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Performance Analysis of Empirical Models for Daily Global Solar Radiation in Jiri, Nepal

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Accurate estimation of global solar radiation (GSR) is essential for solar energy system design, climate analysis, and sustainable energy planning. In mountainous countries such as Nepal, direct measurement of solar radiation is limited due to high instrumentation costs and sparse monitoring networks. As a result, empirical models based on routinely measured meteorological parameters provide a practical alternative for solar resource assessment. This study evaluates the performance of twenty empirical models for estimating daily global solar radiation in Jiri, a mid-hill region of eastern Nepal characterized by moderate altitude, frequent cloud cover, and strong monsoonal influence.

Long-term meteorological data, including sunshine duration, air temperature, and relative humidity, were used as model inputs. Extraterrestrial solar radiation and day length were calculated using standard astronomical relations, and model coefficients were derived through regression analysis. Model performance was assessed primarily using error-based statistical indicators, namely Root Mean Square Error (RMSE), Mean Bias Error (MBE), and Mean Percentage Error (MPE) and coefficient of determination (R^2),which are more appropriate than correlation-based measures under complex climatic and topographic conditions.

The results show that the Modified Angstrom (new) models M14 and M15 outperform the other models, exhibiting the lowest RMSE values (3.63–3.67 MJ m^{-2} day^{-1}), minimum MPE (approximately 9.2–9.4%), and negligible bias, indicating high accuracy and long-term stability. Models M17, M18, and M20 also demonstrate satisfactory performance and can be considered reliable alternatives. In contrast, simpler sunshine- or temperature-based models show relatively higher errors and reduced suitability for the Jiri region.

The average annual global solar radiation in Jiri was estimated as 15.05 MJ m^{-2} day^{-1} (approximately 4.18 kWh m^{-2} day^{-1}), confirming significant solar energy potential. The findings highlight the importance of site-specific validation and support the use of multi-parameter empirical models for solar energy planning in Nepal's mid-hill regions.

Keywords: Global solar radiation, Sunshine hours, Regression technique, Empirical constants, Statistical tools

1 Introduction

The growing demand for clean and sustainable energy has intensified global interest in solar energy as a reliable alternative to fossil fuels. Among various renewable sources, solar energy is particularly attractive due to its abundance, environmental friendliness, and suitability for decentralized energy systems. Accurate knowledge of global solar radiation (GSR) is a fundamental requirement for the design, performance evaluation, and optimization of solar energy technologies, as well as for applications in agriculture, hydrology, and climate studies[1-4]. Comprehensive theoretical foundations and engineering principles of solar energy systems have been extensively discussed in standard textbooks[5,6].

Despite its importance, direct measurement of GSR remains limited in many developing countries because of the high cost, maintenance requirements, and sparse distribution of pyranometer-based radiation stations. This limitation is especially pronounced in mountainous regions such as Nepal, where complex terrain, variable cloud cover, and strong seasonal monsoon influences create significant spatial and temporal variability in solar radiation[7,8]. The measurement techniques and instrumentation for solar radiation monitoring have been systematically described in the literature[9]. Consequently, empirical and semi-empirical models that estimate GSR using commonly available meteorological parameters have become essential tools in solar resource assessment.

Empirical solar radiation models, particularly those based on sunshine duration, temperature, and relative

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humidity, have been widely applied across different climatic regions. Classical formulations such as the Ångström–Prescott model and its numerous modifications remain extensively used due to their simplicity and reasonable accuracy[10-12]. Several studies have demonstrated that sunshine-based models often outperform temperature-only models, especially in regions where cloud dynamics strongly influence solar availability[13,14].

In the South Asian and Himalayan context, a number of studies have evaluated empirical models to estimate GSR under diverse climatic conditions. Research conducted in Nepal has shown that model performance varies significantly between lowland, mid-hill, and high-altitude regions, highlighting the necessity of site-specific validation[15,16]. More recent studies using RadEst software have further emphasized that no single empirical model is universally applicable across Nepal's varied topography[17,18].

