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Insolation Dynamics and Their Influence on Climate Variability in Northern Malaysia: A Case Study of Perlis

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Abstract – Solar insolation represents one of the Earth's most important renewable energy sources. In Perlis, Malaysia, high levels of solar radiation are experienced year-round, with notable variations in weather conditions. These fluctuations play a significant role in shaping the region's insolation patterns. Therefore, this study aims to explore the interdependency between weather variability and insolation patterns in Perlis, focusing on two main objectives: first, to examine seasonal variations in weather conditions, and second, to determine correlations between weather variables and insolation throughout the year. To achieve these objectives, the study begins with comprehensive data acquisition, where meteorological data are analysed to identify seasonal trends and fluctuations in weather conditions. At the same time, solar radiation data are carefully generated using a Digital Terrain Model (DTM), ensuring accurate representation of spatial variability. Following this, statistical analyses, particularly correlation methods, are applied to evaluate the relationships between key meteorological variables and insolation. The findings reveal that temperature and precipitation exhibit moderate correlations with insolation patterns, with coefficients of determination (R^2) of 0.5549 and 0.5458, respectively. In contrast, wind speed shows only a weak relationship with insolation, indicated by a low R^2 value of 0.0537. Building on these results, Geographic Information System (GIS) techniques are employed to map the spatial distribution of both insolation and weather variables across the study area. Overall, the integration of statistical and spatial analyses provides a comprehensive understanding of how seasonal weather variations influence solar radiation in Perlis. These insights are valuable for supporting environmental management strategies and enhancing local-level planning and decision-making, particularly in the context of renewable energy development.

Keywords *– Insolation; Renewable Energy GIS; Weather Variation*

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1.0 Introduction

Insolation is an important element in the Earth's energy balance and climate regulation. It is the energy from the sun received on Earth's surface after going through the atmosphere, where it is scattered, absorbed, or reflected. Solar energy at the outer edge of the atmosphere is, on average, 1.94 calories per minute per square centimetre, equivalent to roughly 1361 watts per square metre. Solar radiation's energy characteristics are determined by its wavelength and frequency, which are directly related and inversely proportional; shorter wavelengths correspond to higher frequencies and greater energy levels (Zorzi et al., 2022; Navarro-Serrano et al., 2020).

Insolation is also crucial to Earth's processes, such as photosynthesis, evaporation, and climate control. Precise modelling of solar radiation is needed to forecast climate patterns, estimate impacts of urbanisation, and maximise solar energy installations (Li et al., 2019; Sengupta et al., 2023). Technological developments in satellite and radiometry have significantly enhanced the observation of solar energy across spatial and temporal scales, boosting global energy assessments (Potapenko et al., 2019). The diffusion of solar radiation on Earth is heavily influenced by atmospheric factors such as cloud cover, aerosols, and atmospheric composition. Seasonal changes and geographic locations affect sunlight levels and regional climates (Chase et al., 2021). Although equatorial regions receive constant sunlight, they are still subject to climate variability in precipitation and humidity (Mantsis et al., 2011). Moreover, human activities, such as greenhouse gas emissions, are altering atmospheric heat retention, thereby disturbing planet-wide climatic and hydrological cycles (Cassia et al., 2018; Wang & Liu, 2023).

Perlis, Malaysia, was selected as the study area due to its distinctive tropical monsoon climate, which is characterised by pronounced seasonal variability in rainfall, temperature, humidity, and cloud cover. These climatic fluctuations significantly influence insolation patterns, making the region highly suitable for examining weather–insolation relationships (Mehazzem et al., 2022). In addition, Perlis experiences consistently high levels of solar radiation throughout the year, indicating strong potential for solar energy exploitation, particularly for photovoltaic (PV) systems. The state also plays an important role in agricultural production, where crop growth cycles are closely linked to variations in solar radiation and weather conditions. As highlighted by Zhang et al. (2022), climate variability and change can substantially affect both solar energy generation and agricultural productivity in tropical regions, further reinforcing the relevance of this study area. Moreover, the relatively small spatial extent of Perlis enables more detailed and accurate spatial analysis using Geographic Information System (GIS) techniques, allowing for clearer identification of insolation patterns and their controlling factors.

Topographic factors such as aspect, slope, and terrain attributes result in significant variations in sun exposure. Sun-facing areas receive more direct sunlight, while shaded spots receive less (Dusyarov et al., 2023). Advanced GIS and digital terrain analysis methods allow scientists to readily map these differences and incorporate them into broader ecological and climatic research (Jin et al., 2010). As such, topographic modelling is critical for elucidating localised impacts of solar radiation. Substantial research has enhanced our understanding of insolation variations driven by natural cycles and human activities affecting global climate systems. Solar input variations have been linked with variations in precipitation and temperature, as well as ecological stability (Saad et al., 2014; Matsushita et al., 2024). Variations can significantly affect agriculture and regional biodiversity (McGrath et al., 2021). In that sense, insolation dynamics is critical to climate science as well as effective environmental administration (Bosmans et al., 2015; An et al., 2020).

