Improving of global solar radiation forecast by comparing other meteorological parameter models with sunshine duration models

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Abstract
The aim of this study is to compare sunshine duration-based models and the other meteorological parameter-based models and to develop new forecasting models. The estimation and comparison of global solar radiation has been made by using twenty-four empirical models including three new models for different location named Arbil, Dohuk, and Sulaimania of Northern Iraq. The reason of using these different locations is to test the accuracy of the other meteorological parameter models by comparing the sunshine duration models for different region. Mostly common statistical error values are used to evaluate the performance of the estimation models and to identify the models that will give the closest results to the actual values. According to the results, it was seen that the models based on other meteorological parameters have better predictions than the models based on the sunshine duration. While the \( R^2 \) value of the best models depending on the sunshine duration ranged from 0.97 to 0.99, the \( R^2 \) values of the best models of other meteorological parameters are above 0.99. Furthermore, it is observed that the new proposed models provide better estimates of global solar radiation at different locations than all models used in this study.

Keywords Prediction · Solar energy · Solar radiation · Sunshine duration

Introduction
Global solar radiation coming to earth has an important place in the world solar system. The information on this subject has an inevitable significance in terms of agriculture, environment, and energy.

Today, solar radiation and renewable energy are imperative energy technologies, which can assist handling the issues climate change. When the use of renewable energy sources are increased, the results of these are that the reduction of CO\(_2\) emissions, the cut of local air contamination, the creation of high-value occupations, and diminish of the dependency of a country on importations of fossil energy. When the solar energy is compared with other fossil-based energy sources, it can be seen that the solar energy, an important source of energy, does not harm the environment and has no effect on global warming (Jiandong et al. 2015). Solar radiation data is especially important for manufactures, designers of solar energy systems, architects, and agriculturists. But solar radiation measurements have been made in very few places around the world. There are several reasons for this such as installation cost, maintenance, and calibration (Hunt et al. 1998). But, the measurement of solar radiation can only be measured in various regions of developing countries.

Since solar radiation measurements were not made for each region on the earth, many models have been developed for the regions where there were no measuring stations. The development of global solar radiation models is increasing day by day. However, these models may give different results in different regions. Therefore, it is necessary to develop models for each region as much as possible. Therefore, a study was conducted to develop solar radiation models for India (Makade et al. 2021). In the absence of solar radiation measurement data, several models have been developed to obtain solar radiation more easily. There are several empirical methods used to estimate global solar radiation, which are expressed as an empirical function of one of the such parameters: sunshine hours, cloudiness, and meteorological parameters.
parameters. Therefore, solar radiation prediction models for unmeasured regions of solar energy have been developed to facilitate the use of solar radiation for these regions (Elagib and Mansell 2000). Furthermore, various methods such as empirical methods (Chukwuindu 2017; Jahania et al. 2017), artificial intelligence methods (Peng et al. 2020; Benghanem et al. 2009), and based on satellite data (Janjai et al. 2011; Baemehr and Sabetghadam 2021) have been developed to eliminate the lack of solar radiation measurement. The first empirical model was found by Angstrom (1924), who derived a linear relationship between the ratio of average daily global radiation to the corresponding value on a completely clear day at a given location and the ratio of average daily sunshine duration to the maximum possible sunshine duration (Paulescu et al. 2008). However, the solar radiation under clear sky conditions involves some ambiguity. Thus, Prescott (1940) suggested replacing it for the extraterrestrial radiation on a horizontal surface, an amount that has also the advantage of being estimated theoretically (Manzano et al. 2015). In the literature, many models have tried to estimate the solar radiation on the earth using parameters such as ambient temperature (Fan et al. 2018; Tao et al. 2021), sunshine duration (Chen and Li 2013; Li et al. 2011; Suerhcke et al. 2013), cloud cover (Ehnhberg and Bollen 2005), relative humidity (Liu et al. 2017; Su et al. 2022), and rainfall (Liu and Scott 2001). For global solar radiation calculations, temperature-dependent models can be measured easily, so they are very practical and interesting. However, due to the fact that only temperature-dependent models are not sufficient in humid regions, higher-quality models have been developed by taking into account relative humidity values (Rehman and Mohandes 2008). Hasan et al. (2016) developed new models depending on the outdoor temperature as an alternative to sunshine duration models generally used in solar radiation estimation since solar radiation measurement is not possible in all locations on the earth. Furthermore, some models based on measurement data for various time intervals have been developed to further improve the accuracy (Chen et al. 2004; Zhou et al. 2018; Yao et al. 2014). Also, different models have been developed in the literature by using different regression equations such as logarithmic, exponential, linear, and quadratic depending on sunshine duration (Almorox and Hontoria 2004; Ampratwum and Dorvlo 1999).

Meteorological stations generally measure atmospheric data such as temperature and humidity and can be easily accessed at each station. However, it may not be possible to find the data depending on the sunshine duration at all stations (Bakirci 2009b; El-Metwally 2005). In addition, solar radiation is affected by many physical factors such as albedo, air molecules scattering, water vapor content, dust scattering, and other atmospheric components until it reaches the earth. Therefore, these factors have negative effects on the measurement of sunshine duration. The challenge nowadays is to develop models that are an important issue for solar applications, achieving good performances and significantly reducing forecast error rates at different time scales. Some researchers have examined the sunshine duration and temperature-based models separately and compared these models with each other. As a result of these studies, they showed that the temperature-dependent model results performed better than sunshine duration-based models (Liu et al. 2009; Isikwue et al. 2013). In addition, relative humidity, geographic location, air temperature-based models recorded in the vast majority of meteorological stations are applicable models, and in some studies (Allen 1997; Li et al. 2013), these meteorological data have been used in solar radiation estimation models.

