International Journal on Food, Agriculture, and Natural Resources
Volume 05, Issue 04, Page 100-104
ISSN: 2722-4066
http://www.fanres.org

Original Paper

Validation of a Sunlight Availability Simulation Model

Ar Man[1], Chatchawan Chaichana[2], Damrongsak Rinchumphu[3], Suwimon Wicharuck[4] and Ramnarong Wanison[2]*

1) *Graduate Master's Degree Program in Energy Engineering, Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*
2) *Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*
3) *Department of Civil Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*
4) *Energy Technology for Environment Research Center, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand*

*) *Corresponding Author: chatchawan.c@cmu.ac.th*

Received: 07 October 2024; Revised: 04 November 2024; Accepted: 13 November 2024
DOI: *https://doi.org/10.46676/ij-fanres.v5i4.411*

***Abstract*— Sunlight availability for plants plays an important role in determining whether a plant can produce its maximum productivity output. The study developed a Rhinoceros simulation model that can predict the sunlight availability received in the surface of interest on a vertical farming (VF) shelf design for a particular crop, given that the weather data of the location is known. The simulation model was developed and validated against the experiment. Moreover, the simulation model is compared against other research data from different countries. The dimensions of the experiments from Indonesia and Japan were replicated in the developed Rhinoceros simulation model, and the simulation results were compared against the experiment results. The analysis shows that the model can predict sunlight availability in a similar way to the research data of other studies.**

***Keywords*— Sunlight Availability, Validation, Sunlight model, Vertical Farming**

I. Introduction

Sunlight is crucial for plants as it provides the necessary energy for photosynthesis [1]. Solar radiation consists of Ultraviolet (UV) radiation (2 to 4% of the total), Photosynthetically Active Radiation (PAR) (45–50% of the total), and Infrared (IR) radiation (50% of the total) [2]. Only PAR is essential for plant growth and influences their production rate [3].

To determine whether a place chosen for a plantation will receive enough sunshine, a few criteria must be considered. The seasonal variability brought on by the yearly solar cycle and diurnal and annual temporal variations affect PAR [4]. Throughout the day, there will be varying amounts of sunlight. Studies have shown that the instantaneous PAR distribution varies significantly with the number of sunshine hours [5]. Plant photo-inhibition may result from conditions of highly varying instantaneous PAR. Systems for farming should be created to lessen the effects of excessive PAR, high temperatures during the day, and seasonal variations in PAR brought on by the sun's north-south oscillation [6]. The effectiveness of radiation is assessed based on agricultural factors that vary depending on the type of crop [7]. Shade has a serious effect on plant growth. Shade can increase specific leaf area and chlorophyll content but decrease photosynthetic capacity in certain plants [8]. PPFD (photosynthetic photon flux density) indicates the amount of light available for the plant. PPFD measures the amount of PAR that is hitting the plant at a specific location and time [9].

Solar energy is also a prominent source of energy for electrification. Direct conversion of solar energy into electricity is achieved by photovoltaic (PV) modules. Several PV modules are arranged to improve electrical production to form PV arrays. However, the productivity of PV arrays is highly susceptible to weather conditions [10]. The amount of solar radiation received by the solar panels determines how much electricity they can produce [11]. Agrivoltaic systems are designed to provide the optimum outputs in terms of crop yields and electricity production. Plants should receive the optimum PPFD in a range that ensures the survival of the plant and maximizes crop productivity, while solar panels should produce economically feasible electricity [12].

The Rhinoceros simulation model can predict the sunlight availability received on the surface of interest. The input data are the dimensions of the structure and the weather data of the location. When the structure is drawn in the Rhinoceros, the model simulates the sunlight radiation from the weather data onto the drawn structure and produces shading effects. The result is the sunlight availability received on the surface of interest. For our study, the surface of interest is an area where the crops were grown on the VF shelves. The model replicates the shading effects produced by the shelves and gives the solar radiation received on each level of the shelf.