This study aims to investigate patterns of solar radiation's relationship with variations in meteorological parameters, specifically precipitation, temperature, wind velocity, and wind direction in equatorial regions with special reference to Perlis, Malaysia. Located at the northernmost part of Peninsular Malaysia, Perlis enjoys a tropical equatorial climate with high levels of solar radiation, narrow seasonal variations, and well-marked wet and dry seasons. Since equatorial regions are known to exhibit unique climatic characteristics with high levels of solar irradiance, the intensity and distribution of solar radiation can significantly affect local weather patterns.

According to existing research on tropical climates, shifts in annual temperature and rainfall patterns (Zorzi et al., 2022; Navarro-Serrano et al., 2020). Meteorological parameters also have significant impacts on agricultural productivity, as the region's agricultural sector strongly depends on appropriate weather conditions, with temperature and precipitation variations directly affecting crop growth and yield (Chase et al., 2021). Hence, two objectives have been defined: first, to examine the seasonal variation in weather conditions, and second, to determine the correlation between weather variables and insolation throughout the year.

Furthermore, understanding the impact of weather on insolation can improve the performance of photovoltaic installations, with potential added value for energy sustainability, as solar installations become increasingly important for meeting energy demand through efficient agricultural and energy resource utilisation in regions like Perlis, Malaysia.

2.0 Literature Review

2.1 Incoming Solar Radiation (Insolation)

One of the main factors in Earth's climate and ecological balance is insolation, influencing phenomena ranging from biological productivity to weather patterns. Due to complex interactions among topography, atmospheric processes, and human disturbances, it is increasingly essential to adopt a multidisciplinary approach to conceptualising and forecasting the effects of solar radiation across varied geographical locations. It has a profound impact on the energy balance and the development of surface climate processes, such as vegetation distribution, photosynthesis, metamorphism, soil moisture, and sensible and latent heat fluxes. Furthermore, sustained global climate studies require linking local, regional, and global range variability in solar radiation and other climate variables. Many factors contribute to the variability in solar radiation, and those closely related to topography include surface albedo, slope, aspect, illumination angle, shading, altitude, and atmospheric conditions (Dubayah, 1991).

Solar radiation, the primary source of global climate, impacts water, energy, and biophysical fluxes at the surface. Its fluctuations are affected by factors such as topography, latitude, surface reflectance, and atmospheric conditions. Among these, topography plays a key role in estimating incoming solar radiation at coarse spatial and temporal scales (Loechel, 1996).

2.2 Concept of Insolation

The quantity of solar energy that the Earth's surface receives per unit area is known as insolation, or incoming solar radiation. Multiple important factors influence the distribution and intensity of insolation. One such element is the sun's angle: the sun's rays strike the surface more directly when it is higher in the sky, closer to a 90° angle, which increases the intensity and concentration of energy, as shown in Figure 1. Since Earth's angle of tilt induces fluctuations within sun exposure over the span of a year, both seasonality and latitude similarly contribute significantly. Although extreme-latitude points exhibit pronounced seasonal variations, equatorial points often experience greater consistency in direct sunlight.

