684	0.3799	-0.2137	-0.4800	1.8235	-0.1385	0.7421
Sylhet (24°54'N)	0.2569	0.5161	1.5324	-1.9072	0.3760	-0.2169	-0.5464	1.9366	-0.1236	0.7434
Comilla (23°26'N)	0.2315	0.5473	1.4902	-1.8417	0.3934	-0.2367	-0.4839	1.8204	-0.1588	0.7762
Mymensingh (24°44'N)	0.2484	0.5264	1.5695	-1.9986	0.3818	-0.2286	-0.5457	1.9460	-0.1308	0.7469
Bogra (24°51'N)	0.2296	0.5561	1.5115	-1.8683	0.3949	-0.2401	-0.4722	1.7802	-0.1538	0.7680
Rangpur (25°44'N)	0.2296	0.5527	1.4843	-1.8310	0.3893	-0.2351	-0.4851	1.8299	-0.1591	0.7853
Average	0.2393	0.5336	1.5132	-1.8787	0.3864	-0.2283	-0.4686	1.7970	-0.1444	0.7576

Using the average values of the coefficients a and b for ten stations, a linear equation is recommended for the estimation of monthly average global solar radiation in any area over Bangladesh, even where the radiation data is missing or unavailable and is given in the following equation:

$$\frac{G}{G_o} = 0.2393 + 0.5336 \left(\frac{n}{N}\right) \tag{16}$$

Which implies that about 23.93% of extraterrestrial radiation over Bangladesh penetrates the atmosphere on a fully cloudy day ($n=0$) and about 77.29% on a clear sky day respectively. The values of the sum of the regression constants ($a + b$) which represent the maximum clearness index (when $n/N = 1$) are found to be almost equal for these locations. The values of the sum ($a + b$) are obtained as 0.7896, 0.7641, 0.7613, 0.7616, 0.7586, 0.7730, 0.7788, 0.7748, 0.7857 and 0.7823 for Dhaka, Chittagong, Rajshahi, Khulna, Barisal, Sylhet, Comilla, Mymensingh, Bogra and Rangpur, respectively.

The maximum and minimum values of other correlation coefficients c , d , c' , d' , e , f , e' and f' are (1.5695 and 1.4357), (-1.7210 and -1.9986), (0.4011 and 0.376), (-0.2072 and -0.2510), (-0.3811 and -0.5464), (1.946 and 1.6456), (-0.1206 and -0.1684) and (0.7984 and 0.7000) respectively. Their maximum variations due to location are (1.5022±0.0672), (-1.8598±0.1388), (0.3885±0.0125), (-0.2291±0.0219), (-0.4637±0.0826), (1.7958±0.1502), (-0.1445±0.0239) and (0.7492±0.0492) respectively.

Table 2: Station wise values of new correlation coefficients.

Station	c_o	d_o	e_o	f_o
Dhaka (23°47')	1.0703	-1.0392	-0.0576	1.0066
Chittagong (22°21')	1.0188	-0.9042	-0.0060	0.8691
Rajshahi (24°22')	1.1408	-1.1031	-0.0589	1.0089
Khulna (22°47')	1.0829	-1.0095	-0.0751	1.0032
Barisal (22°43')	1.0843	-1.0217	-0.0962	1.0536
Sylhet (24°54')	1.0433	-0.9863	-0.0495	1.0007
Comilla (23°26')	1.0685	-1.0164	-0.0691	1.0084
Mymensingh (24°44')	1.0795	-1.0651	-0.0729	1.0456
Bogra (24°51')	1.0873	-1.6476	-0.0680	0.9982
Rangpur (25°44')	1.0667	-1.0169	-0.0677	1.0163
average	1.0742	-1.0210	-0.0621	1.0010

Table (2) shows the values of the correlation coefficients c_o , d_o , e_o and f_o (eq: 9-10) for ten stations of Bangladesh. The maximum and minimum values of the new correlation coefficients c_o , d_o , e_o and f_o are (1.0843 and 1.0188), (-0.9042 and -1.1031), (-0.0060 and -0.0962) and (-0.8691 and -1.0536) respectively. Their maximum variations due to location are (1.0515±0.0327), (1.0036±0.0994), (-0.0511±0.0451) and (0.9613±0.0922) respectively.

Using the average values of the coefficients in equations (10) to (15), the linear equations recommended for the estimation of monthly average diffuse and direct solar radiation all over Bangladesh are:

$$\frac{D}{G} = 1.5132 - 1.8787 \left(\frac{G}{G_o} \right) \quad (17)$$

$$\frac{D}{G_o} = 0.3864 - 0.2283 \left(\frac{n}{N} \right) \quad (18)$$

$$\frac{D}{G} = 1.0742 - 1.0210 \left(\frac{n}{N} \right) \quad (19)$$

$$\frac{I}{G} = -0.4686 + 1.7973 \left(\frac{G}{G_o} \right) \quad (20)$$

$$\frac{I}{G_o} = -0.1444 + 0.7576 \left(\frac{n}{N} \right) \quad (21)$$

$$\frac{I}{G} = -0.0621 + 1.0010 \left(\frac{n}{N} \right) \quad (22)$$

6. CONCLUSION

The applications of solar energy require information of the availability of solar energy for its optimum use. But the measured radiation data for a long period are not available all over Bangladesh. The correlations proposed for Bangladesh in this study can be used in future for estimation of solar radiations if the meteorological data are available. From the study it is clear that Bangladesh is endowed with sufficient solar radiation throughout the year. Therefore, we can say that the solar energy is the best option of energy supply in Bangladesh if it can be used in a cost effective manner. The correlations proposed for Bangladesh in this study can be used in future for estimation of solar radiations if the meteorological data are collected.

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