In the author's previous studies, a simulation model was developed to predict the required setup for a VF shelf design that can grow strawberries. It was a six-shelf set up with three levels for each shelf. The simulation model can simulate the sunlight availability received by plants grown on the VF shelf. The model was constructed in Rhinoceros, and the physical shelves were built at a farm in Chiang Mai, Thailand where the measurements were made by the sensors. The two results were compared, and the simulation model was validated [13–15].

A study in Indonesia investigated different building shapes and ran simulations to determine the impacts of building shapes on solar radiation received by each surface of the building shape. The study was conducted to reduce the cost of air conditioning to cool down the building. Building shapes were explored to find a design with the least solar radiation received so that it would not be costly to cool down the building [16].

Another study in Japan developed a calculation method for PPFD values under arrays of solar panels where crops were grown in an agrivoltaic system. Shading projected by solar panels was calculated in the study. The calculation was formulated by considering the movements of the sun and solar panels' positions projecting shades to the area of interest. The calculated data were validated against the measurements made by PPFD sensors in an experiment [17].

This study aims to validate the developed Rhinoceros simulation model that can simulate the sunlight availability received on the surface of interest under the shading effects of different structures. The model is compared against the data of other studies in Japan and Indonesia. With this validated model, we could find the best potential VF shelf design using natural sunlight to grow strawberries for the allotted growing space at a farm in the province of Chiang Mai [13–15].

II. Materials And Methods

Firstly, an experiment was conducted to measure the sunlight availability received by a VF shelf design in a lot of 10m length, 10m width, and 2.5m height. The crops were grown on the VF shelves with dimensions of 8m in length, 0.3m in width, and 2.2m in height. The VF shelves were designed at a farm in Chiang Mai, Thailand, and sensors were placed on the shelves to record the sunlight availability on each shelf. After that, the Rhinoceros simulation model was developed using the experiment design. The dimensions were taken from the experiment and replicated in the simulation. The simulation gave out the sunlight availability on each shelf. The model consists of a workflow that can show the sunlight availability of the surface of interest when the object is drawn using Rhinoceros software. The model requires drawing design and weather data for the location of interest. When the object is drawn in the software, it simulates the shading effects projected onto the surface of interest and gives out the radiation received on the surface within a set time frame. Then, the results of the model were validated against the measured values from the experiment [13–15]. The time step of the Rhinoceros simulation is hourly. This study compares this model against other research in Japan and Indonesia using location-specific weather data. The objects' dimensions in Japanese and Indonesian studies were replicated in the Rhinoceros simulation model, and then the results were compared against each other, as shown in the research methodology flow chart in (Figure 1).

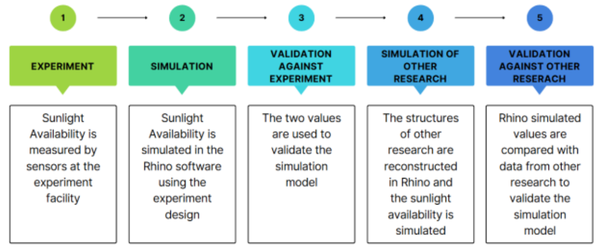

Figure 1. Research Methodology

The Indonesia study ran the simulation using the Formit application to find the solar radiation value on each side of the office building. The simulation depends on the orientation and the sun's position [16]. The radiation results of the Formit simulation are in W/m2. The Rhinoceros simulation replicated the building design of the Indonesian study and simulated the average radiation values (W/ m2) received on each side of the building. The radiations on each side between the Formit simulation and Rhinoceros simulation were compared by drawing a regression analysis plot and by calculating the R2 (coefficient of determination), RMSE (Root Mean Squared Error) and accuracy.

The Japanese study [17] used a PPFD sensor for the measurement of the PPFD (IKS-27 from Koito). The sampling period was 10 min. The solar irradiance measurement acquired every 10 s was averaged every 10 min. Data from a sunny weather day (May 29, 2017) was unaffected by the shadowing of the crops, and it was selected and compared against the Rhinoceros simulation. The Rhino simulation took into consideration all the dimensions of the Japanese experiment and acquired the hourly average PPFD values received on May 29. A line graph was plotted for each research with time (hr) Vs PPFD (μmol m2/s). The two line graphs are compared side by side to see the similarities. The two sets of values are also compared using a regression analysis plot and by calculating the R2, RMSE, and accuracy.

