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Research Article

Modeling the Incident Solar Radiation of the City of N'Djamena (Chad) by the Capderou Method

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Chad is like many African countries with no meteorological station at the moment to measure solar radiation throughout the country. Thus, theoretical models are used to estimate incident solar radiation. These models are established in correlation form. Our objective was to present a model, which allows the determination of the solar component on two surfaces (horizontal and inclined). This model allowed us to determine, over time, the component of global, direct, and diffuse solar radiation over a period that will cover the different seasons of the year. The calculation is done according to Klein's days over all the months of the year. The hourly results of the global, direct, and diffuse radiation obtained for all the planes going from January to December are satisfactory compared to the results of the other authors quoted in the literature, which give the maximum and minimum values very close to theirs. These results allowed us to validate the applicability of this model in a climate other than the desert climate.

1. Introduction

The knowledge of temporal distribution of solar irradiation on the ground and across the atmosphere is necessary for the modeling of local warming of the atmosphere as well as the planning of energy production systems. Solar energy is abundant, free, and environmentally friendly [1]; unpredictable intermittence is the only drawback. Indeed, solar energy being the most important source of extraterrestrial energy controls most of the atmospheric phenomena that ultimately have an impact on the productivity on land (control of the flow of the rivers, exchange of quantities of materials between the surface and atmosphere). Ground measurements provide accurate information on the estimation of the solar component necessary for the proper design of an energy conversion system [2]. The parameters of the atmosphere and solar irradiation also play a very important role in climate monitoring, environmental control, and human activities [3]. They can be obtained by direct measurement [4], remote sensing or simulation [5], artificial neural network [6–8], and satellite data [9, 10]. It is this lack of information on the solar energy potential of Chad that motivated this work. It is therefore necessary to carry out an investigation on it. Many research studies are being done to develop empirical, theoretical, analytical, and statistical models [11]. These models are correlations depending on several factors (latitude, atmospheric disorder, and seasonal rhythm of the year) that vary according to the localities. Numerous methods have been proposed by different researchers to estimate solar radiation on any given plane; these models take into account astronomical meteorological parameters in situ [12, 13]. The work published by [14] used five models to estimate solar radiation in the south Pakistan regions, based on meteorology and geographic parameters in situ. To evaluate their efficacy, the author calculated the average prediction errors and showed that the efficacy of the model varies with respect to the regions. The works done by [15] used empirical models to estimate the solar component on an inclined plane of 11° (degree). They concluded that only Liu Jordan's model is best suited for predicting solar radiation on an inclined plane from their chosen sites. In their work, [16] believes that the DYB (day of the year-based) Gaussian model is favorable compared to the other models of daily solar radiation; they then enumerate that this model is highly variable to the climatic conditions of the study zone. Hence, [17] developed Pro-Energy algorithms based on a chronologic series to predict sunshine errors during variable hours. Ref. [18] tested many theoretical models to estimate the solar time potential of Nairobi (Kenya) for 10 years, and the result showed that for most of the tested models that estimated global daily monthly average radiation, the Akinoglu and Ecevit model had the best estimation. In Ref. [19], authors have evaluated 12 models of solar radiations based on the meteorologic data, obtained from 21 meteorologic stations in China. The authors showed in their results a satisfied correlation with a statistical value less than 0.01.

Authors like in Ref. [20] included seven statistical Tarpley models calculating horizontal global solar radiation on a horizontal plane based on astronomical and meteorological data from seven stations in Uruguay. The work published by Ref. [16] states that the McClear model accurately estimates global radiation. Researchers such as Ref. [21] used linear regression models to estimate the monthly and annual hourly mean of the global solar radiation of the city of Troyes-Barberey. Then, they compared the models with the data measured over 3 years and finally showed that the regression models used to estimate the global radiation give satisfactory results where the errors between the measured and calculated values are almost negligible.

Some empirical models link the components of solar radiation to major meteorological parameters to estimate global radiation, which has been the subject of much work in the literature. Thus, in this work, Ref. [22] developed a model that allows estimating the global irradiation on a horizontal plane from the insolation duration and relative humidity. Ref. [23] developed a model taking into account six astronomical and meteorological parameters to calculate global radiation. Another model was developed by Ref. [24] to estimate global irradiation, but this one is based on measurements of daily monthly averages, absolute humidity, and duration of insolation. Ref. [25] revealed that solar radiation could also be estimated by means of the correction factor without applying meteorological parameters on locations in which the longitude varies from 70 to 125. Artificial neuron network has recently attracted a lot of attention in the domains of solar energy prediction. Based on this, Ref. [26] used two functions to predict solar radiation on a year by subdividing a year into four seasons. The author was able to show that BPNN and RBFNN network are less performant during a cloudy day and efficient during variable meteorological conditions.

