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Determining the Optimal Empirical Model for Estimating Global Solar Radiation in the Eastern Mid-Hills of Dhankuta, Nepal

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Abstract. Accurate estimation of global solar radiation (GSR) is essential for designing, sizing, and evaluating the performance of solar energy systems. However, in Nepal, direct solar radiation data are limited due to the high cost of advanced measuring instruments. To address this gap, the present study develops and validates empirical models to estimate daily average GSR using easily measurable parameters such as sunshine duration, temperature, and relative humidity. Meteorological data for Dhankuta (26.983°N, 87.346°E, 1192 m altitude) were collected for 2021–2022, including sunshine hours, air temperature, atmospheric pressure, wind speed, and relative humidity. Fifteen mathematical models were tested, and their performance was evaluated using four widely accepted statistical indicators: Mean Bias Error (MBE), Mean Percentage Error (MPE), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2). Among the evaluated models, Model 10 (a modified form of the Abdalla model) achieved the best statistical performance, with the lowest MBE, RMSE, and MPE values and the highest R^2 (0.637). The derived empirical constants for Model 10 are: a = –0.1976, b = 0.37824, c = 0.0209, d = –0.00057. The goal of this study is twofold: first, to identify the statistically optimal model, and second, to assess its broader applicability in Dhankuta and similar geographic regions of Nepal. This dual perspective ensures both methodological rigor and practical value for engineers, architects, agriculturists, hydrologists, and policymakers engaged in solar energy planning and applications.

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1. INTRODUCTION

Solar energy, generated by thermonuclear fusion converting approximately 5×10^6 tons of hydrogen per second, is the most abundant and sustainable form of energy on Earth [1]. It plays a vital role in promoting renewable energy solutions, especially in countries like Nepal, where access to modern energy services remains limited in many regions. Global solar radiation (GSR), the amount of solar energy received at the Earth's surface, is influenced by atmospheric and geographical factors, including temperature, relative humidity, cloud cover, aerosols, altitude, latitude, and solar angles [2–5]. Among these, cloudiness and sunshine duration are particularly important, as they directly affect solar radiation availability [4]. Accurate solar radiation data are crucial for the planning, design, and optimization of solar energy systems. They are also essential for energy policy development, climate studies, and environmental research. However, in many parts of Nepal, including Dhankuta, continuous and reliable radiation measurements are not available due to the high cost and maintenance demands of instruments like pyranometers [8-10]. To overcome these challenges, researchers rely on empirical models that estimate GSR using more accessible meteorological parameters. Among the earliest models is the Angstrom equation (1924), which relates solar radiation to sunshine duration [14]. Prescott (1940) later modified the model by introducing extraterrestrial radiation as a factor, forming the well-known Angstrom–Prescott model [15]. These models have been widely validated in various climates with reasonable accuracy [16–18]. While sunshine duration remains a dominant input parameter, other climatic variables such as temperature, latitude, humidity, rainfall, and cloud cover [19] have been incorporated into extended empirical models to improve estimation accuracy. These models are expressed in various mathematical forms—linear, exponential, logarithmic, polynomial, power, and hybrid types [11–13]. In Nepal, where about 83% of the population resides in rural areas and relies heavily on traditional biomass for energy, solar energy represents a clean and sustainable alternative [6, 7]. Estimating solar energy potential is thus critical for advancing energy access, especially in hill districts like Dhankuta, which have high solar exposure but limited measurement infrastructure. In Nepal, the availability of solar radiation data is limited, and research activities in this field remain relatively low. As a result, only a small number of studies have been conducted to estimate global solar radiation (GSR). Nonetheless, some progress has been made through the use of empirical models and tools like RadEst v3.0 [20]. For instance, Rajbanshi et al. utilized RadEst v3.0 to estimate daily GSR in various regions, including Okhaldhunga (eastern hilly region) [21], Biratnagar (eastern lowland area) [22], and Taplejung (eastern upland) [23]. Likewise, Kharel et al. applied the same software to study GSR in Jumla, a hilly region in western Nepal [24]. This study focuses on evaluating the performance of fifteen empirical models to estimate global solar radiation in Dhankuta. Using available meteorological data, regression analysis is performed, and statistical indicators such as Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Percentage Error (MPE), and coefficient of determination (R^2) are applied to assess model accuracy. The aim of this study is twofold: (a) to identify the statistically optimal model based on performance indicators, and (b) to assess its broader applicability for solar energy planning in Dhankuta and similar regions of Nepal where direct radiation measurements are scarce.