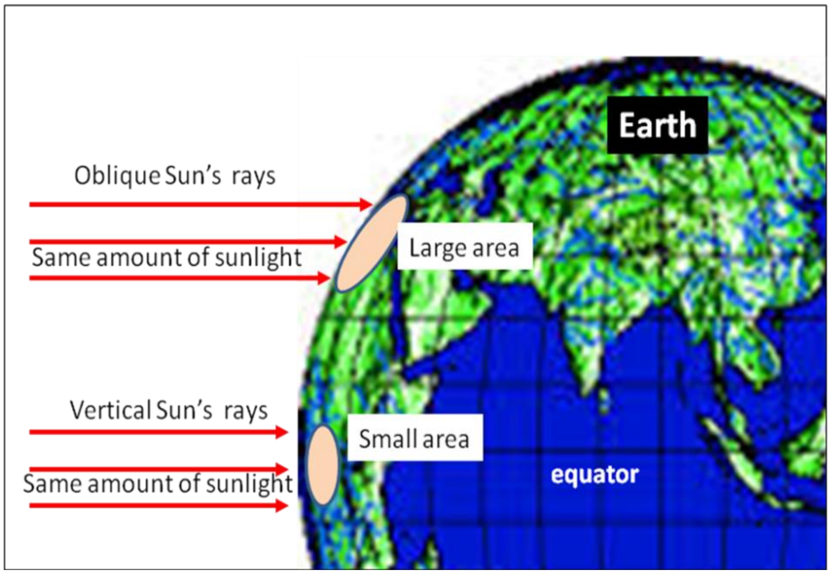

Figure 1: Effect of latitude on insolation value

2.3 Types of Insolation

According to Li et al. (2015), there are three types of incoming solar radiation: direct, diffuse, and reflected. Kumar et al. (1997) state that these components vary due to interactions between atmospheric constituents and the solar radiation passing through them. The absorption of different gases in the atmosphere, the molecular effects of permanent gases, and the scattering effects of particles are a few examples of these interactions. Direct irradiance, diffuse irradiance, and reflected irradiance are the three components of solar radiation that will be covered in the following discussion, as shown in Figure 2.

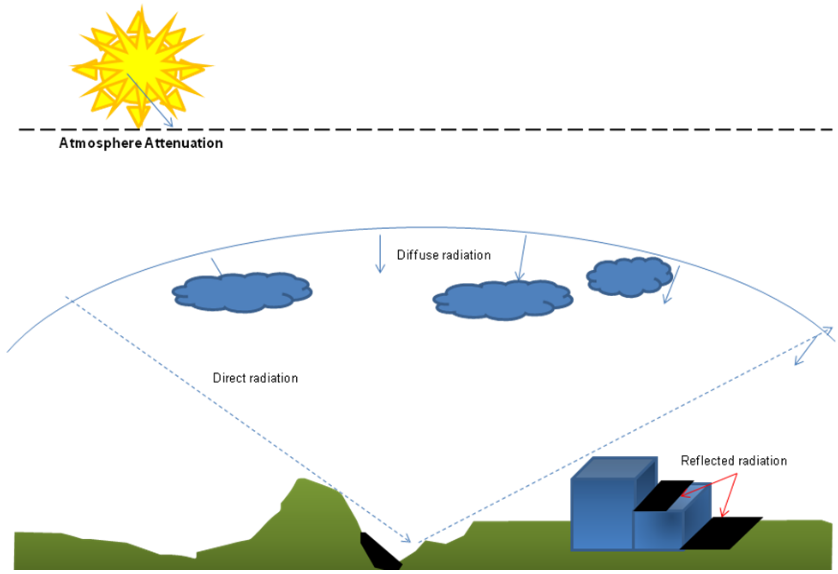

Figure 2: Illustration of solar irradiance received by the Earth's surface: Direct, diffused and reflected irradiance

2.4 Climate Patterns in the Northern Malaysia Region, Perlis

Perlis, Malaysia, experiences significant seasonal variations due to its location. Understanding how temperature, humidity, rainfall, and solar radiation interact to drive these changes is essential for improving solar energy utilisation and agricultural productivity. Unpredictable weather results from the area's high insolation, which affects temperature and precipitation patterns, especially during monsoon seasons. Increased solar radiation exposure can stress crops, reduce soil moisture, and increase evaporation, all of which can affect agricultural productivity (Zorzi et al., 2022; Chase et al., 2021). In tropical locations, climate variables, including rainfall and sun radiation, have a major impact on agricultural productivity (Zorzi et al., 2022). Crop management and planning are improved by accurate temperature and precipitation forecasts enabled by a deeper understanding of these processes. Additionally, incorporating solar energy into agriculture can promote food security and improve regional sustainability (Mantsis et al., 2011).

2.5 Study on the Relationship Between Insolation Patterns and Weather Variables

Researching the connection between insolation patterns and climatic variability is essential in tropical regions, such as Perlis, Malaysia, where solar radiation drives key weather processes. Management of agricultural and renewable energy resources can be improved by knowing how insolation affects temperature, wind, and rainfall. Monsoon rainfall, sea surface temperatures, and surface winds in tropical regions are significantly affected by seasonal changes in insolation, according to research (Zhou et al., 2024; Wen et al., 2022). In areas that depend on the monsoon, increased insolation has a significant impact on rainfall distribution and agricultural outcomes by increasing moisture availability and intensifying monsoon activity.

It is commonly known that insolation and climate variability are related across time. Changes in tropical spring insolation, for instance, may cause abrupt shifts in Asian summer monsoon dynamics over long timescales, as Zhang et al. (2024) show. Precipitation patterns and temperature dynamics are significantly influenced by both local and regional insolation levels, according to this relationship. Precipitation anomalies across different habitats can be attributed to interhemispheric insolation gradients, according to studies. Deininger & Co. Deininger et al. (2020) described how differential reactions in monsoonal systems are caused by changed regional land-sea temperature gradients brought on by shifting insolation. In addition to affecting local weather, these variations also provide insight into longer-term, more general weather-related changes.