The quality of the simulation model was evaluated using R2, RMSE, and accuracy. Including R2 and MSE in many data-model comparison studies makes for a good combination for demonstrating how the model behaves relative to the observations [18].

The coefficient of determination is defined as the proportion of the variance in the dependent variable that is predictable from the independent variables. The worst value is $-\infty$, and the best value is +1 [19]. R2 is an estimation of the distribution of the spread between the measurable real-valued dataset and the predicted dataset [20]. R2 has negative values if the regression performed poorly and has values between 0 and 1 if the regression was good. A positive value of R-squared can be considered similar to the percentage of correctness obtained by the regression [21]. R2 is defined as equation (1).

$$R^2 = 1 - \frac{Sum\ squared\ regression\ (SSR)}{Total\ sum\ of\ squares\ (SST)} \quad \text{.............................(1)}$$

The root mean square error (RMSE) measures the average difference between a statistical model's predicted and actual values [22]. RMSE values are always greater than zero. If the value is near zero, the model can be estimated as the actual measured value [20]. RMSE is defined in equation (2).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_{exp} - S_{sim})}{n}} \quad \text{...(2)}$$

where, S_{exp} = sunlight availability from the experiment
S_{sim} = sunlight availability from the simulation
n = the number of measurements.

Accuracy is the degree of approximation to a particular expected value [23]. It is a measure of correctness. Accuracy assesses whether a series of measurements is correct on average. It is the correct value of a measured standard [24]. Accuracy is defined as equation (4).

$$\%\,Error = \frac{|Measured - Simulation|}{Measured}\ X\ 100 \quad \text{.......................(3)}$$

$$Accuracy = 100 - Average\ percentage\ error \quad \text{........(4)}$$

III. Results And Discussion

The dimensions of the experiments conducted in Indonesia and Japan are used as inputs for the Rhinoceros simulation model. The structures are replicated in the simulation models, and then the EnergyPlus Weather File (epw) weather files of the location's (TMY) typical methodological year's weather for each location are applied to the model. The results show the sunlight availability of the interested surface area for each experiment. The simulation results are then compared with the experimental results.

A. Comparison against Indonesian Research

The validation for the simulation was carried out by comparing the Rhinoceros model with other researchers' data. Research in Indonesia [16] simulated different office building shapes in a business district in South Jakarta for solar radiation on each facade of the building. The location of the study was at Jalan Perintis RT.3/RW.5, Kuningan, East Kuningan, Setiabudi, South Jakarta, Daerah Khusus Ibukota Jakarta. A square-shaped building with a footing area of 55 m2 and a height of 12.5 m was constructed in their simulation. The solar insolation was simulated for the north, east, south, and west sides of the building. The study used Formit simulations to get the results. The result from the study shows that the north side of the building would receive 724.6 W/m2, the east side of the building would receive 908.4 W/ m2, the south side would receive 522.7 W/m2 and the west side would receive a solar radiation of 883.3 W/ m2. Total average radiation received by the building amounts to 759.7 W/m2 [16].

The simulation carried out by Formit was recreated using Rhinoceros with Grasshopper plug-in, as shown in (Figure 2). Jakarta's TMY weather file was used for the simulation [25]. The results from the two simulations were similar, with an R2 value of 0.947, as shown in (Figure 3). The result is the best fit. The RMSE is 99.19. The error between the results of the two models is at an acceptable rate compared to the scale of the data. The accuracy of the simulation compared to the experimental values is approximately 87.19%. These values show that the two models can predict the sunlight availability at a similar range.