1.1 Study Area

Nepal is located within one of the most favourable regions for solar energy utilisation on the global solar map. Dhankuta, a mid-hill district in the eastern hill region of Nepal, lies between latitudes 26°53’ N to 27°19’ N and longitudes 87°8’ E to 88°33’ E. The district’s elevation ranges from 243 meters to 629 meters above sea level. Dhankuta experiences a warm and moderate climate, with significantly lower precipitation during the winter months compared to the summer season.

2. DATA AND METHODOLOGY

The study commenced with the collection of detailed meteorological data for the selected study area. Regression analysis was employed to determine the regression coefficients for various empirical models, based on the specific meteorological parameters incorporated in each model. From the extensive literature, fifteen (15) models were selected for evaluation. For each model, it was necessary to compute the regression coefficients along with key statistical performance indicators: Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), and the coefficient of determination (R^2). These computations were carried out using MATLAB and Excel. This approach not only identifies the statistically best-fit model but also allows assessment of its broader applicability under the meteorological conditions typical of Dhankuta and similar regions of Nepal.

2.1 Data set

Daily data on GSR, sunshine duration, relative humidity, rainfall, and maximum and minimum air temperatures on a horizontal surface were collected for Dhankuta for the years 2021–2022. These datasets were obtained from the Alternative Energy Promotion Centre (AEPC), Government of Nepal, in collaboration with the World Bank Group, and the Department of Hydrology and Meteorology (DHM), Government of Nepal. Ground-based solar radiation was measured using a CMP21 pyranometer. Air temperature and relative humidity were recorded with a CS215 sensor from Campbell Scientific, while precipitation was measured using a 52203 R.M. Young tipping-bucket rain gauge [25]. Based on an extensive literature review, one empirical model was selected as appropriate for estimating empirical constants specific to the study location.

2.2 Astronomical Parameters

2.2.1 Declination angle (δ)

The declination angle is the angle between the Earth–Sun line and the Earth’s equatorial plane. This angle varies throughout the year, ranging from $-23.45°$ during the winter solstice to $+23.45°$ at the summer solstice. It can be estimated using the following equation [13-16]:

$$\delta \text{ (degrees)} = 23.45 \sin\left[\frac{360}{365}(284 + n_d)\right], \quad (1)$$

where n_d is the number of days corresponding to a given date, starting from 1 on 1 January to 365 on 31 December.

2.2.2 Sunset Hour Angle (ω)

The sunset hour angle in degrees can be calculated from [13-16]

$$\omega = \cos^{-1}(-\tan\phi \tan\delta) \quad (2)$$

2.2.3 Number of Daylight Hours (Daylight Duration)

The duration of daylight (total hours of sunlight) depends on the hour angle and can be calculated using the following equation [13-16]:

$$N = \frac{24}{\pi} \cos^{-1}(-\tan\phi \tan\delta) \qquad (3)$$

2.2.4 Extraterrestrial Radiation

The extraterrestrial global solar radiation (H_0) can be calculated from the following equation [26]:

$$H_0 = \frac{24}{\pi} I_{sc} \left[1 + 0.033 \cos\left(\frac{360 n_d}{365}\right)\right] \cdot \left(\cos\phi \cos\delta \sin\omega + \frac{\pi}{180}\omega \sin\phi \sin\delta\right), \qquad (4)$$

where:

- I_{sc} = solar constant (= 1367 W/m^2),
- ϕ = the latitude of the site (in radians),
- δ = the solar declination angle (in radians),
- ω = the mean sunrise hour angle (in degrees),
- n_d = the Julian day number of the year starting from January 1.

2.3. GSR Models

A wide range of empirical correlations have been developed and tested for estimating GSR, making it challenging to identify the most suitable model for a specific location and application [15]. These models are generally categorised into four types: sunshine-based, cloud-based, temperature-based, and hybrid models. Model selection typically depends on two key factors: (1) the availability of required meteorological or environmental input data, and (2) the model's prediction accuracy. Among the most widely used approaches, the Angström–Prescott model estimates the average daily GSR based on the corresponding average sunshine duration [17–18]:

$$\frac{H_g}{H_0} \approx f\left(\frac{n}{N}\right).$$

In this context, H_g represents the average daily GSR (MJ/m²), Ho is the average daily extraterrestrial radiation (MJ/m²), n denotes the average daily measured sunshine duration, and N is the average daily daylight duration. The earliest form of this relationship was introduced by Ångström and later modified by Page. It describes a linear regression between GSR and sunshine duration and remains one of the most practical and widely adopted models [19]

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right).$$

Over time, to enhance the model's performance, especially at extreme values, researchers proposed non-linear polynomial variations derived from the original Ångström equation [14, 17]. Numerous refinements have since been introduced to further improve its accuracy. Several representative sunshine, relative humidity, temperature-based and hybrid models developed through these modifications are presented below [12, 25].