Agriculture in areas like Perlis is directly affected by how insolation influences climate variability. Changes in solar radiation directly affect crop yields and agricultural productivity patterns because they are correlated with variations in temperature and rainfall distribution. According to Wen et al., high temperatures resulting from increased insolation can cause heat stress in crops, which could impair growth and yield (Wen et al., 2024). The importance of precise meteorological and insolation data for guiding planting decisions and agricultural operations is underscored by this relationship.

Furthermore, sectors related to renewable energy are affected by changes in the global climate. Photovoltaic (PV) systems and energy production techniques can be optimised by knowing how insolation affects wind and precipitation dynamics.

3.0 Methodology

The Phase II data acquisition process consists of two main elements, as shown in Figure 3: the acquisition of meteorological parameters such as rainfall, temperature, and wind velocity and direction, and the application of Sentinel-1A satellite imagery to develop a Digital Terrain Model (DTM). These data were processed using Inverse Distance Weighting (IDW) to produce accurate spatial representations. In line with the overall initial aim of obtaining detailed spatial portrayals of meteorological parameters, Phase III is on data processing. The accumulated data is used to produce several maps: an insolation map, a rainfall map, a temperature map, and a map showing wind direction and speed. To fulfil the secondary goal of ascertaining links among variations in weather and insolation patterns, Phase IV conducts a results analysis in which correlation analyses are carried out on processed data. This is a systematic approach that yields insightful findings on the impacts of weather factors on solar radiation in the region, with a coherent line from data acquisition to complete analysis.

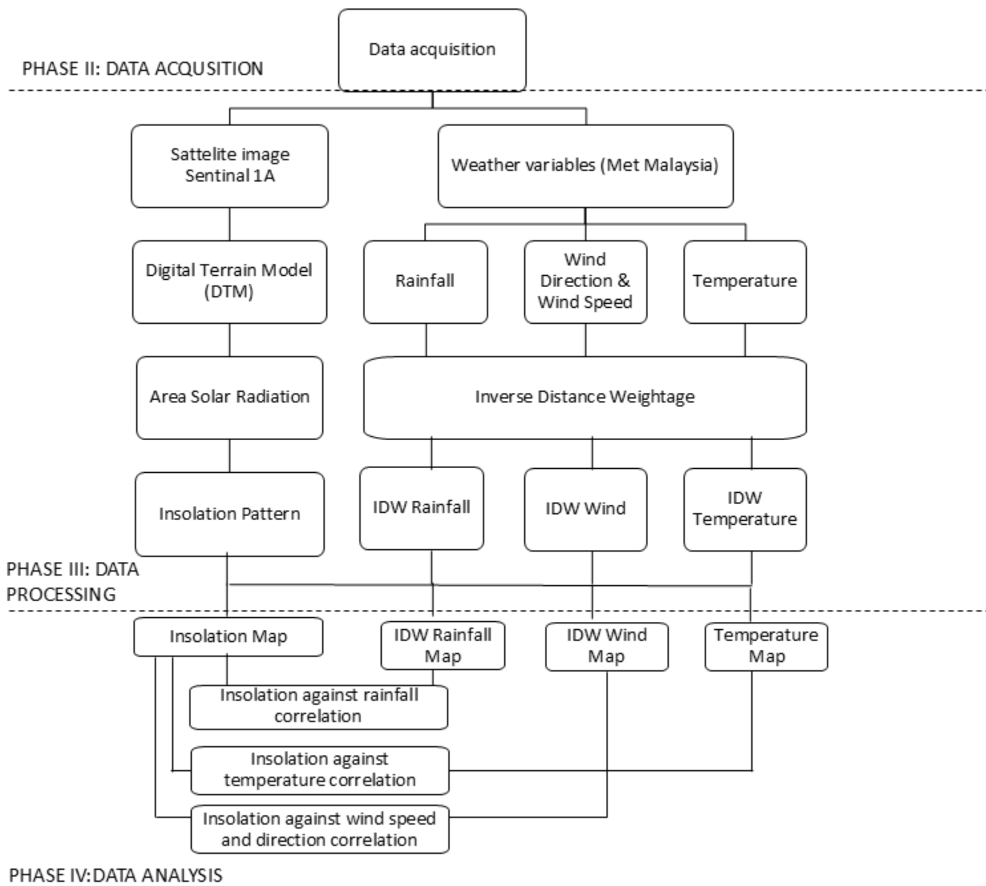

Figure 3: General flowchart of methodology

4.0 Result and analysis

4.1 Insolation Pattern of Perlis

Figure 4 shows monthly insolation amounts (Wh/m²) in Perlis, Malaysia. Solar power was highest in Perlis during the Southwest Monsoon in May, at 463,739 Wh/m². It then rose slightly to 464,293 Wh/m² in June, after which insolation began to decrease. In July, the maximum insolation was 472,410 Wh/m². August and September show significant reductions to 444,104 Wh/m² and 410,465