The knowledge of solar resource is a major challenge in Chad due to the unavailability of meteorological station measurements to ensure the collection and popularization of meteorological information in Chad. It becomes imperative to find alternatives for the determination of the solar climate of the city of N'Djamena located in the Sahelian region with geographic coordinates presented in Table 1. The approach advocated here is to find a well-adapted model compatible with our region; this model will allow us to make a numerical modeling of the solar resource to estimate the temporal incident solar radiation component of the city of N'Djamena (Sahelian climate). In order to carry out this investigation in a year, we choose the most appropriate days of the month as recommended by S. A. Klein presented in Table 2, where we calculated the corresponding relative daily insolation. The model chosen to estimate the incident radiation is that of Capderou, which is widely used in Algeria (desert climate) [27, 28]. This model links solar radiation components to major weather parameters, such as sunstroke duration, and astronomical parameters, such as maximum daylight duration, sun declination, earth-to-sun distance variation, and solar irradiation at the limit of the atmosphere.

Table 1: Geographic coordinates of the town of N'Djamena [21].

Position studied	Latitude (°)	Longitude (°)	Altitude (m)	Climate	Albedo
N'Djamena	12.07	15.04	295	Sahelian	0.2

Table 2: Representative day of each month after Klein [22].

Months	Number agenda, X, in the year	Dated
January	17	17^{th} January
February	47	16^{th} February
March	75	16^{th} March
April	105	15^{th} April
May	135	15^{th} May
June	62	11^{th} June
July	198	17^{th} July
August	228	16^{th} August
September	258	15^{th} September
October	288	15^{th} October
November	318	14^{th} November
December	344	10^{th} December

2. Site Location

The region of N'Djamena is located in the Sahelian climate with a total area of 395 km^2. The average value of the normal direct component per hour available on any plan varies from 5 to 6 kWh/m^2 for the favorable month and from 2.5 to 3 kWh/m^2 for the unfavorable month according to a study made on the analysis of estimation of the direct component of solar radiation by Ref. [29]. Table 1 presents the geographic coordinates of the town of N'Djamena.

The choice of the convenient day is made according to the days of Klein's year [30].

3. Calculation of Different Components of Normal Direct Solar Radiation

The calculation of incident solar energy depends on the geometric position of the sun vector with respect to the surface.

The calculation procedure begins by estimating the position of the sun in space and calculating azimuth angles and elevation of the sun. These angles are used to calculate angles of incidence on the study surface.

3.1. Calculation of Solar Declination. It is the angle formed by the direction of the sun with the equatorial plane; it varies during the year between −23.45° and +23.45°. This inclination has as effect the presence of seasons and also is the cause of the longest or shorter hours of light within the seasons and is calculated at any day of the year.

$$d = \frac{180a}{\pi} \sin\left(0.369 \sin\left(\left((n-82)\left(\frac{360}{365}\right) + 2\sin\left[\frac{(n-2)\pi}{180}\left(\frac{360}{365}\right)\right]\right)\left(\frac{\pi}{180}\right)\right)\right). \quad (1)$$

3.2. Horizontal Coordinates. The sun is located with respect to the horizontal plane of the altitude by two angles, the height, and azimuth of the sun.

3.3. Calculation of the Hour Angle. It is the angle formed by the projection of the sun on the equatorial plane at a given moment and the projection of the sun on the same plane at true midday. The hour angle of the sun increases approximately 360° in 24 hours (about 15° per hour); it is measured negatively in the morning and positively in the afternoon.

$$\begin{aligned} H &= \left(\frac{15\pi}{180}(\mathrm{TSV}-12)\right), \\ \mathrm{TSV} &= \mathrm{TL} - \mathrm{DE} + \frac{\mathrm{ET}+4\lambda}{60}, \\ \mathrm{ET} &= 9.87\sin\left(\frac{2n_2\pi}{180}\right) - \frac{7.35n_2\pi}{180} - 1.5\sin\left(\frac{n_2\pi}{180}\right), \end{aligned} \quad (2)$$

with

$$n_2 = \frac{(n-81)360}{365}, \mathrm{DE} = 1. \quad (3)$$

3.4. Calculation of the Height of the Sun. The height of the sun is the angle made by the direction of the sun with its projection on the horizontal plane of the place. The height evolves at each moment of the day according to the following expression:

$$h = \arcsin\left[\cos(d)\cos(\varphi)\cos(H) + \sin(\varphi)\sin(d)\right]. \quad (4)$$

3.5. Calculation of the Angle of Incidence on any Plane. This is the angle between the direction of the sun and the normal of the plane. This angle is determined by the knowledge of the incident ray cosine direction and the normal in cylindrical coordinate.