Model 1: Angstrom–Prescott–Page

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) \qquad (5)$$

Model 2: Temperature-based Model

$$\frac{H_g}{H_0} = a + bT_1 \qquad (6)$$

Model 3: Humidity-based Model

$$\frac{H_g}{H_0} = a + b \cdot RH \qquad (7)$$

Model 4: Garcia Model (1994)

$$\frac{H_g}{H_0} = a + b\left(\frac{\Delta T}{N}\right) \qquad (8)$$

Model 5: Ampratwum and Dorvlo Model

$$\frac{H_g}{H_0} = a + b \cdot \log\left(\frac{n}{N}\right) \qquad (9)$$

Model 6: Modified Angstrom Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\Delta T \qquad (10)$$

Model 7: Newland Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c \cdot \log\left(\frac{n}{N}\right) \qquad (11)$$

Model 8: Modified Angstrom Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + cT_1 \qquad (12)$$

Model 9: Olomiyesan–Oyedum Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\left(\frac{\Delta T}{N}\right) \qquad (13)$$

Model 10: Abdalla Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + cT_1 + d \cdot RH \qquad (14)$$

Model 11: Modified Angstrom (new) Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\Delta T + d \cdot RH \tag{15}$$

Model 12: Modified Angstrom (new) Model

$$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\left(\frac{\Delta T}{N}\right) + d \cdot RH \tag{16}$$

Model 13: Chen et al. Model

$$\frac{H_g}{H_0} = a + b \cdot \ln(\Delta T) \tag{17}$$

Model 14: Chen et al. (2004)

$$H_g = a + b\left(\frac{n}{N}\right) + c \cdot \sin\delta + dT_{\max} \tag{18}$$

Model 15: Chen et al. (2004)

$$H_g = a + bH_0 + c\left(\frac{n}{N}\right) + d \cdot \sin\delta + eT_{\max} + f \cdot RH \tag{19}$$

3. EVALUATION PARAMETERS OF THE MODEL PERFORMANCE

All the models described above for estimating solar energy on a given surface must be validated for accuracy and reliability. In solar energy research, various statistical techniques are commonly employed to evaluate and compare the performance of solar radiation estimation models [26]. In this study, four statistical indicators have been used for model evaluation: Mean Bias Error (MBE), Mean Percentage Error (MPE), Root Mean Square Error (RMSE), and the Coefficient of Determination (R^2).

These indicators were chosen not only to determine the statistically best-fit model but also to provide a reliable basis for evaluating its broader applicability in regions of Nepal with similar meteorological conditions to Dhankuta. MBE provides insight into a model's long-term performance, with values close to zero indicating better accuracy. i.e. an MBE value of zero represents a perfect agreement between measured and estimated data. A positive MBE implies systematic overestimation, while a negative value indicates underestimation. However, one drawback of MBE is that it can hide individual errors because overestimated and underestimated values may cancel each other out [27]. RMSE, on the other hand, reflects short-term prediction accuracy by measuring the average magnitude of the deviations between predicted and observed values. Since it squares the individual errors, RMSE is always positive and particularly sensitive to large discrepancies. Ideally, a model should yield an RMSE as close to zero as possible [5]. The coefficient of determination (R^2) assesses how well the regression line fits the actual data. The closer R^2 is to 1, the better the model's predictive ability. The mathematical definitions of these error metrics are provided below.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(H_{i,c} - H_{i,m})^2} \quad \text{MJ/m}^2/\text{day} \tag{20}$$

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N}(H_{i,c} - H_{i,m}) \quad \text{MJ/m}^2/\text{day} \tag{21}$$

$$\text{MPE} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{H_{i,c} - H_{i,m}}{H_{i,m}} \times 100\right) \quad (\%) \tag{22}$$

$$R^2 = \frac{\sum_{i=1}^{N}\left(H_{i,m} - \overline{H}_m\right)\left(H_{i,c} - \overline{H}_c\right)}{\sqrt{\sum_{i=1}^{N}\left(H_{i,m} - \overline{H}_m\right)^2 \sum_{i=1}^{N}\left(H_{i,c} - \overline{H}_c\right)^2}} \quad (\%) \tag{23}$$

where,
$H_{i,m}$ = measured value,
$H_{i,c}$ = estimated (calculated) value,
N = number of data points,
$\overline{H}_m$ = average of measured solar radiation,
$\overline{H}_c$ = average of estimated solar radiation.