Wh/m², respectively, implying that wind blowing is at its peak. Varying amounts of insolation characterise the Northeast Monsoon between November and March. In November, the value was 354,366 W/m², while in December, it increased slightly to 350,682 W/m². January's value was 363,946 Wh/m². March has a peak of 401,235 Wh/m², indicating better skies, whereas February decreases to 336,972 Wh/m². In October, the range of 0 to 377,216 Wh/m² indicates increased cloud cover, while in April, the range is 0 to 429,156 Wh/m², indicating clearer skies. The intersessional monsoon transitions are represented by these numbers. These variations highlight how the monsoons affect the availability of solar energy, which is essential for optimising solar energy harvesting in the area.

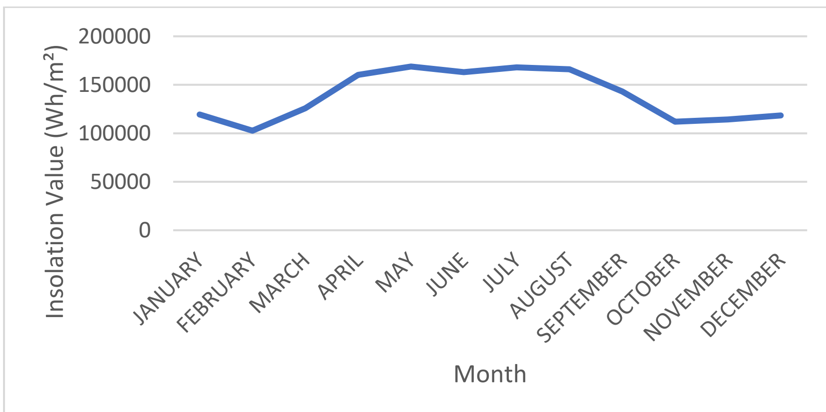

Figure 4: Graph of insolation pattern throughout a year in Perlis

4.2 Monthly Weather Variation in Perlis, Malaysia

4.2.1 Rainfall

The monthly rainfall distribution during the Southwest and Northeast Monsoon seasons is presented in Figure 5. With the orographic effect, rainfall starts at 172–251 mm in May, peaks in June at 237–277 mm, then declines from July (136–220 mm) to September (135–181 mm), with the highest amounts near the coast, particularly around Hospital Kangar. November's rainfall ranges from 241.21 mm to 385.2 mm, December's peaks at 370.01 mm to 444.5 mm, and January's rainfall ranges from 7.61 mm to 24.8 mm, indicating a transitional phase during the Northeast Monsoon. Sites such as Wang Kelian and Hospital Kangar have high rainfall; in February, rainfall ranged between 205.77 mm and 247.66 mm, while in March, it fell between 157.61 mm and 230.5 mm. Although rainfall amounts were not very high in other months (172.31 mm – 223 mm), this period is characterised by a noticeable increase (242.02 mm – 388.21 mm) from the Southwest through the Northeast Monsoon until October sets in, mostly around Hospital Kangar. These trends demonstrate how monsoons affect rainfall, hence altering local water systems, agriculture, and resource planning.

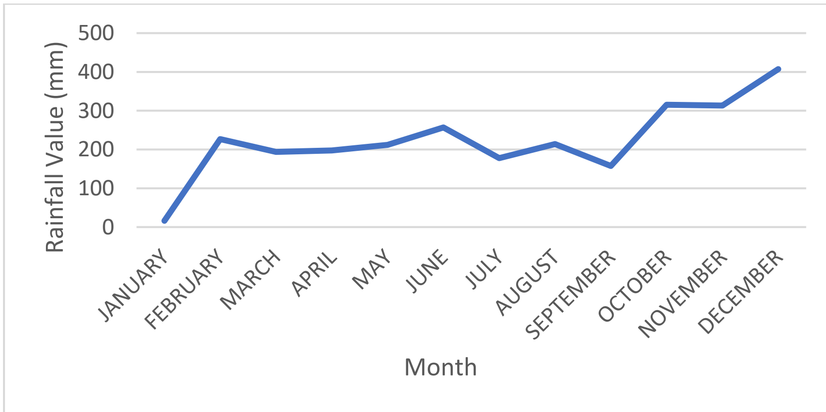

Figure 5: Graph of monthly rainfall throughout a year in Perlis

4.2.2 Temperature

Figure 6 shows the monthly temperature graph in Perlis influenced by the monsoon. Hospital Kangar station records the highest temperatures during the Southwest Monsoon (May to September) due to its urban location and the urban heat island effect. Felda Chuping ranks second in terms of temperature, probably because of its open land and agricultural activities. By contrast, lower temperatures are experienced at Wang Kelian and Padang Veterinar Padang Besar stations in higher, more vegetated locations. With cooler air brought by the Northeast Monsoon (November to March), temperatures range from 25°C to 28°C; northern areas, including Wang Kelian and Padang Veterinar Padang Besar, generally show a drop in temperatures. Temperatures range from 25°C to 28°C during the intersessional monsoon seasons in April and October; the highest temperatures are near Hospital Kangar and Felda Chuping, while cooler temperatures are in the northern and eastern sections, reflecting the transitional weather patterns between the two monsoon seasons.