$$\begin{aligned} \beta &= 15, \\ \omega &= \frac{(90-\beta)\pi}{180}, \\ \alpha &= 0, \\ \cos(i) &= \sin(\alpha)\cos(\omega)\sin(H)\cos(d) + \cos(\alpha) \\ &\quad \times \cos(\omega)\left[\cos(H)\cos(d)\sin(\varphi) - \sin(d)\cos(\varphi)\right] \\ &\quad + \sin(\omega)\cos(H)\cos(d)\cos(\varphi) + \sin(d)\sin(\varphi). \end{aligned} \quad (5)$$

4. Variations of Solar Irradiation Incident on the Ground

Solar radiation is the fraction of solar energy emitted in the form of electromagnetic energy passing through the earth's atmosphere; the latter attenuates part of this radiation by absorption, reflection, or diffusion by particles in suspension, water vapor, ozone content, and atmospheric pressure of solar geometry. Thus, in general, the component of global solar radiation has been defined as the sum of these various components which are the component of direct solar radiation, the component of diffuse radiation, and the component of reflected radiation.

$$I_G = I_D + I_d + I_r. \quad (6)$$

4.1. Capderou Model. The Capderou model is based on an atmospheric disorder balance due to absorption and diffusion caused by the constituents of the atmosphere and can be expressed by the cloud factor to determine the components of solar radiation on a surface. This factor can be obtained from the empirical formula developed by Capderou in 1987 in the Solar Atlas of Algeria in the case of a clear sky.

4.2. Calculation of the Link Atmospheric Factor. The atmosphere is the layer of air consisting mainly of O_2, O_3, H_2O, and CO_2 that surround the planet earth. Solar radiation along its path to the surface is modified as a result of interactions with atmospheric components. This disturbance factor characterizes the atmospheric disturbance due to water vapor, mist, fumes, and dust from a clear or slightly obscured sky. This factor makes it possible to take into account the atmospheric transmission as a function of the altitude of the point and turbidity coefficient, related to the particular microclimate of the site resulting from its development. This factor is the sum of gaseous absorption disorder, aerosol diffusion disorder, and aerosol scattering disorder.

4.2.1. Disorder due to Gas Absorption. This factor can be defined as the atmospheric disorder that depends only on the geoastronomical parameter of the atmosphere and the fixed constituents of the atmosphere: ozone and water vapor are determined from the following equation:

$$\begin{aligned} T_0 &= 2.4 - 0.9\sin(\varphi) + 0.1(2+\sin(\varphi))\mathrm{Ahe} - 0.2z \\ &\quad - (1.22 + 0.14\mathrm{Ahe})(1-\sin(h)), \end{aligned} \quad (7)$$

where

$$\text{Ahe} = \sin\left[\left(\frac{360}{365}\right)(N-121)\left(\frac{\pi}{180}\right)\right]. \quad (8)$$

4.2.2. Turbidity due to Both Gas Absorption (O_2, CO_2, and O_3) and Molecular Diffusion of Rayleigh. The calculation of this parameter is given by

$$T_1 = 0.89^z. \quad (9)$$

4.2.3. Aerosol Diffusion Disorder Calculation. The aerosol diffusion disorder is determined from

$$T_2 = 0.63^z(0.9 + 0.4\text{Ahe}). \quad (10)$$

The link trouble factor calculation is the sum of these three atmospheric components:

$$T_L = T_0 + T_1 + T_2. \quad (11)$$

4.2.4. Calculation of Direct Irradiation on a Horizontal Plane by Clear Sky. The direct solar radiation component represents the solar flux that has directly touched a surface. It depends on the height of the sun and angle of exposure of the wall to the sun at the moment considered, but before entry into the Earth's atmosphere, which is composed of a mixture of dry air and clean (gas), water vapor, and aerosols, the latter attenuates. The following equations below are used to calculate the direct solar radiation incident on any plane at ground level [31]:

$$I_{\text{dir}} = I_0\psi \sin(h) \exp\left(\frac{-T_L}{0.9 + (9.4/0.89^z)\sin(h)}\right), \quad (12)$$

where

$$\psi = 1 + 0.033\cos\left[\left(\frac{360}{365}\right)(n-3)\left(\frac{\pi}{180}\right)\right],\ I_0 = 1367\,\frac{\text{W}}{\text{m}^2}. \quad (13)$$

4.2.5. Calculation of Diffuse Irradiation on a Horizontal Plane by Clear Sky. A diffuse radiation comes from multiple diffractions and reflections from all other directions. This fraction of diffuse radiation depends at every moment on meteorological and astronomical phenomena expressed by

$$I_{\text{dif}} = I_0\psi \exp\left(-1 + 1.06\log\left[\sin(h) + a - \sqrt{a^2+b^2}\right]\right), \quad (14)$$

where

$$a = 1.1,\ b = \log(T_1 - T_0) - 2.8 + 1.02(1-\sin(h))^2. \quad (15)$$

4.2.6. Calculation of the Global Irradiation on a Horizontal Planed Clear Sky. The global radiation on a horizontal plane is the sum of two components on the same horizontal plane given by

$$I_g = I_{\text{dir}} + I_{\text{dif}}. \quad (16)$$

5. Solar Radiation on an Inclined Plane

For any inclined surface at an angle of inclination i with the horizontal plane and the azimuth angle counted from the south direction, the radiation is equal to the product of the radiation on the normal plane and the cosine of the incident angle i.