In this context, some of the other meteorological parameter-based models and sunshine duration-based models taken from the literature were examined and compared with each other. Furthermore, this study presents new other meteorological-based models for estimating global solar radiation as alternatives to the widely used sunshine-based models owing to it performs closer to real results.

Although the oil production in the Northern Iraq is very high, it is a less developed region. In this area, the use of petroleum products in domestic and industrial electricity generation causes serious environmental pollution and causes a significant increase in the level of CO2 (Birol 2017; Al-Douri and Abed 2016). Nowadays, renewable energy sources, especially solar energy, are increasingly entering our lives, and solar radiation data is needed due to increasing use of solar energy systems. The use of solar energy with high energy potential is very important to reduce the level of harmful gases in this region. But there is not much work done in this area about solar radiation data.

The aim of the presented work is that prediction of global solar radiation is generally done by developing models based on sunshine duration in the literature. However, it is known that many parameters such as temperature, humidity, and declination angle are effective in solar radiation coming to earth. However, so far there have been few studies by producing equations that incorporate too many parameters such as temperature, humidity, altitude, and sunshine duration. Therefore, this study, unlike the previous studies, is to develop new models by considering many parameters affecting the solar radiation coming to the earth. In addition, the models developed based on many parameters were compared with the models used in the literature for the most commonly used sunshine duration, and which model would yield more realistic results were investigated. This study was conducted in the case of Northern Iraq. The presented work is to make the system designs that connected to solar energy by using the solar radiation-based models instead of reliable missing data in the region of Northern Iraq and similar climate.
The main objectives of this study are listed below.

- To examine the applicability of current solar radiation models depending on sunshine duration and other meteorological parameters over the Northern Iraq
- To compare sunshine duration models with the other meteorological parameter models for global solar radiation prediction models
- To develop new best general models by utilizing many data such as sunshine duration, maximum temperature, minimum temperature, relative humidity, and declination angle for estimating monthly global solar radiation
- To compare the newly developed models in the literature and to reveal the best model of these models as a result of statistical evaluation
- Finally, to evaluate the applicability of these models for three cities in different latitude, longitude, and geographic regions

The temperature, humidity, latitude and longitude, and declination angle used in this study can be taken from at any meteorological station in the world. Therefore, this study is not only a local study, but can also be used globally. So, the global solar radiation estimation on horizontal surface based on sunshine duration and the other meteorological model of this region has been made by using twenty-four empirical models including three new models. Furthermore, the best approach model in the estimation of global solar radiation on the horizontal surface for the Dohuk, Arbil, and Sulaimania in the Northern Iraq has been evaluated. Besides, statistical indicators are used to show performance analysis of the models.

Material and methods

In this study, the average daily global solar radiation data were received from the General Directorate of Meteorology and Seismology Forecasting Department and on Ministry of Agriculture and Water Resources in Arbil. Several parameters such as sunshine hours, relative humidity, and maximum and minimum temperature were assessed. As measurements of sunshine duration are easy, it is common to find data on sunshine duration. In this work, the sunshine duration sensor model: 217078 have been used as shown in Fig. 1a. For measuring global solar radiation, the Pyranometer model QMS101 has been used, and it is easily installed on the sensor support arm as shown in Fig. 1b. The technical information of Pyranometer model QMS101 is clarified in Table 1.

The data logger model QML201 is a complete AWS logger designed on one printed board only. This board contains a 32-bit Motorola CPU for data processing and 10
differential (20 single ended) analog sensor inputs (these can also be used as digital inputs). Moreover, there are two frequency sensor interfaces, a 16-bit A/D converter, 1.7 Mb of secure Flash memory for data logging, as well as excitation power supply for sensors and charger for the internal backup battery. The last mentioned is not needed in the systems where a backup battery with higher capacity is used. The board uses the latest SMD (Surface Mount Device) technology and is conformal coated for improved protection in high humidity. Each sensor input has a varistor (VDR) protection against induced transients. The serial line connections, that is, RS-232 labeled as COM0 and RS-485 labeled as COM1, have two level ESD protection circuits with VDRs directly at input pins, as shown in Fig. 1d.

**Studied region and data collection**

The common way for estimating the global solar radiation is to set several pyranometer device in a location to record data. In the current research, the evaluation of various global solar radiation models for three city of Iraq was investigated. The global solar radiation on a horizontal surface of Arbil, Dohuk, and Sulaimania was estimated using meteorological data. The reason for choosing three different regions in this study is due to different temperature and latitude and longitude values for every region. In addition, the reason for using these different locations is to test the accuracy of the other meteorological parameter models for different regions by comparing the sunshine duration models. The dispersion of the stations used in this study is illustrated in Fig. 2. In addition, the geographic information about the latitude, longitude, and altitude of each station is given in Table 2.