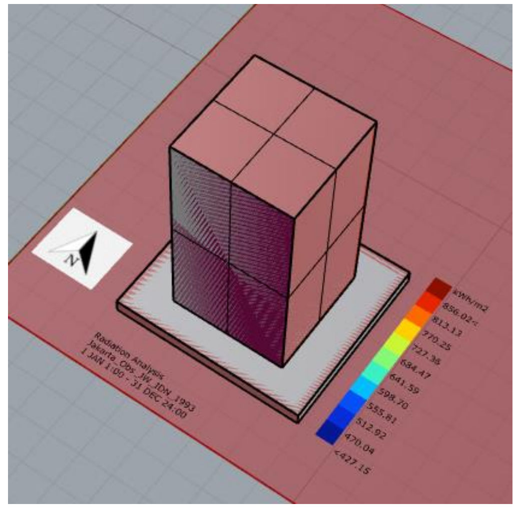

Figure 2 Indonesia office solar radiation simulated by Rhinoceros

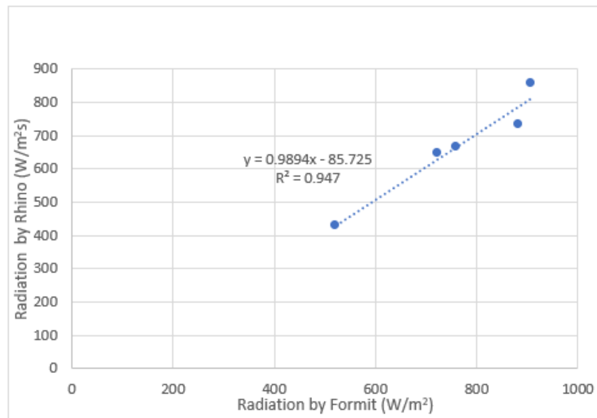

Figure 3 R^2 of solar radiation simulation results by Formit vs Rhinoceros

B. Comparison against the Experiment in Japan

Another study from Japan experimented at the University of Miyazaki. An agrivoltaic system was constructed with dimension as shown in (Table 1) and (Figure 4). The solar panels were placed at an angle of 0-degree tilt, and the sensor was placed below the solar panels in the plantation area. Then, solar insolation on surfaces above and below the PV panels was experimentally accessed. The PPFD at the point without the shading of solar panels was measured, as shown in (Figure 5a). They also performed measurements for the shaded areas under the solar panels which were recorded, as shown in (Figure 6a) [17].

Table 1 Dimensions of the experiment [17]

Items	Length/ Height/ Width (cm)
Length between centers of the solar panels	73
Width of solar panel	55
Length of solar panel	240
The diameter of the supporting tube	5
Height from PPFD sensor to center of solar panel	230
Width of spaces between each array	34

The experiment was remodeled in Rhinoceros with weather data from Miyazaki, as shown in (Figure 4). Miyazaki's TMY weather file was utilized for the simulation [25]. The results of the radiation at the location without shading were simulated, as shown in (Figure 5b). After that, the structure of the Miyazaki test was constructed in the Rhinoceros model, and PPFD values under the shading were simulated, as shown in (Figure 6b)

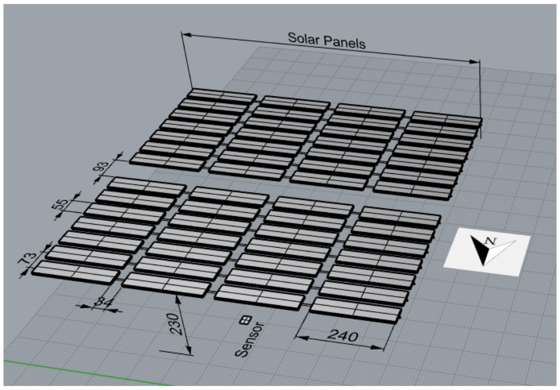

Figure 4 Japanese experiment remodeled in Rhinoceros (Dimensions are in cm).