5.1. Direct Irradiation on an Inclined Clear Sky. For an inclined surface at ground level, the direct irradiation is expressed mathematically as

$$I_{\text{inc}} = I_{\text{nor}}\cos(i), \quad (17)$$

where

$$I_{\text{nor}} = I_0\psi \exp\left(-0.9T_1 + \frac{0.89^z}{9.4\sin(h)}\right). \quad (18)$$

5.2. Calculation of Diffuse Irradiation on a Clear Sky Inclined Plane. To calculate the diffuse radiation, we will use the equations described below:

$$\sigma_d = I_0\psi \exp\left(-2.48\sin(h) + a_1 - \sqrt{a_1^2 + 4b_1^2}\right), \quad (19)$$

where

$$\begin{aligned} a_1 &= 3.1 - 0.4b_1, \\ b_1 &= \log(T_1 - T_0) - 2.28 - 0.5\log(\sin(h)). \end{aligned} \quad (20)$$

(i) The isotropic component corresponds to a sky of uniform luminance:

$$\sigma_i = I_{\text{dif}} - \sigma_d \sin(h) \quad (21)$$

(ii) Component of the circle of the horizon comes from a horizon band of a height of 6°; it seems associated with an accumulation of aerosols in the atmospheric lower layers:

$$\sigma_h = -\frac{0.02\psi I_0 \exp(\sin(h))}{a_2^2 + a_2 b_2 + 1.8}, \quad (22)$$

where

$$a_2 = \log (T_1 - T_0) - 3.1 - \log (\sin (h)),$$
$$b_2 = \exp (0.2 + 1.75 \log [\sin (h)]). \tag{23}$$

5.3. Diffuse Irradiation of the Sky.

$$d_{\mathrm{cl}} = \sigma_d \cos (i) + \frac{\sigma_i}{2}(1 + \sin (\omega)) + \sigma_h \cos (\omega). \tag{24}$$

5.4. Diffuse Soil Irradiation.

$$d_{\mathrm{sol}} = \frac{\sigma_s}{2(1 + \sin (h))}, \tag{25}$$

where

$$\sigma_s = \rho I_{\mathrm{gh}}. \tag{26}$$

5.5. Backscattered.

$$d_{\mathrm{re}} = 0.9(\rho - 0.2) I_{\mathrm{gh}} \exp \left(-\frac{4}{\sqrt{T_1 - T_0}} \right). \tag{27}$$

5.6. Calculation of Diffuse Irradiation Incident on an Inclined Plane. The diffused component received on an inclined plane is divided into three components, the diffused sky, diffusion of the ground, and the backscattered diffusion which is given by

$$I_{\mathrm{din}} = d_{\mathrm{sol}} + d_{\mathrm{cl}} + \frac{d_{\mathrm{re}}}{2}(1 + \sin (\omega)). \tag{28}$$

5.7. Calculation of the Global Irradiation Incident on an Inclined Plane. Global solar radiation is evaluated as the sum of the diffused and direct solar radiation with respect to any angle of incidence.

$$I_{\mathrm{Gin}} = I_{\mathrm{inc}} + I_{\mathrm{din}}. \tag{29}$$

6. Results

The theoretical results of the model thus described are presented in Figures 1(a)–1(l), according to the days of Klein for the horizontal plane, and Figures 2(a)–2(l) for the inclined plane representing the sunshine of the city of N'Djamena. Each panel represents the daily variation of temporal distribution of the incidental illuminations on a plane; in order to distinguish the curves, we chose the global in blue, the direct in green, and the diffusion in red. We noted that the amplitude variations are strong for the months of March, April, and May that characterize the dry season. Also noted is that the minimum values are in July and August, characterizing the rainy season. All curves have the same paces, and the maximum value reached by the global, direct, and diffusion in a horizontal plane for the favorable month exceeds 1000 Wh/m^2 for the total, 900 Wh/m^2 for direct, and 200 Wh/m^2 for diffusion. The same observations were made for the inclined surface. Though Chad does not have a solar radiation measuring station, it is preferable to model the solar radiation incident on a sensor to estimate solar radiation in situ. To validate an estimation of the various components of solar radiation to the ground, it is necessary to compare the calculated values with the measured values. In this investigation, it is not the case because we do not have these data, but we compared our theoretical results with the results of Refs. [28, 32, 33] in Algeria using the same model. In their work, they compared the theoretical results with the experimental one and observed a relatively small error (about 5%). We also compared our results with those of Ref. [29] which are almost the same.