Jiri, located in the mid-hill region of eastern Nepal, presents a unique climatic setting characterized by moderate altitude, frequent cloud formation, and strong seasonal contrasts between monsoon and dry periods. Despite its strategic importance for rural electrification and solar energy deployment, detailed assessments of GSR estimation models for Jiri remain scarce. Most existing studies in Nepal have focused on either lowland urban centers or high-altitude Himalayan regions, leaving mid-hill locations comparatively underrepresented in the literature[19].

Therefore, the present study aims to evaluate the applicability and performance of multiple empirical models for estimating daily global solar radiation in Jiri, Nepal. Using long-term meteorological data and standardized statistical performance indicators, this study seeks to identify the most suitable models for this mid-hill region. The outcomes are expected to support solar energy planning, improve regional solar resource assessments, and contribute to the development of reliable solar databases for Nepal.

2 Study Area and Data Description

Jiri, located in the Dolakha district of eastern Nepal, lies within the mid-hill physiographic region. Administratively, it falls under Jiri in Dolakha District, Nepal. The area is at an average altitude of 1,877 m above sea level, with rugged topography, undulating slopes, and valley systems typical of Himalayan mid-hills. These features contribute to substantial spatial variability in solar exposure, and the site's location is shown in Fig. 1[20].

Climatically, Jiri experiences warm, humid summers during the monsoon (June-September) and cool, relatively dry winters. Dense cloud cover, high humidity, and frequent rainfall in summer reduce global solar radiation (GSR), whereas clearer winter skies increase solar transmissivity despite shorter days. Seasonal contrasts strongly influence solar radiation variability and the accuracy of empirical models[21], with atmospheric water vapor, clouds, and elevation being key factors[22].

Meteorological data for this study, monthly averages of sunshine duration, maximum and minimum air temperature, and relative humidity, were obtained from the Department of Hydrology and Meteorology, Government of Nepal, covering 2021–2024. These variables are widely used in solar radiation modelling due to their availability and reliability. Sunshine duration indicates cloudiness, temperature accounts for diurnal atmospheric clarity, and relative humidity reflects atmospheric moisture affecting radiation[23].

Extraterrestrial radiation and maximum sunshine duration were calculated using standard astronomical relations based on latitude and day numbe. All datasets were quality-checked to remove missing or anomalous values. Processed inputs were applied in empirical models via RadEst 3.0, previously validated for Nepal[24].

Overall, Jiri's mid-hill location, monsoon climate, officially sourced meteorological data (2021–2024), and standardized procedures provide a robust basis for evaluating empirical GSR models in the region shown in Table 1.

Among these, M-1, M-5, and M-9 are sunshine-based models; M-2, M-4, and M-6 are temperature-based models; M-3 is humidity-based; and M-7 to

Fig. 1 — Location map of Jiri, Dolakha district, Nepal

Table1 — List of different empirical models

S.N.	Models	Mathematical Relations
M-1	Angstrom-Prescott-Page[25]	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right)$
M-2	Temperature based Model	$\frac{H_g}{H_0} = a + bT_1$
M-3	Humidity based Model	$\frac{H_g}{H_0} = a + b\,RH$
M-4	Garica model	$\frac{H_g}{H_0} = a + b\left(\frac{\Delta T}{N}\right)$
M-5	AmpratwumandDorvlomodel[26]	$\frac{H_g}{H_0} = a + b * \log\left(\frac{n}{N}\right)$
M-6	Chen*etal*.model1	$\frac{H_g}{H_0} = a + b * \ln(\Delta T)$
M-7	Modified Angstrom Model	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(\Delta T)$
M-8	Swartzman-Ogunlade2	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(RH)$
M-9	Newlandmodel	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c * \log\left(\frac{n}{N}\right)$
M-10	Modified Angstrom Model	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(T_1)$
M-11	Olomiyesan-Oyedum Model	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\left(\frac{\Delta T}{N}\right)$
M-12	Abdalla model[27]	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(T_1) + d(RH)$
M-13	Togruland Onat model1	$H_g = a + b\left(\frac{n}{N}\right) + c\sin\delta + dT$
M-14	Modified Angstrom (new) Model	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(\Delta T) + d(RH)$
M-15	Modified Angstrom (new) Model	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\left(\frac{\Delta T}{N}\right) + d(RH)$
M-16	Chen *etal*. model2	$H_g = a + b\left(\frac{n}{N}\right) + c\sin\delta + dT_{max}$
M-17	Ododoetal. Model	$H_g = a + b\left(\frac{n}{N}\right) + cT_{max} + d(RH) + eT_{max}\left(\frac{n}{N}\right)$
M-18	Togruland Onat model[3]	$H_g = a + b\left(\frac{n}{N}\right) + c\sin\delta + dT + e(RH)$
M-19	Togruland Onat model[2]	$H_g = a + bH_0 + c\left(\frac{n}{N}\right) + d\sin\delta + eT + f(RH)$
M-20	Coulibaly and Ouedraogo Model	$H_g = a + bH_0 + c\left(\frac{n}{N}\right) + d(RH) + eT_{max} + f\sin\delta$