Figure 3 shows the monthly averages of meteorological data belonging to the cities of Arbil, Dohuk, and Sulaimania. For each city, different results are obtained when looking at meteorological data such as solar radiation, temperature, and humidity.

Among the measured results, the highest monthly average solar radiation was measured at Arbil station with a value of 30.4670 MJ/m². For Dohuk and Sulaimania, these values were measured as 27.9941 MJ/m² and 26.6617 MJ/m², respectively. When looking at in terms of the sunshine duration as shown in Fig. 3, it is seen that there is a

| Table 1 Technical information of Pyranometer model QMS101 |
|-----------------------------|
| **Name** | Specification |
| Sensitivity | 100 µV/W/m² (nominal) |
| Spectral range | 0.4 … 1.1 micron |
| Response time | < 1 s |
| Range | 2000 W/m² |
| Temperature dependence | +0.15% /°C |
| Non-stability | < +2% per year |
| Non-linearity | <1% up to 1000 W/m² |
| Operating temperature | -30 … +70 °C |

**Table 2 Geographic locations of the studied region**

| Station     | Location | Longitude | Latitude  | Altitude |
|-------------|----------|-----------|-----------|----------|
| Arbil       | Central  | 43.66     | 36.2688   | 254      |
| Dohuk       | North    | 43.85     | 36.7314   | 636      |
| Sulaimania  | South    | 45.96     | 35.2015   | 621      |

![Fig. 2 The map of the selected locations](image-url)
difference for the sunshine duration for each of the three cities. As shown in Fig. 3, sunshine duration was available for each city. While sunshine duration is reached between 9 and 11 h for Arbil province, it is seen more between 6 and 8 h for Dohuk province. At the same time, the sunshine duration in Dohuk province is reaching up to 14 h. For Sulaimania the sunshine duration reaches up to 12 h.

While the highest value in terms of solar radiation was measured in Arbil, the highest value for sunshine duration was measured in Dohuk with 11.9447 h. In addition, the maximum, minimum, and average values of the ambient air temperature, which is one of the most important meteorological parameters, were also measured. According to the measurement results, the maximum temperature measurement
was observed in Arbil with 44.7016 °C. At the same time, the measured maximum temperature values for Dohuk and Sulaimanaya are above 40 °C. Relative humidity values are one of the parameters that affect the solar radiation coming to the earth. The relative humidity for this region can be as low as 12% in summer. The relative humidity for the studied area varies from approximately 12 to 76% throughout the year. In order to approach the actual measurement results during modeling, the measurement of all the parameters mentioned above and their inclusion in the models become very important.

Analysis methods for modeling of global solar radiation

The simple model used to predict monthly average daily global solar radiation on horizontal surface are based on the Angstrom-Prescott equation,

$$\frac{H}{H_c} = a + b \left( \frac{S}{S_s} \right)$$  \hspace{1cm} (1)

($H$) is the monthly average daily global radiation on horizontal surface (MJ/m² day).

($H_c$) is the monthly average daily extraterrestrial irradiation (MJ/m² day) that should be calculated from the following equation (Duffie and Beckman 2013),

$$H_c = \frac{24}{\pi} \int \left[ 1 + 0.033 \cos \left( \frac{360}{365} n \right) \right] \left[ \sin w \cos \phi \cos \delta + w \sin \phi \sin \delta \right]$$  \hspace{1cm} (2)

where ($I_o$) is the solar constant, ($\phi$) is the latitude, ($\delta$) is the solar declination, ($\omega_s$) is the mean sunrise hour angle, ($S$) is the monthly average daily hours of bright sunshine, and ($S_s$) is the monthly average daily length where calculated by following equation (Duffie and Beckman 2013),

$$\delta = 23.45 \sin \left( \frac{360}{365} (384+ n) \right)$$  \hspace{1cm} (3)

$$w = \cos^{-1} \tan \phi \cos \delta$$  \hspace{1cm} (4)

$$S_s = \frac{2}{15} w_s$$  \hspace{1cm} (5)

Selection of empirical model

Two different types of empirical models were used in this study. One of them is models that only depend on the sunshine duration. Another is the models which depend on other meteorological parameters, including various meteorological parameters. In this study, 24 models were evaluated.

Among these models, the first 11 models are models that only depend on the sunshine duration. These models are often used in the literature, and the accuracy rates are high models. Examined and, developed models for this work are presented in Table 3.

The remaining 13 models are related to other meteorological parameters. Also, three new developed models are included in these type models. In addition, different regression equations such as linear, exponential, cubic, quadratic, and exponential have been used to increase accuracy of these models.

The selected twenty-one models are the ones accepted in the literature and applied to the regions with different climatic conditions.