This work enabled us to compare our theoretical results of the model applied to our site with those of the aforementioned authors (theoretical and experimental). We note that our results are almost similar together with the observation made on the minimum amplitude and maximum magnitudes for each month of the year. Thus, it can be deduced from this that the Capderou model can also be applied in a semidesert (Sahelian) climate to estimate the solar radiation incident in the case of a clear sky, giving appreciable results. Our work is, like that of several other writers in the literature, a contribution to the evaluation of the solar field of our country. The different models established by the researchers and the close dependence of coefficients of these relations with the climatic conditions specific to the localities where these relations have been established make the choice of the relevant relation to be used to evaluate the solar field. This model is interesting to carry out the study on the sizing of solar systems (thermal photovoltaic). These results confirm those listed by the director general of SNE (National Electricity Company) at an international forum of renewable energies in N'Djamena in February 2012. According to the director, Chad has enormous potential in solar energy; from north to south, respectively, the sun shines 2750 to 3250 Wh/year which gives on average 4 to 6 kWh/m^2/day. This model can be used as a tool to help size the energy system for a country like Chad which has enormous potential in solar energy which is almost not exploited.

Figure 3 shows us the variation of the maximum of global, direct, and diffuse irradiations for the considered days in both Figures 1 and 2. In this figure, the dashed curves are obtained when we consider a horizontal plane and the continuous curves are obtained when we considered an inclined plane. Globally, we see that the irradiations for the horizontal plane are most important in the middle of the year (April to September), while at the beginning and at the end of the year, irradiations are more important for the inclined plane.

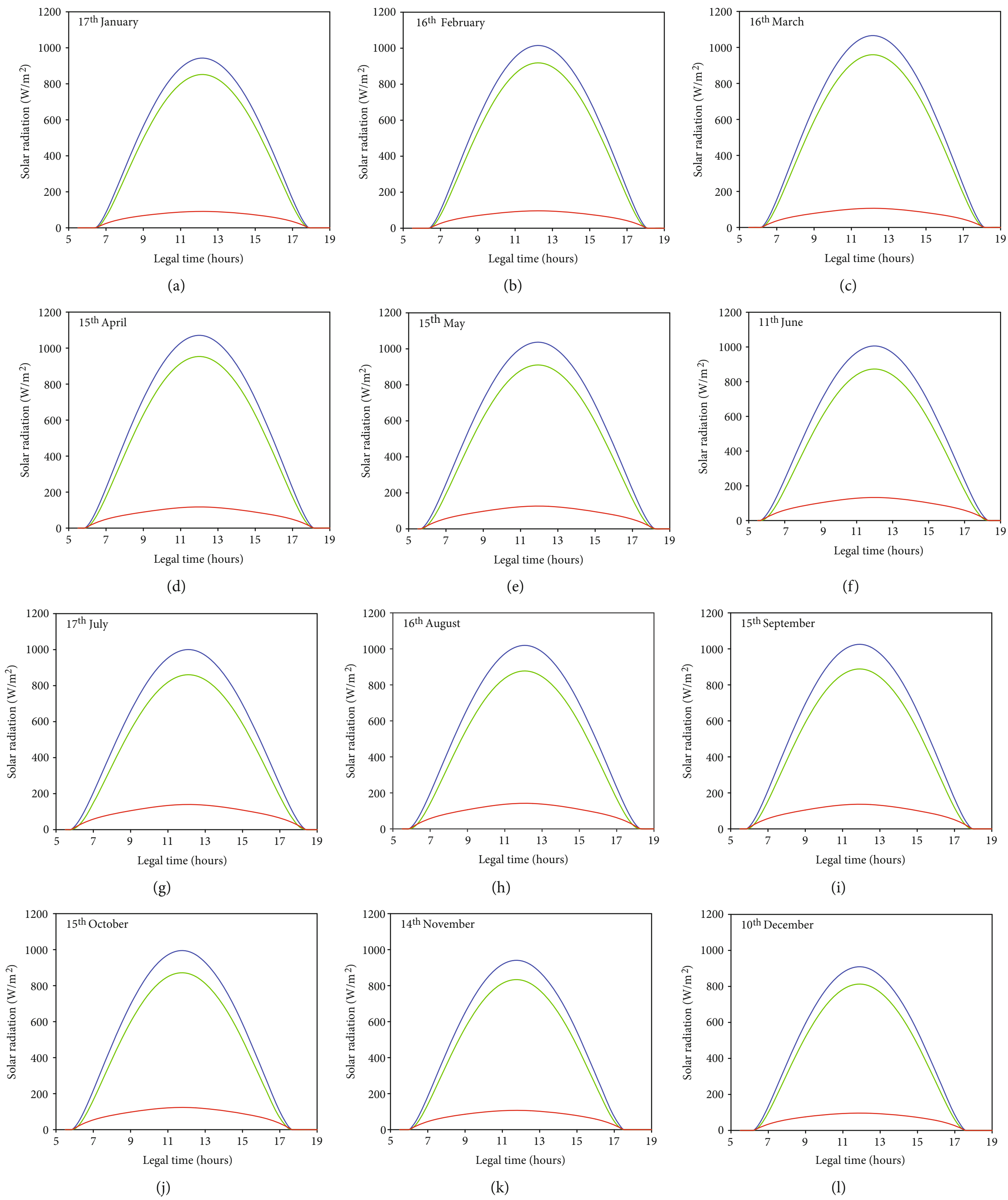

FIGURE 1: Temporal distribution of incident illuminations on a horizontal plane.