M-20 are mixed models combining sunshine, temperature, humidity, and/or solar declination.

2.1 Extraterrestrial Radiation[28,]

The extraterrestrial GSR (Ho) can be calculated from the following equations:

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

Where,
I_{sc} = solar constant (=1367 W m^{-2}),
φ = the latitude of the site (rad),
Δ = the solar declination (rad),
Ω = the mean sunrise hour angle for the given month, and
n_d = the Julian day number of the year starting from the first of January.

The solar declination (δ) and the mean sunrise hour angle (ω) can be calculated by the following equations.

$$(\delta \text{ degree}) = 23.45\sin\left[\frac{360}{365}(284 + n_d)\right] \quad \ldots (2)$$

$$\omega = \cos^{-1}(-\tan\phi \tan\delta) \quad \ldots (3)$$

The relation of the day length is

$$N = \frac{2}{15}\omega = \frac{2}{15}\cos^{-1}(-\tan\phi \tan\delta) \quad \ldots (4)$$

2.2 Statistical Approach

The daily average hourly extraterrestrial radiation and the length of the day were calculated using the given equations. Empirical constants for different models were determined using regression analysis, and then these models were used to estimate the global solar radiation. The accuracy of each model was checked using statistical measures such as RMSE, MPE, MBE, and the R^2.[29] These statistical tools are explained as follows.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum\left(H_{i,c} - H_{i,m}\right)^2} \text{ MJ/m}^2\text{/day} \quad \ldots (5)$$

$$\text{MBE} = \frac{1}{N}\sum\left(H_{i,c} - H_{i,m}\right) \text{ MJ/m}^2\text{/day} \quad \ldots (6)$$

$$\text{MPE} = \frac{1}{N}\left[\sum\left(\frac{H_{i,c}-H_{i,m}}{H_{i,m}}\right) \times 100\right](\%) \quad \ldots (7)$$

$$R^2 = \sum_{k=0}^{n}\binom{n}{k}x^k a^{n-k} = \frac{\sum(H_{i,m}-\overline{H_m})(H_{i,c}-\overline{H_c})}{\sqrt{\sum(H_{i,m}-\overline{H_m})^2(H_{i,c}-\overline{H_c})^2}}(\%) \quad \ldots (8)$$

$$\text{CRM} = \frac{\sum H_{i,m} - \sum H_{i,c}}{\sum H_{i,m}}(\%) \quad \ldots (9)$$

where,
$H_{i,m}$ = measured value,
$H_{i,c}$ = estimated value, is the number of data,
$\overline{H_m}$= the average of measured solar radiation,
$\overline{H_c}$= the average of estimated solar radiation,

3 Results

The calculated values for these statistical errors are summarized in Table 2.