Statistical performance validation

For evaluating the models, different statistical indicators, such as the mean bias error (MBE), mean percentage error (MPE), root mean square error (RMSE), coefficient of determination ($R^2$), and measures of the conformity of the regression model, were used, and these were presented in the following equations:

$$\text{MPE(\%)} = \frac{1}{X} \sum_{i=1}^{X} \left( \frac{H_c - H_m}{H_m} \right) \times 100$$  \hspace{1cm} (6)

$$\text{MBE} = \frac{1}{X} \sum_{i=1}^{X} (H_c - H_m)$$  \hspace{1cm} (7)

$$\text{RMSE} = \sqrt{\frac{1}{X} \sum_{i=1}^{X} (H_c - H_m)^2}$$  \hspace{1cm} (8)

$$R^2 = \frac{\sum_{i=1}^{X} (H_c - H_{\text{cavg}}) \cdot (H_m - H_{\text{mavg}})}{\sqrt{\frac{1}{X} \sum_{i=1}^{X} (H_c - H_{\text{cavg}})^2} \cdot \sqrt{\frac{1}{X} \sum_{i=1}^{X} (H_m - H_{\text{mavg}})^2}}$$  \hspace{1cm} (9)

where $H_c$ and $H_m$ represent the calculated and the measured solar radiation, respectively, and $x$ is the total number of observations. The value of $H_{\text{cavg}}$ and $H_{\text{mavg}}$ are the average of the calculated and measured solar radiation, respectively.

Results and discussion

The constant regression coefficients of the equations used in the application of solar radiation prediction models in any region take different values for each studied region. Therefore, using the correct constant regression coefficients in the application of the equations gives closer results to the actual
values. Although there are many similar studies in the literature, the results of these studies may vary for each region. Therefore, regression coefficients of the models taken in the literature are very important. In this study, sunshine duration models and the other meteorological parameter model regression coefficients that are a, b, c, and d shown in Tables 4 and 5 were developed for 24 models and applied to different regions. These models were widely utilized in the literature, and regression coefficients for every model were found for each province in the studied region. It was observed that the regression coefficients found is different for each model and every city. This difference is due to various factors such as climatic conditions, geographical conditions, latitude, longitude, and altitude. Statistical methods such as MPE, RMSE, MBE, and $R^2$ were used for the correctness of the models.

Various statistical parameters are used in order to determine the accuracy of the solar radiation models. Although many statistical error values have been calculated in most of the previous studies, the performance of the models can be ranked according to $R^2$ indicator (Hassan et al. 2016; El Mghouchi 2016; Besharat et al. 2013). The $R^2$ value is one of the important statistical indicators. Table 4 also gives $R^2$ values for each city. According to this table, eleven sunshine duration models were evaluated for three different cities based on this parameter. As a result of the evaluations, each model provides different performance value for each city. For Arbil province, H11 shows the best performance with 0.9853 and 0.9823 respectively. This study consists of two categories. The first one is the calculation based on the sunshine duration and the another one based on the other meteorological parameters. According to the other meteorological parameters, the statistical values of the models and the constant coefficients of the equations are given in Table 5. A total of thirteen model based on the other meteorological parameters were used for each city. In these models, three new models were developed and applied to three different locations. The monthly global solar radiation values for every models and cities are compared based on statistical parameters. It is observed that there is a difference

| No | Source | Model type | Equation |
|----|--------|------------|----------|
| H1 | Angstrom (1924) and Prescott (1940) | Linear | $H/H_s = a + b(S/S_s)$ |
| H2 | Ogelman et al. (1984) | Quadratic | $H/H_s = a + b(S/S_s) + c(S/S_s)^2$ |
| H3 | Samuel (1991) | Cubic | $H/H_s = a + b(S/S_s) + c(S/S_s)^2 + d(S/S_s)^3$ |
| H4 | Ampratwum and Dorvol (1999) | Linear | $H/H_s = a + b\log(S/S_s)$ |
| H5 | Sen (2007) | Power | $H/H_s = a + b(S/S_s)\frac{1}{T}$ |
| H6 | Bakirci (2009a, b) | Power | $H/H_s = a(S/S_s)^b$ |
| H7 | Elagib and Mansell (2000) | Exponential | $H/H_s = aexp[b(S/S_s)]$ |
| H8 | Almorox and Hontoria (2004) | Exponential | $H/H_s = a + bexp(S/S_s)$ |
| H9 | Bakirci (2009a, b) | Linear-exponential | $H/H_s = a + b(S/S_s) + cexp(S/S_s)$ |
| H10 | Newland (1988) | Linear-logarithmic | $H/H_s = a + b(S/S_s) + clnp(S/S_s)$ |
| H11 | Togrul and Onat (1999) | Linear | $H = a + b\delta + c(S/S_s)$ |
| H12 | El-Sebai et al. (2009) | Linear | $H/H_s = a + b(S/S_s) + c\delta$ |
| H13 | Togrul and Onat (1999) | Trigonometric | $H/Z = a + b(S/S_s)$ |
| H14 | Togrul and Onat (1999) | Linear-trigonometric | $H = a + b(S/S_s) + c\sin(\delta) + d\delta^2$ |
| H15 | Glower and McGulloch (1958) | Trigonometric | $H/Z = acos(p + b(S/S_s))$ |
| H16 | Togrul and Onat, Model (1999) | Linear-trigonometric | $H/Z = a + b(Z) + c\sin(\delta) + d\delta^2$ |
| H17 | New model | Linear-trigonometric | $H/Z = a + b(Z) + c\sin(\delta)$ |
| H18 | Chen et al. (2004) | Logarithmic-power | $H/Z = a\ln(T_{max}/T_{min}) + b(S/S_s)^2 + d(T_{max} - T_{min})^{0.5}$ |
| H19 | Annandale et al. (2002) | Power | $H/Z = a + b(S/S_s) + c\log(T_{max}/T_{min})$ |
| H20 | Swartman and Ogunlade (1967) | Linear | $H/Z = a + b(S/S_s) + c\sin(\delta)$ |
| H21 | El-Sebai et al. (2009) | Linear | $H/Z = a + b\delta + c\sin(\delta)$ |
| H22 | New model | Linear-power | $H/Z = a + b(S/S_s) + c\delta + d\delta^2$ |
| H23 | Abdalla (1994) | Linear | $H/Z = a + b(S/S_s) + c\delta + d\delta^2$ |
| H24 | New model | Linear-logarithmic | $H/Z = a + b\ln(\delta) + c(T_{max} + T_{min}) + d\delta$ |
between two type models. At the same time, the newly developed models that depend on the other meteorological parameters show a better performance than the models depending on the sunshine duration. Furthermore, the models giving the best results are found for every city. Detailed explanations of the work done for each city were explained in the following subheadings.