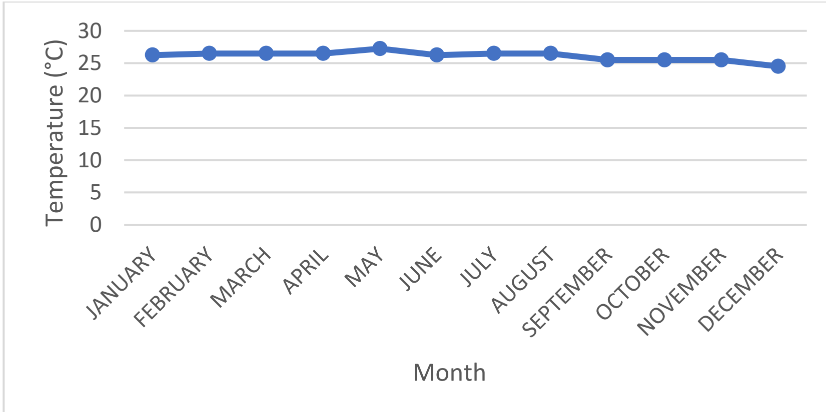

Figure 6: Graph of monthly temperature map throughout a year in Perlis

4.2.3 Wind speed and wind direction

Wind speed patterns during the Southwest Monsoon (May-September) and Northeast Monsoon (November-March) seasons, as well as the transitional periods in April and October, are depicted in Figure 7. In May, the wind speeds near Hospital Kangar reached a peak of 8.686 m/s before decreasing to 6.891 m/s in June and increasing to 7.990 m/s in July before dropping to 6.792 m/s in August and slightly increasing to 7.988 m/s in September. This is the Southwest Monsoon. The strongest winds are directed from the northeast toward the southwest during the Northeast Monsoon, with wind speeds reaching as high as 13 m/s in January and December. The wind speeds in the northern regions, such as Wang Kelian and Padang Veterinar Padang Besar, are lower.

In contrast, the southern regions, such as Hospital Kangar and Felda Chuping, experience stronger winds. The intensity of the winds decreases gradually from January to March. Wind speeds during the April and October inter-monsoon periods do indicate some transition between the monsoon seasons. They vary from 4.211 to 6.686 m/s. The highest speeds were recorded around Hospital Kangar. This is because their static direction reflects how the prevailing winds evolve with seasonal variations, as clearly seen around regions like Hospital Kangar.

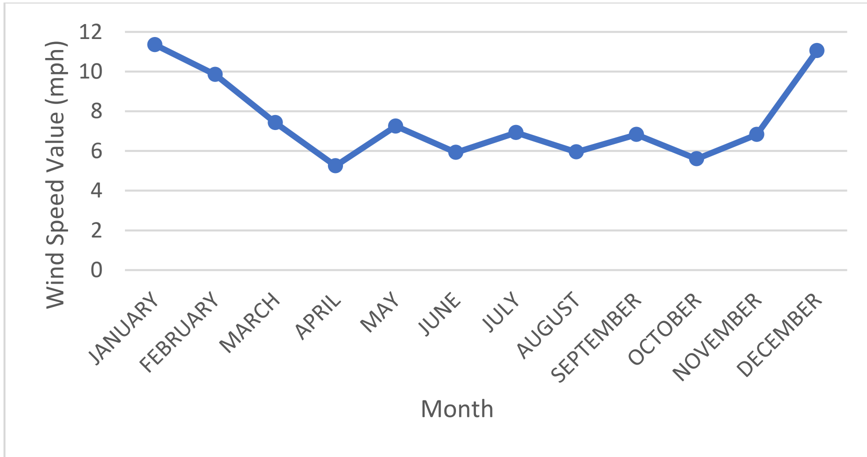

Figure 7: Graph of monthly wind speed throughout a year in Perlis

4.3 Relationship between Weather Variation and Insolation Pattern

4.3.1 Rainfall against insolation pattern

Figure 8 illustrates the correlation between insolation and rainfall in Perlis, with distinct patterns observed during the Northeast and Southwest Monsoons. The Northeast Monsoon (January to March and November to December) is characterised by substantial fluctuations in both rainfall and insolation. In November and December, rainfall is particularly high, resulting in increased cloud cover and reduced solar radiation. Conversely, the Southwest Monsoon (May to September) is characterised by consistent rainfall and slightly higher insolation, indicating fewer cloudy days and more direct sunlight. The moderate positive correlation coefficient ($R^2 = 0.5458$) indicates that increased rainfall is likely correlated with higher insolation, which is likely due to higher evaporation rates. This is consistent with research conducted in Eastern India, where vegetation growth is influenced by solar radiation and is correlated with increased rainfall.