4. RESULTS AND DISCUSSION

The empirical constants for each model were derived using linear regression analysis based on meteorological data from 2021 to 2022. The corresponding model equations are presented in Equations (24) to (38). Model performance was evaluated using four statistical indicators: MBE, RMSE, MPE, and R^2. A model is considered more reliable when it exhibits lower values of MBE, RMSE, and MPE, and a higher value of R^2. The results of the statistical evaluation for all models are summarised in Table 1.

Model 1: Angstrom–Prescott–Page

$$\frac{H_g}{H_0} = 0.3020 + 0.3693\left(\frac{n}{N}\right) \tag{24}$$

Model 2: Temperature-based Model

$$\frac{H_g}{H_0} = -0.0009 + 0.0186T_1 \tag{25}$$

Model 3: Humidity-based Model

$$\frac{H_g}{H_0} = 0.8421 - 0.0048RH \tag{26}$$

Model 4: Garcia Model (1994)

$$\frac{H_g}{H_0} = 0.2550 + 0.2596\left(\frac{\Delta T}{N}\right) \tag{27}$$

Model 5: Ampratwum and Dorvlo Model

$$\frac{H_g}{H_0} = 0.5612 + 0.2109 \cdot \log\left(\frac{n}{N}\right) \tag{28}$$

Model 6: Modified Angstrom Model

$$\frac{H_g}{H_0} = 0.3281 + 0.4016\left(\frac{n}{N}\right) - 0.0041\Delta T \tag{29}$$

Model 7: Newland Model

$$\frac{H_g}{H_0} = 0.3265 + 0.3248\left(\frac{n}{N}\right) + 0.0204 \cdot \log\left(\frac{n}{N}\right) \quad (30)$$

Model 8: Modified Angstrom Model

$$\frac{H_g}{H_0} = -0.2447 + 0.3953\left(\frac{n}{N}\right) + 0.0207T_1 \quad (31)$$

Model 9: Olomiyesan–Oyedum Model

$$\frac{H_g}{H_0} = 0.3694 + 0.4697\left(\frac{n}{N}\right) - 0.1345\left(\frac{\Delta T}{N}\right) \quad (32)$$

Model 10: Abdalla Model

$$\frac{H_g}{H_0} = -0.1976 + 0.3782\left(\frac{n}{N}\right) + 0.0209T_1 - 0.0006RH \quad (33)$$

Model 11: Modified Angstrom (new) Model

$$\frac{H_g}{H_0} = 0.3246 + 0.4017\left(\frac{n}{N}\right) - 0.004\Delta T + 0.00003RH \quad (34)$$

Model 12: Modified Angstrom (new) Model

$$\frac{H_g}{H_0} = 0.4472 + 0.4640\left(\frac{n}{N}\right) - 0.1568\left(\frac{\Delta T}{N}\right) - 0.0073RH \quad (35)$$

Model 13: Chen et al. Model

$$\frac{H_g}{H_0} = -0.0664 + 0.5491 \cdot \ln(\Delta T) \quad (36)$$

Model 14: Chen et al. (2004)

$$H_g = -16.507 + 5.1037\left(\frac{n}{N}\right) - 34.6047\sin\delta + 0.6914T_{\max} \quad (37)$$

Model 15: Chen et al. (2004)

$$H_g = -11.4307 - 0.05693H_0 + 2.4619\left(\frac{n}{N}\right) - 39.5061\sin\delta + 0.7047T_{\max} - 0.0514RH \quad (38)$$

Among the fifteen models analysed, most showed reasonable agreement between the estimated and observed daily global solar radiation (GSR) values. Model 10, a modified form of the Abdalla model, exhibited the best performance, achieving the lowest MBE, RMSE, and MPE values as well as the highest R^2(0.637). Although Model 14 yielded the lowest MBE (-0.00000424), its overall performance was not superior to that of Model 10. The moderate R^2 value may be explained by measurement uncertainties, limited data availability, natural climatic variability (e.g., cloud cover and aerosols), local topographical effects, and the simplicity of the regression approach. Thus, Model 10 is identified as the most statistically reliable model for estimating daily average GSR in Dhankuta, Nepal. Beyond its statistical performance, Model 10 relies on readily available meteorological parameters such as sunshine duration, temperature, and relative humidity, making it practically applicable for regions across Nepal with similar climatic and geographic conditions. Nevertheless, the dataset is limited to 2021–2022 due to incomplete data for 2023 and 2024. Limiting the analysis to fully verified data ensures consistency and reliability, while future studies incorporating additional years would improve the robustness of the findings.