The detailed analysis between the sunshine duration and the other meteorological parameter models is given in Table 5 according to the $R^2$ values. One of the main aims of this study is to compare the models based on the sunshine duration and other meteorological parameters with each other. In this study, it was applied in different places to reveal the difference between two different type models more clearly. Table 6 shows the first three models for different cities, which show the best results, depending on the sunshine duration and other meteorological parameters among twenty-four models used in this study. When looking at this table, it is seen that the models depending on other meteorological parameters generally perform much better than the models depending on the sunshine duration. While the $R^2$ value of the best models depending on the sunshine duration ranged from 0.97 to 0.99, the $R^2$ values of the best models of other meteorological parameters are above 0.99. For Arbil, the H11 model shows the best performance in sunshine duration models with 0.9903. But, for the same city, the best performance in the other meteorological parameters is indicated by the H16 model with a value of 0.9971. While the H5 model shows the best performance according to the sunshine

### Table 4 Results of sunshine duration models with the statistical indicators and correlation coefficient

| Station | Models | $R^2$ | MBE | RMSE | MPE | a  | b  | c  | d  | Rank |
|---------|--------|------|-----|------|-----|----|----|----|----|------|
| Arbil   | H1     | 0.9654 | -0.3377 | 1.8079 | -0.6341 | 0.1997 | 0.6431 | - | - | 9    |
|         | H2     | 0.9767 | -0.2718 | 1.528 | -0.5007 | -1.0201 | 4.2329 | -2.6018 | - | 5    |
|         | H3     | 0.9769 | -0.2254 | 1.4264 | -0.5349 | 10.080 | -45.61 | 71.116 | -35.91 | 4    |
|         | H4     | 0.9874 | -0.5909 | 1.9739 | -0.5951 | 0.7112 | 0.4481 | - | - | 2    |
|         | H5     | 0.9701 | -0.3311 | 1.6388 | -0.0533 | 0.8261 | -0.0655 | -2.6018 | - | 7    |
|         | H6     | 0.9637 | -0.3729 | 1.818 | -0.293 | 0.8411 | 0.7245 | - | - | 10   |
|         | H7     | 0.9607 | -0.3927 | 1.8849 | -0.3171 | 0.3122 | 1.0386 | - | - | 11   |
|         | H8     | 0.9668 | -0.3374 | 1.8325 | -0.8611 | 0.0448 | 0.2995 | - | - | 8    |
|         | H9     | 0.9772 | -0.2775 | 1.5208 | -0.4982 | 1.8509 | 5.9538 | -2.6567 | - | 3    |
|         | H10    | 0.9734 | -0.3446 | 1.5346 | 0.3703 | 4.5573 | -3.9330 | 7.3225 | - | 6    |
|         | H11    | 0.9903 | -0.0428 | 0.7767 | 0.6737 | -7.3271 | 0.8605 | 1.9753 | - | 1    |
| Dohuk   | H1     | 0.9837 | -0.1226 | 1.0359 | -0.2612 | 0.1332 | 0.6263 | - | - | 8    |
|         | H2     | 0.9847 | -0.1129 | 1.0076 | -0.2437 | -0.1269 | 1.3691 | -0.5157 | - | 3    |
|         | H3     | 0.9850 | -0.1062 | 1.0029 | -0.2882 | -2.4496 | 11.583 | -15.289 | 7.0219 | 2    |
|         | H4     | 0.9841 | 0.1512 | 1.0152 | -0.3541 | 0.7393 | 1.0521 | - | - | 7    |
|         | H5     | 0.9853 | 0.0674 | 0.9701 | -1.3529 | 1.4685 | -0.7255 | -0.5157 | - | 1    |
|         | H6     | 0.9844 | 0.3393 | 1.0201 | -3.0226 | 0.7701 | 0.7532 | - | - | 4    |
|         | H7     | 0.9827 | -0.1496 | 1.0686 | -0.1368 | 0.2658 | 1.0803 | - | - | 9    |
|         | H8     | 0.9825 | -0.1526 | 1.0674 | -0.0674 | -0.053 | 0.3075 | - | - | 10   |
|         | H9     | 0.9843 | -0.1508 | 1.009 | 0.1386 | 0.5123 | 2.0282 | -0.6717 | - | 5    |
|         | H10    | 0.9843 | -0.1501 | 1.0068 | 0.1442 | 1.0481 | -0.3207 | 1.5777 | - | 6    |
|         | H11    | 0.9781 | -0.1199 | 1.1218 | 1.8732 | -12.759 | 0.6683 | 14.877 | - | 11   |
| Sulaimania | H1     | 0.9799 | -0.1469 | 1.1394 | -0.4011 | 0.1987 | 0.5038 | - | - | 2    |
|         | H2     | 0.9787 | -0.1518 | 1.1471 | -0.3952 | 0.2519 | 0.3418 | 0.1188 | - | 5    |
|         | H3     | 0.9823 | -0.1291 | 1.0229 | -0.3389 | 1.8074 | -7.0923 | 11.6310 | -5.7864 | 1    |
|         | H4     | 0.9786 | -0.1897 | 1.1526 | 0.0142 | 0.6770 | 0.7843 | - | - | 6    |
|         | H5     | 0.9776 | -0.1901 | 1.1494 | 0.0252 | -2.3455 | 3.0258 | 0.1188 | - | 9    |
|         | H6     | 0.9798 | -0.192 | 1.1604 | 1.1604 | 0.6864 | 0.6096 | - | - | 3    |
|         | H7     | 0.9782 | -0.1885 | 1.1692 | -0.2159 | 0.2854 | 0.9279 | - | - | 7    |
|         | H8     | 0.9787 | -0.2032 | 1.1719 | 0.0312 | 0.0184 | 0.2616 | - | - | 4    |
|         | H9     | 0.9778 | -0.1979 | 1.1536 | 0.0549 | 0.1346 | 0.3686 | 0.0772 | - | 8    |
|         | H10    | 0.9775 | -0.2006 | 1.1572 | 0.0606 | -0.0235 | 0.7408 | -0.3339 | - | 10   |
|         | H11    | 0.9765 | -0.1265 | 1.0777 | 1.8627 | -9.1202 | 0.7135 | 6.6346 | - | 11   |
duration for Dohuk province with 0.9853, the H22 model show the best performance with 0.9942 value according to the other meteorological parameters. In addition, the newly developed H22 and H24 models have the best performance for Dohuk and Sulaimania, respectively, in the all models.