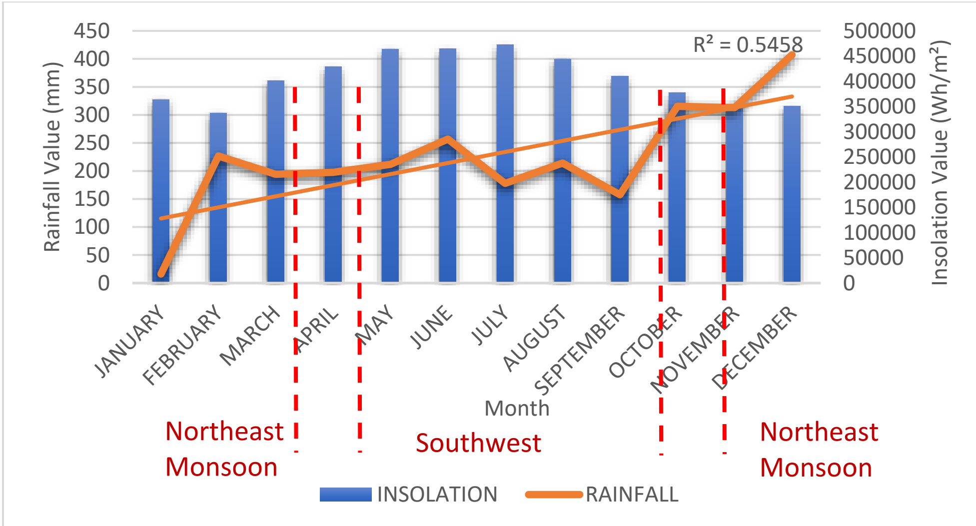

Figure 8: Rainfall vs mean insolation value

4.3.2 Temperature variations against insolation pattern

Temperature and insolation trends in Perlis during 2022, as influenced by the monsoon seasons, are shown in Figure 9. Temperature (°C) is shown as an orange line that drops from around 27.5°C in January to 26°C in December, while insolation (kWh/m²), calculated using equation (1), is shown as blue bars that peak in June and July during the Southwest Monsoon. $R^2 = 0.5549$, which is moderate and indicates that temperature and insolation are related, but not fully reliant on one another. The Northeast Monsoon (October-December) differs from the Southwest Monsoon (May-September) in terms of cooler temperatures and sun energy. The Southwest Monsoon experiences higher insolation because of its clearer skies, whereas the Northeast Monsoon experiences lower insolation because of cloud cover and precipitation. Factors such as humidity and wind patterns contribute to the relatively consistent temperature. Lower temperatures characterise the Northeast Monsoon, with reduced solar radiation due to cold Siberian air currents.