3.1 Model Performance Analysis for Jiri, Nepal

The performance of twenty empirical models (M1–M20) for estimating daily global solar radiation (GSR) in Jiri, Nepal, was evaluated using Root Mean Square Error (RMSE)**,** Mean Bias Error (MBE)**,**Mean Percentage Error (MPE)**,** and the coefficient of determination (R^2)**.**

3.2 Error-Based Performance

Among all models, M14 and M15 exhibited superior performance, with the lowest RMSE values **(**3.64 and 3.67 MJ/m²/day) and minimum MPE (9.19% and 9.40%), indicating high accuracy and low relative error. Both models also showed small and stable MBE, confirming the absence of significant overestimation or underestimation.

Table 2 — Empirical constants and statistical metrics of different models for Jiri, with the best-performing values shown in bold

	Empirical constants						Statistical metrics			
	a	*b*	*c*	*d*	*e*	*f*	*MBE (MJ/m²/day)*	*RMSE (MJ/m²/day)*	*MPE (%)*	*R²*
M1	0.461	0.041					0.030	4.699	14.980	0.321
M2	0.304	0.008					0.030	4.597	14.362	0.342
M3	1.042	-0.007					0.030	3.973	11.526	0.491
M4	0.273	0.202					0.031	4.072	10.774	0.502
M5	0.487	0.016					0.031	4.703	14.996	0.494
M6	0.491	0.454					0.032	3.962	9.596	0.482
M7	0.267	-0.080	0.0206				0.028	3.951	10.086	0.497
M8	1.021	0.055	-0.007				0.030	3.949	11.395	0.492
M9	0.459	0.044	-0.002				0.030	4.700	14.985	0.503
M10	0.199	0.108	0.011				0.031	4.529	13.931	0.510
M11	0.289	-0.090	0.226				0.031	4.020	10.442	0.501
M12	0.827	0.096	0.007	-0.007			0.030	3.875	10.963	0.513
M13	8.442	-2.576	-0.503	0.6448			0.000	3.897	9.876	0.526
M14	0.713	-0.032	0.014	-0.005			0.029	3.635	9.189	0.671
M15	0.751	-0.035	0.149	-0.005			0.030	3.673	9.400	0.643
M16	6.136	3.548	0.393	0.3485			0.000	4.476	13.690	0.504
M17	23.539	7.991	0.321	-0.205	-0.228		-0.000	3.803	10.678	0.514
M18	25.867	3.123	0.218	0.2150	-0.204		-0.000	3.809	10.736	0.521
M19	25.627	0.008	3.123	0.224	0.215	-0.204	0.000	0.000	10.736	0.519
M20	1.289	-0.015	0.100	-0.007	0.007	0.008	-0.000	3.814	10.717	0.532

Models M17, M18, and M20 also demonstrated acceptable predictive capability, with RMSE around 3.80 MJ/m²/day, MPE close to 10.7%**,** and near-zero MBE, making them reliable alternatives for GSR estimation in Jiri. In contrast, models such as M1, M5, and M9 had higher RMSE **(**~4.7 MJ/m²/day**)** and larger MPE (~15%)**,** reflecting weaker performance and limited suitability for accurate GSR prediction.

3.3 R^2-Based Performance

Based on the coefficient of determination, M14 again performed best **(**R^2 = 0.671**),** followed by M15 (R^2 = 0.643). The next three models; M20 (R^2 = 0.532)**,**M13 (R^2 = 0.526)**,** and M18 (R^2 = 0.521)**,** showed moderate agreement with observed data. These results highlight M14 and M15 as the most reliable models for estimating daily GSR in Jiri, with M20, M13, and M18 as reasonable alternatives.

4 Discussion

The evaluation of empirical models shows that M14 and M15 are the most reliable for estimating daily global solar radiation (GSR) in Jiri, with the strongest correlation to measured data (highest R^2) and minimal bias, as detailed in the Model Performance Analysis section. Models M20, M13, and M18 performed moderately well and can serve as alternative options. The dominance of M14 and M15 indicates that incorporating multiple meteorological parameters, particularly temperature and humidity, enhances model accuracy and stability under local climatic conditions.