In the models depending on the sunshine duration for Sulaimania, the H3 model shows the best performance with 0.9823 values. However, the newly developed H24 model based on the other meteorological parameters shows the best performance among all of the models with the value of 0.9910 for Sulaimania.

**Comparison of the empirical models for Arbil**

Eleven sunshine duration models including linear, quadratic, cubic, linear, power, exponential, linear-exponential, linear-logarithmic, and quadratic-exponential were utilized to estimate the global solar radiation on the horizontal surfaces.
as shown in Table 3. The values of the regression constants for Arbil province were calculated, and the results of these are shown in Table 4. Illustrated models that are models H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, and H11 show accuracy with $R^2$, 0.9654, 0.9767, 0.9769, 0.9874, 0.9701, 0.9637, 0.9607, 0.9668, 0.9772, 0.9734, 0.9731, and 0.9903, respectively.

The results revealed that the model H11 had the most appropriate data in comparison to the other models. In addition, in terms of data accuracy, the models H11, H4, H9, H3, H2, H10, H5, H5, H8, H1, and H6 were ranked correspondingly. However, model H7 was the least accurate comparing to the other models. Several statistical error indicators of MBE, RMSE, $R^2$, and MPE value were applied to confirm the performance of the models. It is observed that the results have in low error and with an acceptable range as shown in Table 3, and it is seen that the model H11 had a good acceptance and high accuracy according to the other model with the coefficient of determination, $R^2$, (99.03%); the statistical errors were within an acceptable range of low error observed in the model H11, and the values of MBE, RMSE, and MPE are $-0.0428 \text{MJ/m}^2$, $0.7767 \text{MJ/m}^2$, and $0.6737$, respectively.

At the same time, the models depending on the other meteorological parameters were applied to Arbil province, and three new models were derived for this location. In these models regression equations such as linear, cubic, exponential, and logarithmic were used. The constant regression coefficients and statistical values such as MBE, RMSE, $R^2$, and MPE for the equations are given in Table 5. The models H12, H13, H14, H15, H16, H17, H18, H19, H20, H21, H22, H23, and H24 were used for Arbil province, and the $R^2$ values of these models were found as $0.9855$, $0.9960$, $0.9970$, $0.9669$, $0.9971$, $0.9958$, $0.9535$, $0.9760$, $0.9896$, $0.9897$, $0.9897$, $0.989$, and $0.9636$, respectively. The model results based on the other meteorological parameters are listed according to $R^2$ values. The models in terms of $R^2$ performance values were ranked as H16, H14, H13, H17, H22, H21, H23, H20, H12, H19, H15, H13, H24 and H18, respectively. When looking at the models that show the best performance in relation to the sunshine duration and the other meteorological parameters for Arbil province, it is seen that the models that depend on other meteorological parameters have a much better performance. The first three models with the highest accuracy among the total 24 models used for the province of Arbil were found in the models including the other meteorological parameters. These models are listed as H16, H14, and H13 respectively. The comparison of measured and calculated mean solar radiation data for the Arbil province was illustrated in Fig. 4. In this figure, the first three models with the highest accuracy in a total of 24 models were shown with the average monthly measured solar radiation values. When the figure was examined for this location, the selected best models for Arbil province gave very close results to the measured values. As shown in the figure, it was seen that there is a very good fit between the models which are connected to other meteorological parameters and measurement results.