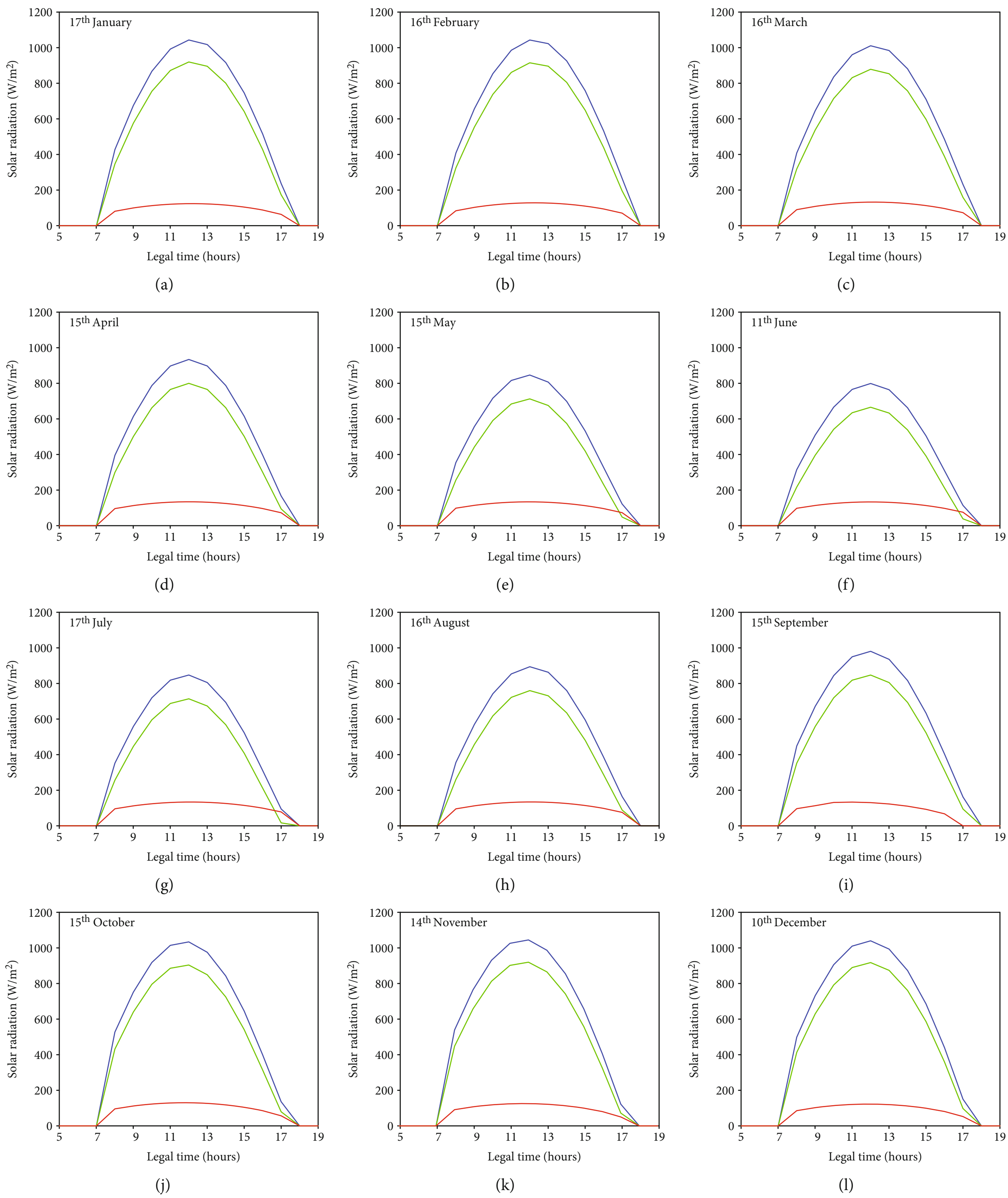

Figure 2: Temporal distribution of incident shifts on an inclined plane.