The annual mean global solar radiation (GSR) at Jiri, Nepal (15.05 MJ/m²/day ≈ 4.18 kWh/m²/day) is largely consistent with neighboring eastern and southern Nepal sites. It is slightly higher than Biratnagar (14.97 MJ/m²/day)[30] and nearly equal to Dhankutta (15.10 MJ/m²/day)[31.32], Taplejung (15.17 MJ/m²/day)[33], and Okhaldhunga (15.17 MJ/m²/day)[34], indicating a relatively uniform solar resource across these eastern and mid-hill regions. However, Jiri's GSR is considerably lower than that of Jumla (19.58 MJ/m²/day)[35]in the high Himalayan plateau, where clearer skies, higher elevation, and reduced cloud cover result in substantially greater solar irradiance. Similarly, Kathmandu exhibits slightly lower radiation (~13.55 MJ/m²/day)[36], reflecting urban and valley effects on solar availability.

When compared with global locations, Jiri's GSR is higher than New York City (14.07 MJ/m²/day) and Hong Kong (13.52 MJ/m²/day**)**, but lower than arid and tropical regions such as Cairo, Egypt (19.92 MJ/m²/day), Amman, Jordan (20.51 MJ/m²/day), and Juba, South Sudan (19.66 MJ/m²/day)[37,38]. This comparison illustrates that Jiri possesses a moderate solar resource typical of humid subtropical and monsoon-influenced mountainous regions, whereas desert and tropical climates exhibit substantially higher solar availability due to clearer skies and lower cloud persistence.

Figures 2–9 illustrate the seasonal and interannual variations of GSR and meteorological parameters. Daily comparisons for 2021–2024 (Figures 2–5) confirm that top-performing models capture seasonal trends accurately, with peak radiation during pre- and post-monsoon periods and minima during the monsoon. Monthly GSR patterns (Figure 6) peak in spring (March–May), while precipitation (Figure 7) and wind speed (Figure 8) highlight the climatic influence on solar availability. Figure 9 confirms that seasonal GSR is highest in the pre-monsoon and lowest during the monsoon, reflecting the strong dependence of solar radiation on local atmospheric conditions.

Overall, the observed GSR at Jiri reflects the characteristic mid-hill climate of Nepal, where cloud