### Comparison of the empirical models for Dohuk

The eleven models based on sunshine duration with different regression equations such as linear, exponential, power, quadratic, and logarithmic model to assess the global solar radiation as shown in Table 3 were employed. The regression coefficients and statistical indicators for estimating sunshine-based global solar radiation of Dohuk province are also given in Table 4. In this work, the models H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, and H11 were evaluated, and the coefficient of determination, $R^2$, were $0.9837$, $0.9847$, $0.9850$, $0.9853$, $0.9841$, $0.9844$, $0.9827$, $0.9825$, $0.9843$, $0.9908$, respectively. It is found that model H5 was the most appropriate among the others models. Moreover, the models H3, H2, H6, H9, H10, H4, H1, H7, and H8 were organized in terms of data accuracy, respectively. Also, the Table 4 exhibits that the model H11 was the least accurate among the other models. Various statistical indicators

### Table 6 Comparison of the best of sunshine duration models and the other meteorological parameter models

| City     | Rank | Sunshine duration models | The other meteorological parameter models | Differences in RMSE |
|----------|------|--------------------------|------------------------------------------|---------------------|
|          |      | $R^2$                    | $R^2$                                    |                     |
| Arbil    | 1    | H$_{11}$                 | H$_{16}$                                 | 0.3442             |
|          | 2    | H$_{13}$                 | H$_{14}$                                 | 1.5394             |
|          | 3    | H$_{6}$                  | H$_{12}$                                 | 1.0214             |
| Dohuk    | 1    | H$_{2}$                  | H$_{22}$                                 | 0.3949             |
|          | 2    | H$_{5}$                  | H$_{20}$                                 | 0.4274             |
|          | 3    | H$_{6}$                  | H$_{23}$                                 | 0.4392             |
| Sulaimania| 1  | H$_{3}$                  | H$_{24}$                                 | 0.3512             |
|          | 2   | H$_{1}$                  | H$_{22}$                                 | 0.4723             |
|          | 3   | H$_{6}$                  | H$_{23}$                                 | 0.4886             |
with high acceptability such as MBE, RMSE, and MPE were applied to approve the performance of the models. According to the evaluation of the all models, the best acceptance with the coefficient of determination, \( R^2 \), (98.53%) is indicated in model H5. Table 4 illustrated that the statistical errors for model H5 were within acceptable limits with low error, and the value of MBE, RMSE, and MPE were 0.0674 MJ/m\(^2\), 0.9701 MJ/m\(^2\), and −1.3529%, respectively.

According to other meteorological parameters, thirteen models were evaluated for Dohuk province. Also, these models include three newly developed models. In addition, the accuracy of the models was evaluated by using statistical indicators such as RMSE, MBE, MPE, and \( R^2 \) for this city. The statistics values and constant regression coefficients based on the other meteorological parameters were given in Table 5. According to this table, the \( R^2 \) values of H12, H13, H14, H15, H16, H17, H18, H19, H20, H21, H22, H23, and H24 models was found as 0.9903, 0.9703, 0.9886, 0.9831, 0.9892, 0.971, 0.9717, 0.9668, 0.9941, 0.9936, 0.9974, 0.9940, and 0.9924, respectively. Also the models in this table are sorted by accuracy. Accordingly, the order of accuracy of the models was found as H22, H20, H23, H24, H12, H16, H14, H5, H17, H18, H13, and H19. Among these models, the newly developed H22 model has the highest precision. The results of statistics indicators such as \( R^2 \), MBE, RMSE, and MPE used for this model were found as 0.9942, −0.0789, 0.5752, and 0.4788, respectively. For the Dohuk city, a total of twenty-four models were investigated, depending on the sunshine duration and the other meteorological parameters. The first three models with the highest accuracy among these models were found as H22, H20, and H23, respectively. These three models are also based on the other meteorological parameters.

### Comparison of the empirical models for Sulaimania

The eleven sunshine duration models that are H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, and H11 are utilized to estimate the global solar radiation on the horizontal surface for Sulaimania city. The values of the regression constants and statistical indicators were calculated as shown in Table 4. The coefficient determination (\( R^2 \)) of these models was found as 0.9799, 0.9787, 0.9823, 0.9784, 0.9782, 0.9782, 0.9787, 0.9778, 0.9782, 0.9775, and 0.9776, respectively. The results revealed that model H3 had the most appropriate data in comparison to the other models. In addition, in terms of data accuracy, the models H1, H6, H8, H2, H4, H7, H9, H5, H10, and H11 were ranked, respectively. It was observed that the model H11 had the least accurate compared with the other models. To confirm the performance of the models, a number of statistical error indicator value like MBE, RMSE, and MPE value were employed. The results of all model shows low error with a standard range as illustrated in Table 4. The model H3 indicated good acceptance and high accuracy with the coefficient of determination, \( R^2 \), (98.23%). For the model H3,
the value of MBE, RMSE, and %MPE were $-0.1291 \text{ MJ/m}^2$, $1.0229 \text{ MJ/m}^2$, and $-0.3389\%$, respectively.