TABLE I: Statistical performance of different models

Models	MBE (MJ/m^2/day)	RMSE (MJ/m^2/day)	MPE (%)	R^2
Model 1	0.0335	3.7353	11.07	0.372
Model 2	0.0292	4.1851	15.18	0.213
Model 3	0.0271	4.3835	14.83	0.138
Model 4	0.0298	4.3124	13.91	0.163
Model 5	0.0319	4.1060	14.08	0.241
Model 6	0.0335	3.7279	11.23	0.373
Model 7	0.0328	3.9667	13.33	0.290
Model 8	0.0349	2.8373	7.30	0.636
Model 9	0.0335	3.6868	11.33	0.388
Model 10	0.0225	2.8329	7.11	0.637
Model 11	0.0344	3.7279	11.24	0.374
Model 12	0.0416	3.6828	11.36	0.390
Model 13	0.0290	4.1421	11.84	0.230
Model 14	-0.00000424	2.9702	8.91	0.596
Model 15	-0.000240	2.9319	8.38	0.607

A multiple linear regression model was also developed, incorporating sunshine duration, temperature, and relative humidity as predictors. The resulting empirical equation is given by:

$$\frac{H_g}{H_0} = -0.1976 + 0.3782\left(\frac{n}{N}\right) + 0.0209T_1 - 0.00057\,RH$$

where H_g is the estimated GSR, H_0 is the extraterrestrial radiation, n/N is the relative sunshine duration, ΔT is the temperature range, and RH is the relative humidity. The derived constants indicate this model's potential applicability for regions with climatic conditions similar to Dhankuta.

The figures illustrate key variations in solar radiation and related climatic parameters during 2021 and 2022. Figure 1 shows the monthly average daily GSR, revealing seasonal fluctuations over the two years. Figures 2 and 3 compare measured and estimated daily GSR for 2021 and 2022, respectively, indicating the performance of the applied empirical models. Figure 4 presents seasonal variation in GSR, while Fig. 5 displays seasonal rainfall patterns, suggesting an inverse relationship with solar radiation.

The annual average GSR in Dhankuta was calculated as 15.14 MJ/m^2/day (4.21 kWh/m^2/day). This value is marginally lower than those reported in Taplejung (4.42 ± 0.09 kWh/m^2/day) [23], Biratnagar (4.28 ± 0.07 kWh/m^2/day) [22], and Okhaldhunga (4.22 kWh/m^2/day) [21], and significantly lower than in Jumla (5.44 kWh/m^2/day) [24]. These variations are attributed primarily to differences in topography, atmo-

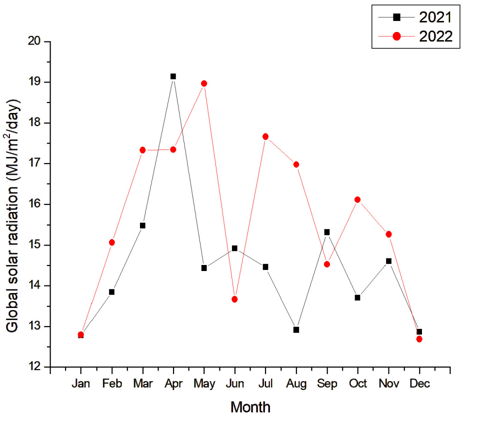

FIGURE 1: Graphic representation of variation of measured monthly average daily GSR for 2021 and 2022

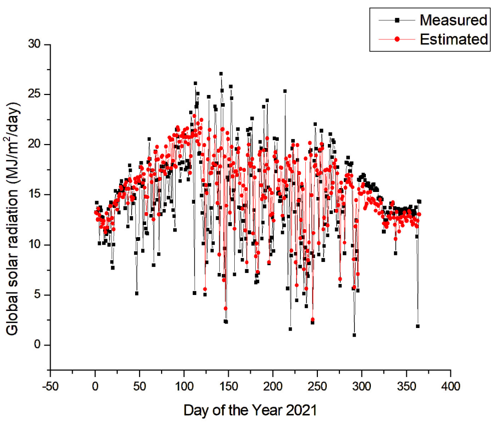

FIGURE 2: Graphic representation of variation of measured and estimated daily GSR for 2021