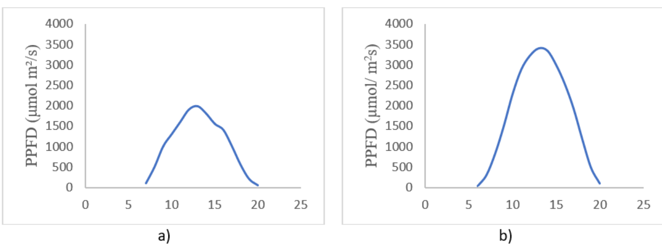

Figure 5 a) Measured PPFDs at the point without the shading of solar panels in sunny weather on May 29, 2017 [17] b) Rhinoceros simulated PPFD at the point without the shading of solar panels in typical weather on May 29

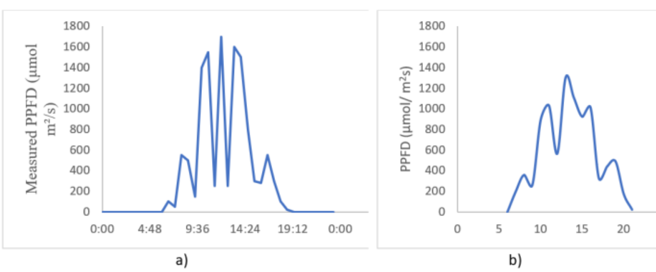

Figure 6 a) Measured PPFDs at the point under the shading of solar panels in sunny weather on May 29, 2017 [17] b) Rhinoceros simulated PPFD at the point under the shading of solar panels in typical weather on May 29

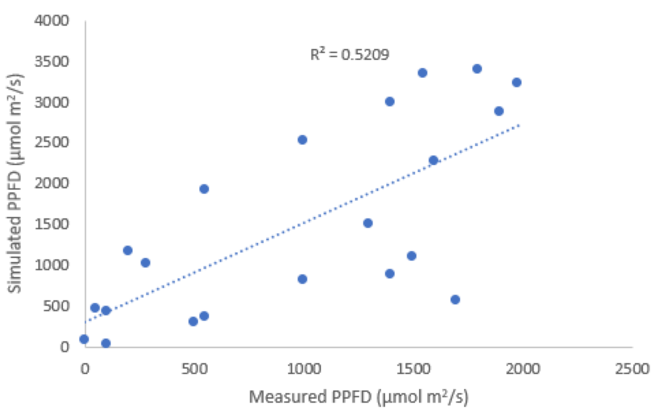

Figure 7 R^2 of the experimental results Vs. simulation results

(Figures 5a) and 5b)) compare the PPFD in the open area, and (Figures 6a) and 6b)) compare the PPFD in the shaded area between the measured and simulated values. It has been observed that the Rhinoceros simulated values of PPFD without the shading of the solar panels have a similar trend to the measured value of the PPFD without the shading of solar panels of the Japanese study. Both measurement and simulation show a study increase in PPFD starting at around 5 am with a peak around noon, which declined steadily until about 8 pm. However, the simulated values are found to be much higher than the measured values.

PPFD of the shaded areas between the measurement and simulation also showed a similar trend with similar patterns of fluctuations. As seen in (figures 6a) and 6b)), peaks in PPFD values occurred around noon for both the measurement and simulation, after which the values fell due to shading effects before climbing again. Both measurement and simulation revealed that there were sharp rises and decreases around noon. As shown in (Figure 7), the R^2 between the measured and simulated PPFD of a combination of both shaded and unshaded areas is found to be 0.5209, which is not very good. The RMSE is 953.57. This is quite a large error, indicating the model isn't performing well. The accuracy of the simulation compared to the measured PPFD values is -40%. This negative value indicates a significant deviation from the measured values. The negative accuracy shows that, on average, the simulation results differ quite substantially from the measured values. This may be due to the weather encountered each hour of the specific date. The experiment was conducted on May 29, 2017, whereas for simulation, the weather data was taken from TMY weather file of Miyazaki city [25]. TMY weather file represents typical weather encountered over several years, while the experiment conducted at the University of Miyazaki measured the PPFD on one specific day. The values could depend on clouds and weather conditions of that specific day. However, the simulated PPFD value at the sensor location under the solar panels shows a similar trend to that of the measured PPFD values of the experiment. The simulation can give out values for every hour, whereas the measurement was made every 10 minutes for the experiment. This affects the pattern of the graph as the time steps are different. Overall, the Rhinoceros simulated values and the Japanese research data show a similar trend with the shades of the solar panels reducing the amount of PPFD received at the point under the panels.