Thirteen models were investigated for Sulaimania province depending on other meteorological parameters. These models include three new models that are H17, H22, and H24. The results of various statistical indicators such as RMSE, MBE, MPE, and $R^2$ for all models used in this study and the constant regression coefficients developed for each model are given in Table 5. According to this table, the $R^2$ values of the H12, H13, H14, H15, H16, H17, H18, H19, H20, H21, H22, H23, and H24 models was found as 0.9894, 0.9813, 0.9881, 0.9771, 0.9903, 0.9830, 0.9796, 0.9781, 0.9907, 0.9908, 0.9909, 0.9908, 0.9910, respectively. Also, these models are ranked according to the value of $R^2$. According to accuracy, the models are ranked as H24, H22, H23, H21, H20, H16, H12, H14, H17, H13, H18, H19, and H15. Among the twenty-four models, the newly developed H24 model has been found to be the most accurate model. The statistical values that are $R^2$, MBE, RMSE, and MPE of this model are found as 0.9910, $-0.0880$, $0.6717$, and $0.2141$, respectively. A total of twenty-four models were examined for Sulaimania province. Among these models, the models based on the other meteorological parameters yielded higher sensitivity results than the models based on sunshine duration. In addition, the H24 and H22 models, which are newly developed according to other meteorological parameters, have given the best results within all models. The first three models with the best results among these models and the average monthly solar radiation measurement results for Sulaimania are given in Fig. 6. As can be seen from the figure, the results of the other meteorological parameter models and the actual measurement results are in good agreement with each other.

While comparing the predictions of our model with other reported models, we found that the results of the model proposed here are promising. For example, Besharat et al. (2013) chronologically collected the extensive models of global solar radiation in the literature and divided them into four categories: sunshine duration, cloud, temperature, and other meteorological parameter-based models. In this study, the evaluated models were compared with each other. As a result of this, the other meteorological parameter-based models have better performance than the other three models. El Mghouchi (2016) evaluated his study according to the value of $R^2$. In this study, the best value according to $R^2$ value was found to be 0.9572. In addition, in the Yaniktepe and Genc study (2015), by examining the models based on the different sunshine duration models, the $R^2$ value of the new proposed model was 0.8883 that is the best results in the all models. Quej et al. (2016) worked to estimate the solar radiation coming to earth as only a function of temperature. He stated that if more meteorological data such as temperature, precipitation, relative humidity, latitude, and longitude were used in their study, it would be possible to estimate daily solar radiation with higher accuracy.

In addition, the correlation coefficient was found for all models examined for each location in this study. Correlation coefficients are different for each studied region and should be calculated for each region. Globally correlated coefficients show less sensitivity compared to local results (Almorox and Hontoria 2004). In addition, there are new
correlation coefficients for the models used in many of the studies (Manzano et al. 2015; Bakirci 2009a, b; Adaramola 2012).

Also, comparisons were made at different locations to test the accuracy of these models divided into two categories that are sunshine duration and meteorological parameter. According to conclusion, the results obtained from the other meteorological parameters for each of the three regions performed better than the results of the sunshine duration model for every location studied. In summarizing the model results, we propose that the model described here can be potentially useful in predicting global solar radiation at different locations due to easily found primary input parameters required, and these data are easily available for any location in the world.

**Conclusion**

The results of the correlation are tested by the statistical indicator to define the performance at low error and at high accuracy. In Arbil, model H16, $H = a + b(S/S_{\circ}) + c\sin(\delta) + dT$, was observed as the best model. In Dohuk, model H22, $H/H_{\circ} = a + b(S/S_{\circ}) + c(T_{\min}/T_{\max})^{-1} + dRH$, was observed as the best model. In Sulaimania, model H24, $H/H_{\circ} = a + b\Delta T + c(T_{\min}/T_{\max}) + dRH$, was observed as the best model.

For Arbil location, the H11, H4, and H9 models have showed the best performance among the models based on sunshine duration, respectively. The $R^2$ values of these models were calculated as 0.9903, 0.9874, and 0.9772, respectively. However, when looking at the models dependent on the other meteorological parameter models for the Arbil city, H16, H14, and H13 models show much better performance than the sunshine duration models with $R^2$ values of 0.9971, 0.9970, and 0.9960, respectively. Likewise, H22 and H24 models, among the other meteorological parameter models, showed the best performance according to sunshine duration models with $R^2$ values of 0.9942 and 0.9910 for the cities of Dohuk and Sulaimania, respectively.

The presented study showed that the models developed based on other meteorological parameters yielded higher accuracy than models based on sunshine duration. Therefore, we propose that the approach described here can be more useful for predicting global solar radiation. In summarizing the model results, we recommend that the model described here can be potentially useful in predicting global solar radiation at different locations due to easily found primary input parameters required, and these data are easily available for any location in the world.

**Author contribution** IU: Supervision, investigation, writing (review and editing), KMK preparing, and writing. All authors read and approved the final version of this manuscript.

**Data availability** All data presented herein are included in this published article.

**Declarations**

**Ethical statement** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.
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