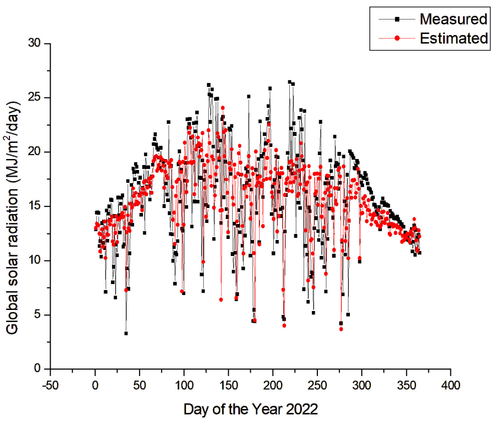

FIGURE 3: Graphic representation of variation of measured and estimated daily GSR for 2022

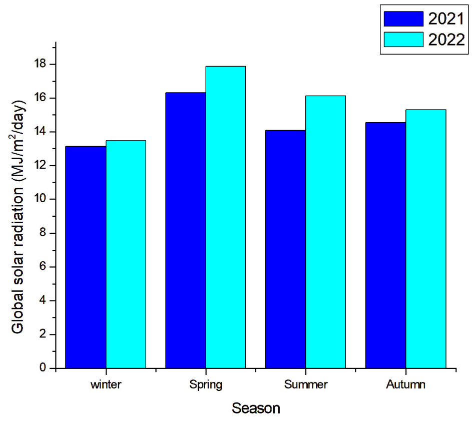

FIGURE 4: Seasonal variation of GSR for 2021 and 2022

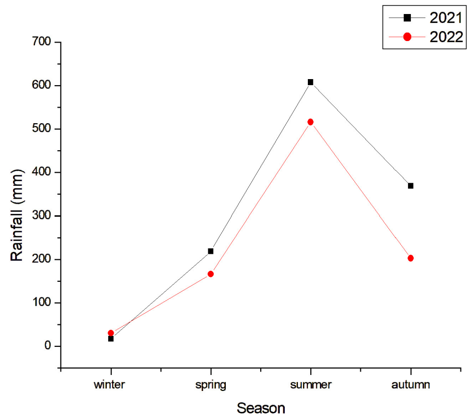

FIGURE 5: Seasonal variation of rainfall for 2021 and 2022

spheric clarity, and cloud cover. For instance, Jumla, located in the high Himalayas, experiences lower humidity and clearer skies, leading to higher solar irradiance. In contrast, Dhankuta's mid-hill geography with frequent cloudiness and higher moisture levels results in comparatively reduced solar radiation.

5. CONCLUSION

This study assessed multiple empirical models for estimating daily average GSR on a horizontal surface in Dhankuta, Nepal. Using meteorological parameters—including sunshine duration, temperature, and relative humidity—model-specific constants were determined through linear regression analysis. Model performance was evaluated using mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), and coefficient of determination (R^2) as statistical indicators.

Among the evaluated models, Model 10 (a modified Abdalla model) showed the highest accuracy, with:

- MBE: 0.0224
- MPE: 7.11%
- RMSE: 2.83
- R^2: 0.637

Given its superior statistical performance and reliance on easily measurable meteorological parameters, Model 10 is recommended not only for estimating daily GSR in Dhankuta but also for broader application in similar mid-hill and climatic regions across Nepal. The average solar insolation in Dhankuta is 4.21 $kWh/m^2/day$, highlighting substantial potential for solar energy utilization. This supports the feasibility of deploying solar technologies in the region.

Nepal's location within the solar-rich latitudinal zone makes it well-positioned to harness solar energy. In areas lacking direct radiation measurements, temperature- and sunshine-based empirical models provide a cost-effective and practical alternative. The findings affirm that sunshine duration, air temperature, humidity, and geographical attributes (e.g., latitude, altitude) are critical parameters for solar radiation modeling. By identifying an optimal model tailored to both statistical performance and practical applicability, this study contributes valuable insights to support solar energy planning and sustainable renewable energy deployment across Nepal and similar regions.

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