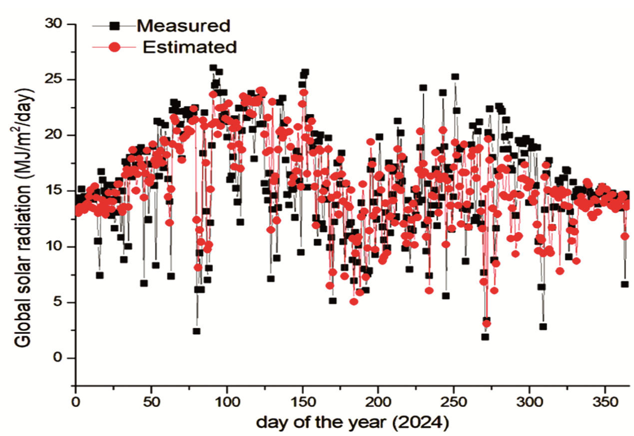

Fig. 2 — Variation of measured and estimated GSR at Jiri for 2024

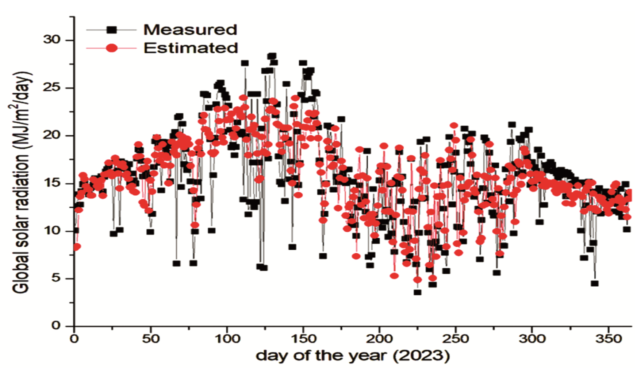

Fig. 3 — Variation of measured and estimated GSR at Jiri for 2023

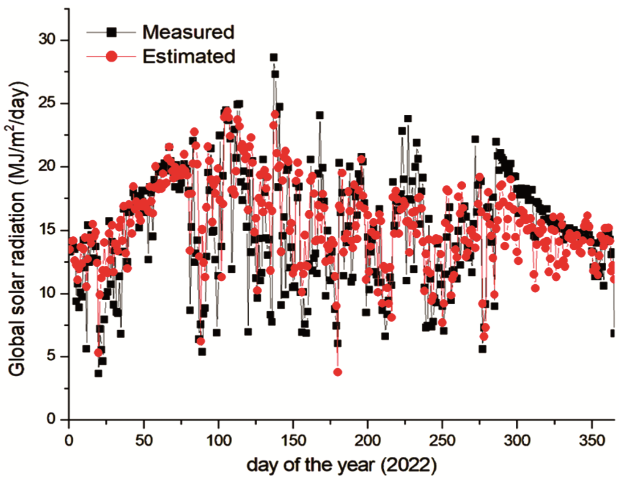

Fig. 4 — variation of measured and estimated GSR at Jiri for 2022

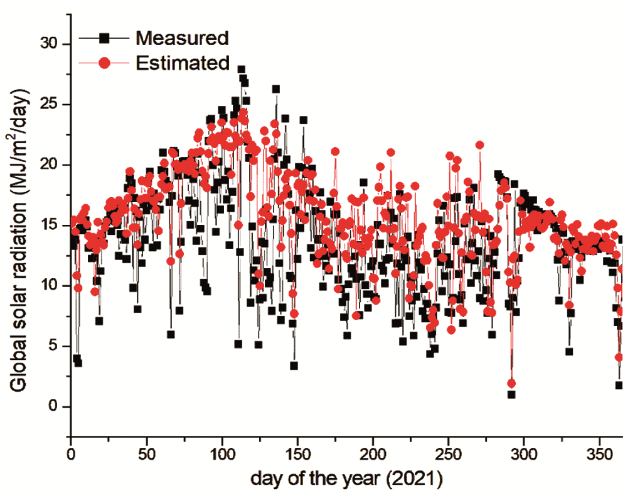

Fig. 5 — variation of measured and estimated GSR at Jiri for 2021

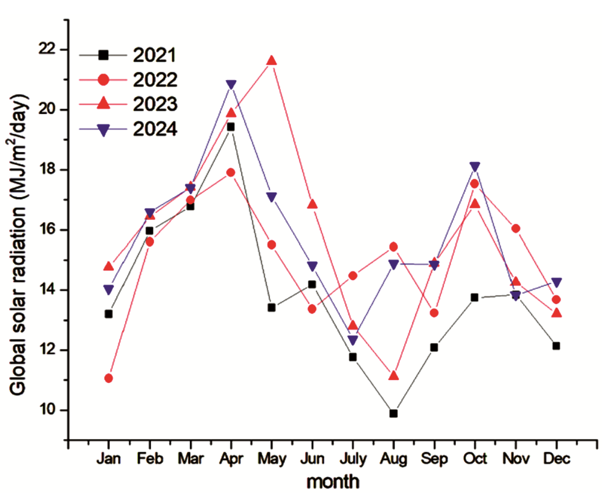

Fig. 6 — Monthly Fluctuation of GSR at Jiri

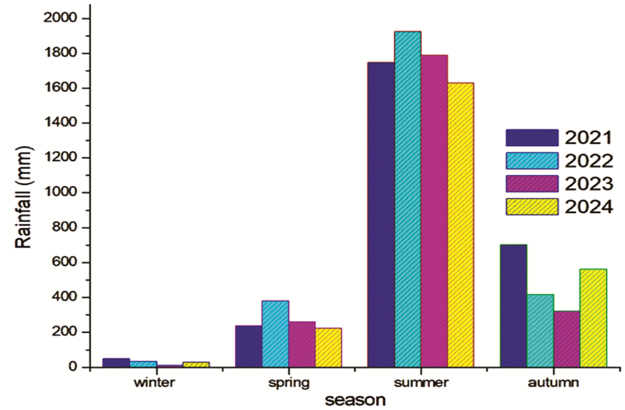

Fig. 7 — Seasonal Fluctuation of Precipitation at Jiri

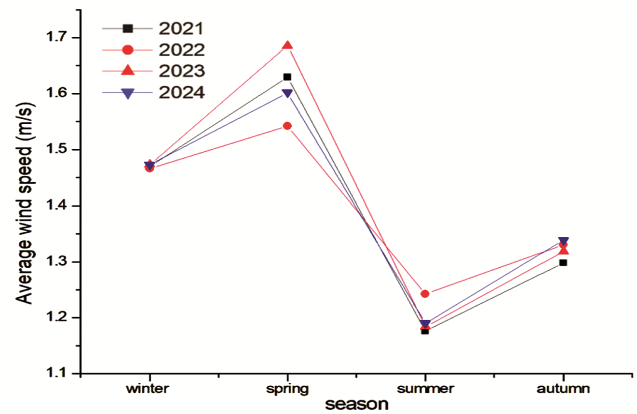

Fig. 8 — Seasonal Fluctuation of Average Wind Speed at Jiri

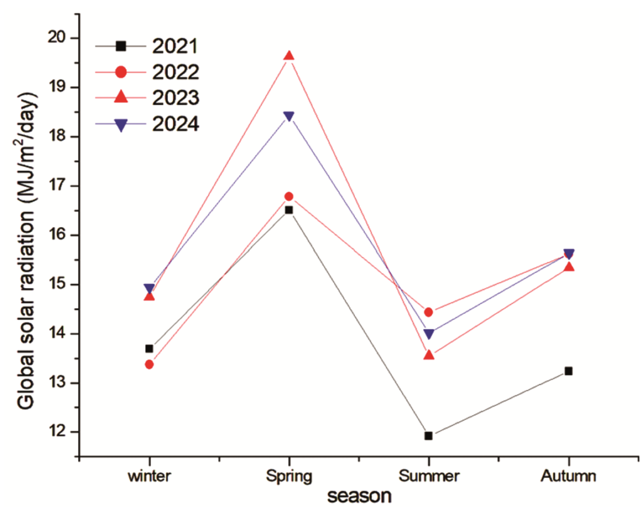

Fig. 9 — Seasonal Fluctuation of GSR at Jiri

dynamics and atmospheric moisture are more decisive than altitude alone in determining solar energy potential, and the R^2-based evaluation reinforces M14 and M15 as the most suitable models for accurate long-term solar assessment in this region.

5 Conclusion

This study assessed the suitability of twenty empirical models for estimating daily global solar radiation in Jiri, Nepal, using RMSE, MBE, MPE and coefficient of determination (R^2) as primary evaluation criteria. The results identified Models M14 and M15 (Modified Angstrom (new) Models) as the most reliable, owing to their lowest prediction errors, minimum relative deviation, and negligible bias.

For Model M14, the regression coefficients are as follows: the intercept a = 0.713, the sunshine duration ratio coefficient b = -0.032, the temperature difference coefficient c = 0.014, and the relative humidity coefficient d = -0.005. The positive **c** indicates that an increase in temperature difference enhances global solar radiation, while the negative b and d values reflect slight inverse effects of sunshine duration ratio and relative humidity, respectively.

For Model M15, the coefficients area = 0.751, b = -0.035**,** c = 0.149 (normalized temperature difference), and d = -0.005**.** Here, the strong positive **c** demonstrates the significant contribution of normalized temperature difference to solar radiation, while relative humidity again shows a negative influence.

The annual average solar insolation of 4.18 kWh/m²/day indicates that Jiri possesses substantial solar energy potential. Therefore, the region is well-suited for promoting and developing solar energy technologies, particularly for decentralized and rural energy applications.

Models M17, M18, and M20 also performed satisfactorily and may serve as alternative options where data availability or model simplicity is preferred. The findings confirm that error-based statistical indicators are more appropriate than correlation-based metrics for estimating global solar radiation in complex mountainous regions such as Jiri.

The recommended models can support accurate solar resource assessment and contribute to effective solar energy planning in Nepal's mid-hill regions.

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