7. Conclusion

The Capderou model presented in this article has made it possible to evaluate the component of solar radiation (global, direct, and diffusion) on horizontal and inclined planes of solar irradiance in the city of N'Djamena. This model is implemented by Capderou using meteorological and astronomical data often based on atmospheric disturbances due to absorption by gases and diffusion and absorption by solid particles (aerosols) and liquid (clouds). A comparison is made with the results of the other authors (theoretical, experimental, and satellite). Our theoretical

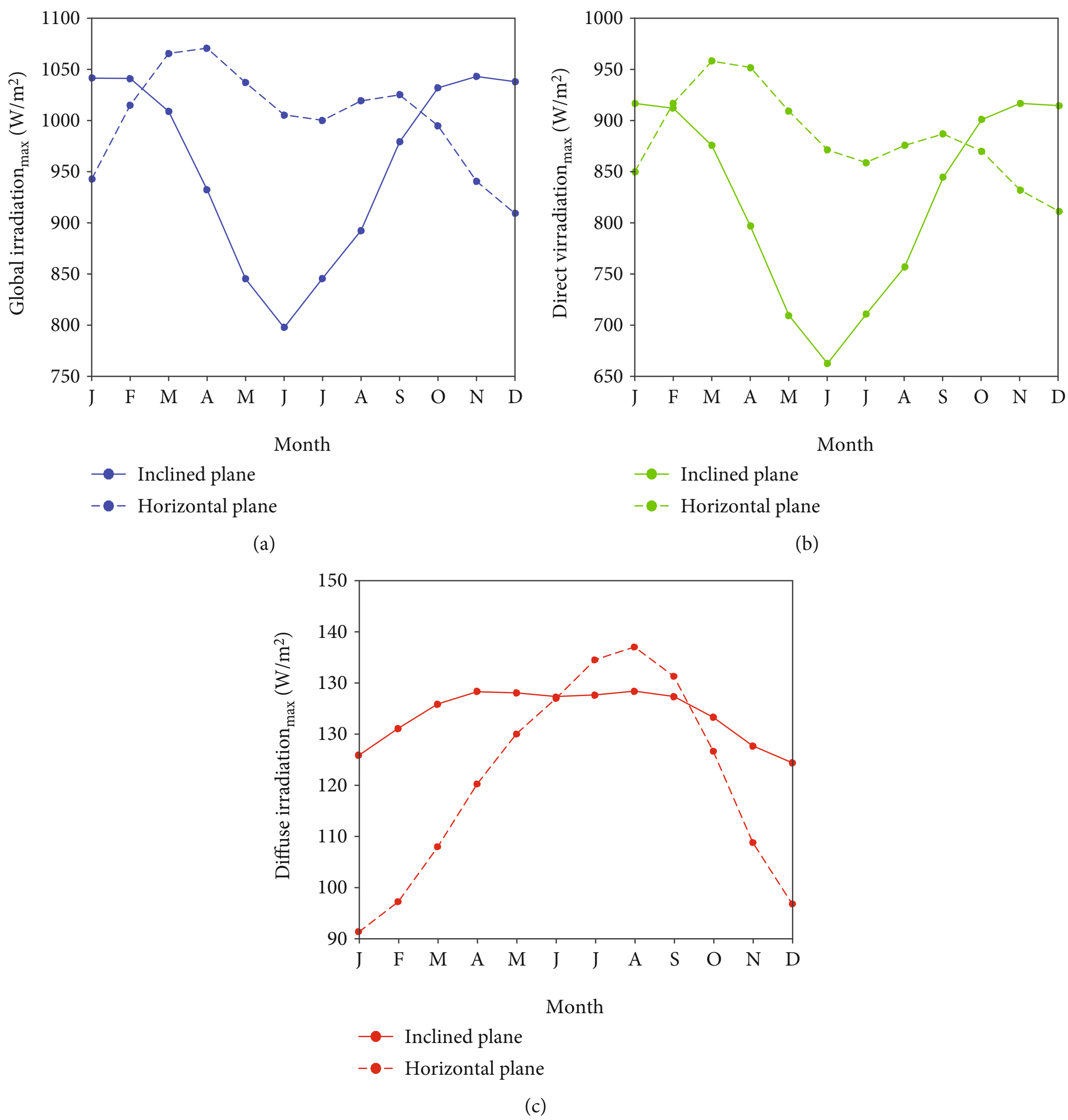

Figure 3: Maximum of global (in (a)), direct (in (b)), and diffuse (in (c)) irradiations during the year for both inclined and horizontal planes.

results of calculation thus obtained are satisfactory for all the months of the year, and consequently, we can say that the model of Capderou can also be applied to a type of semidesert climate.