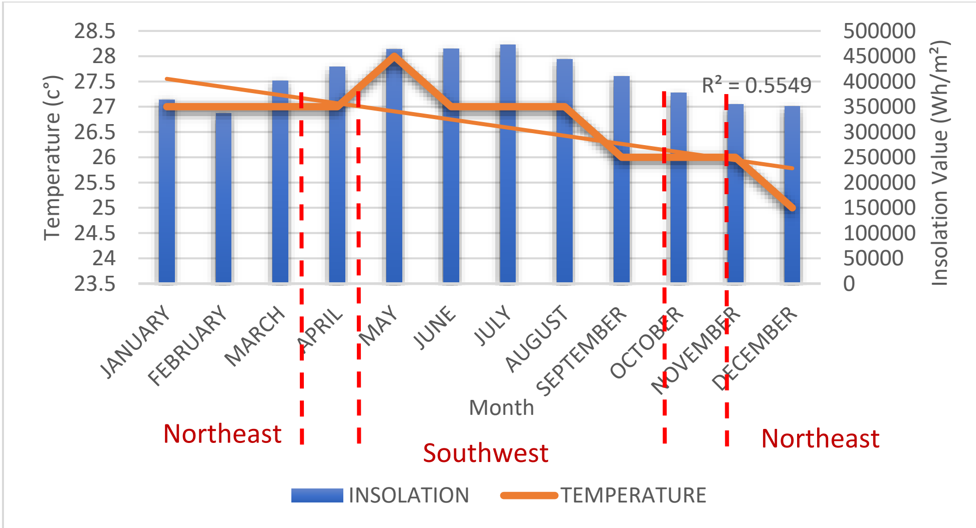

Figure 9: Temperature vs mean insolation

4.3.3 Wind speed and direction against insolation pattern

The relationship between wind speed, wind direction, and insolation patterns, reflecting the influence of the monsoon seasons, is presented in Figure 10. The blue bars represent solar radiation (kWh/m²), while the orange line shows wind speed (m/s). During the Northeast Monsoon (January-March, October-December), wind speeds decrease from 11.35 m/s in January to 5.25 m/s in April, rise slightly during the Southwest Monsoon (May-September), peak at 7.25 m/s in May, then decline again. Solar radiation remains relatively steady, peaking during the Southwest Monsoon at 400,000-450,000 kWh/m² and staying above 300,000 kWh/m² during the Northeast Monsoon. The low R^2 value of 0.0537 indicates a weak correlation between wind speed and solar radiation, suggesting that solar energy potential in Perlis is stable and not significantly affected by changes in wind speed, making it a reliable energy source year-round. Research also supports that monsoon elements have minimal impact on annual solar radiation, with no direct correlation between rainfall, wind speeds, and solar insolation.

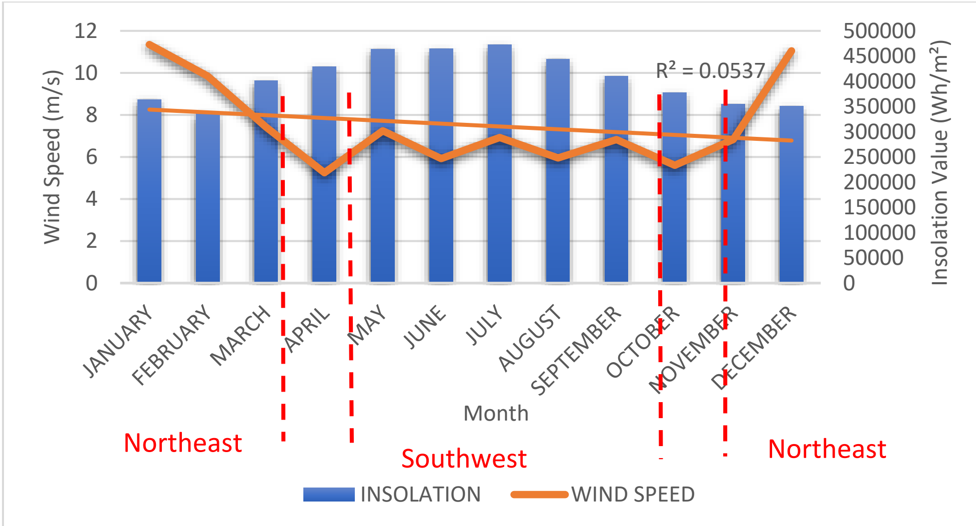

Figure 10: Wind speed and direction vs insolation patterns

5.0 Discussion

Some worthwhile recommendations are presented based on the outcomes of this research to further knowledge and control of weather fluctuations due to insolation over Perlis, Malaysia. Initially, future research needs to expand its temporal scale by utilising multi-year datasets. This would be for ascertaining cyclical variations and long-term trends, as well as anomalies, in the correlation between meteorological elements and insolation.

Furthermore, an improved characterisation of intraseasonal local climate variability can be achieved by increasing the number of meteorological observation stations throughout Perlis, as well as by using fine-spatial-resolution insolation measurements. Improved data resolution and coverage would assist all these applications, including weather forecasting, climate modelling, and insolation mapping, by improving accuracy.

Finally, using additional meteorological characteristics, such as pressure and humidity, could help provide an even more complete understanding of the intricate relationships within the climate system at regional scales. These would also be included to enable further and more detailed climate modelling. Further, even predicting local weather variations based on insolation patterns can presumably be significantly enhanced by using the same higher-order analytical techniques, i.e., predictive modelling and machine learning, for that task alone. In this way, methods such as these could be applied to help find hidden patterns more easily, with higher accuracy and more actionable insights.

6.0 Conclusion

The monsoons during the wet and dry seasons influence Perlis's climate. The northeast monsoon (November – March) is cool and brings high rainfall, causing occasional floods. Conversely, the southwest monsoon (May-September) is hot and dry, which can lead to water scarcity. April and its reverse month, October, are both inter-monsoon months, typified by short spells of rain. Insolation estimates in the area are heavily influenced by dataset resolution. Despite the overall correlation between weather and insolation, this research found only a weak relationship because other variables became more important. It is also possible due to its climatological patterns, data resolution, and regional method limitations. Local agricultural and water supply ecosystems remain heavily dependent on the monsoonal climate. This ongoing reliance on rain-fed agriculture heightens vulnerability to extreme weather events while emphasising the potential for solar energy deployment.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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