Nomenclature

d: Solar declination
H: Hour angle
TSV: True solar time
TL: Local time
ET: Correction of the equation of time
Z: Altitude of place
DE: Time difference from the meridian
ω: Hour angle
T_0: Disturbance factor due to gaseous absorption (ozone and water vapor)
T_2: Angstrom trouble factor
I_{dr}: Horizontal direct radiation
d_{sl}: Diffuse ground
d: Backscatter
I_{Din}: Direct inclined
I_{din}: Inclined diffusion
h: Height of the sun
φ: Latitude of the location
i: Angle of incidence
β: Plane inclination with respect to the horizontal
α: Azimuth of the plane
ρ: Albedo
ψ: Earth-sun correction
T_L: Link trouble factor
T_1: Disturbance factor due to absorption by atmospheric gases (O_2, CO_2, O_3, and Rayleigh scattering)
I_g: Global horizontal radiation

I_{dif}: Horizontal diffuse radiation
d_{cl}: Diffusion from the sky
I_{Gin}: Inclined global
I_0: Solar constant.

Data Availability

The data we used are just geographique coordinates of the town of N'Djamena: latitude, longitude, altitude, and albedo as found in Table 1. Based on these, we carried out our calculations before doing numerical simulations. They are found and accessible at the general direction meteorological center of N'Djamena.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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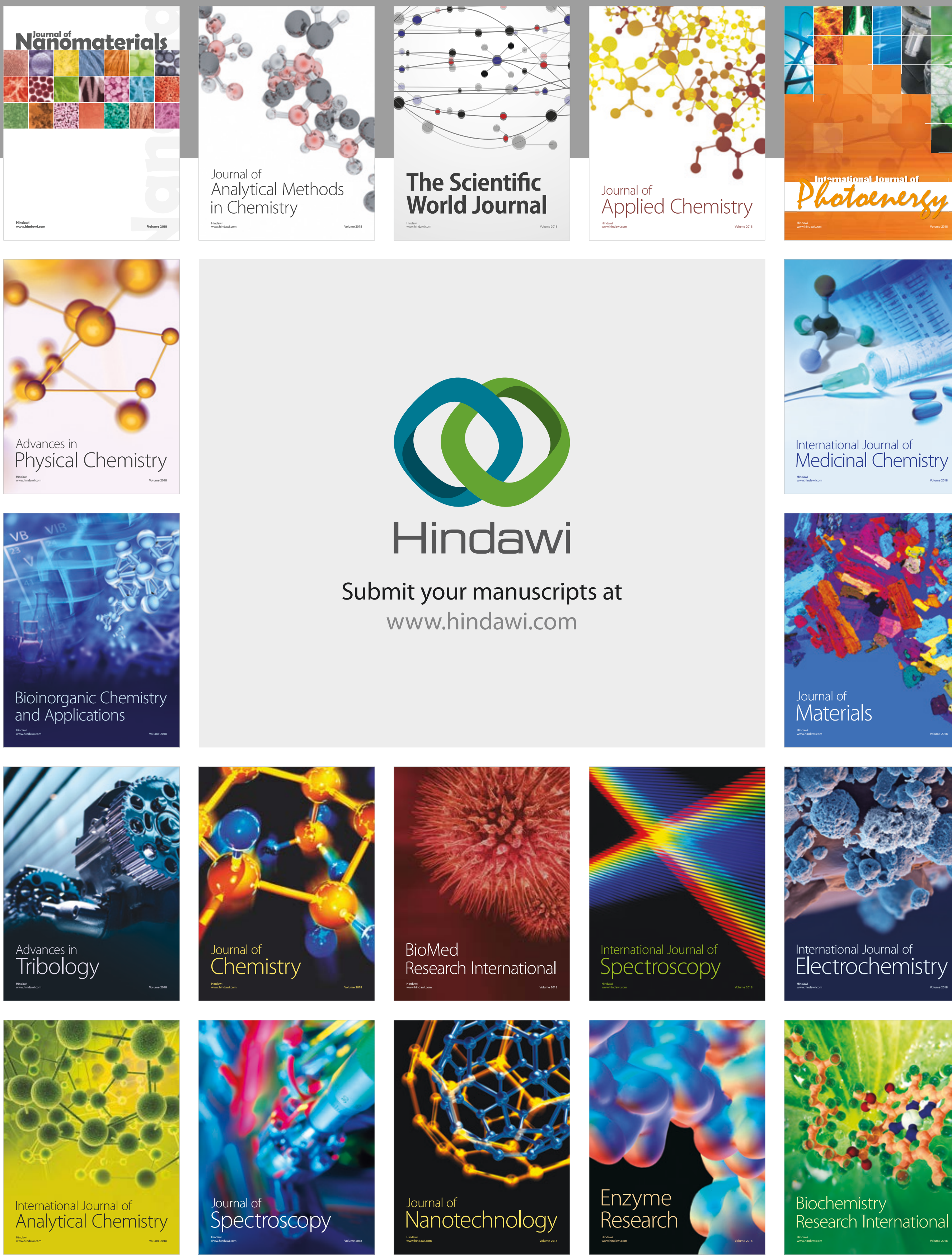

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