IV. Conclusions

The developed Rhinoceros simulation model is tested for different locations, and the shading patterns in each case are simulated. The simulation is compared with other research. The model comparison between the Indonesian Formit simulation study and the Rhinoceros simulation was found to have an R2 value of 0.947 and deemed as an accurate model. The RMSE is 99.19, and the accuracy is 87.19%. The Rhinoceros model also showed a similar hourly PPFD trend to that of the measurements made by the Japanese model. However, the R2 is found to be 0.5209, and the RMSE is 953.57. The accuracy is -40%. The Rhinoceros model depends on the epw weather file derived from a typical methodological year. So, the precise prediction of sunlight availability at a particular time on a particular date might be limited due to varying weather conditions each hour at the location. Rather, it generates sunlight availability results anticipated on a typical day of the year. To record precise sunlight availability values encountered each hour of a specific day, measuring with sensors on that date at the specific location will be more accurate. Generally, the model can be used to predict the availability of sunlight on a typical day in any given location, provided that the weather data is known for each location.

References

[1] Fiorucci AS, Fankhauser C. Plant Strategies for Enhancing Access to Sunlight. Current Biology 2017;27:R931–40. https://doi.org/10.1016/J.CUB.2017.05.085.

[2] Ma Lu S, Amaducci S, Gorjian S, Haworth M, Hägglund C, Ma T, et al. Wavelength-selective solar photovoltaic systems to enhance spectral sharing of sunlight in agrivoltaics. Joule 2024;8:2483–522. https://doi.org/10.1016/J.JOULE.2024.08.006.

[3] Wang C, Du J, Liu Y, Chow D. A climate-based analysis of photosynthetically active radiation availability in large-scale greenhouses across China. J Clean Prod 2021;315:127901. https://doi.org/10.1016/J.JCLEPRO.2021.127901.

[4] Kotilainen T, Aphalo PJ, Brelsford CC, Böök H, Devraj S, Heikkilä A, et al. Patterns in the spectral composition of sunlight and biologically meaningful spectral photon ratios as affected by atmospheric factors. Agric For Meteorol 2020;291:108041. https://doi.org/10.1016/J.AGRFORMET.2020.108041.

[5] Mercado LM, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M, et al. Impact of changes in diffuse radiation on the global land carbon sink. Nature 2009 458:7241 2009;458:1014–7. https://doi.org/10.1038/nature07949.

[6] Song XP, Tan HTW, Tan PY. Assessment of light adequacy for vertical farming in a tropical city. Urban For Urban Green 2018;29:49–57. https://doi.org/10.1016/J.UFUG.2017.11.004.

[7] Amaducci S, Yin X, Colauzzi M. Agrivoltaic systems to optimise land use for electric energy production. Appl Energy 2018;220:545–61. https://doi.org/10.1016/J.APENERGY.2018.03.081.

[8] Asnur P, Kalsum U, Kanny PI, Yuliani S. The Influence of Shade on the Growth and Production of Butterfly Pea Plants (Clitoria ternatea). International Journal on Food, Agriculture and Natural Resources 2024;5:124–8. https://doi.org/10.46676/IJ-FANRES.V5I2.327.

[9] Baligar VC, Elson MK, He Z, Li Y, De A, Almeida AAF, et al. Light Intensity Effects on the Growth, Physiological and Nutritional Parameters of Tropical Perennial Legume Cover Crops. Agronomy 2020, Vol 10, Page 1515 2020;10:1515. https://doi.org/10.3390/AGRONOMY10101515.

[10] Jantharamin N, Lousuwankun P. Maximum-Power-Point Tracking for Photovoltaic Arrays with Partial-Shading Detection. Naresuan University Engineering Journal 2022;17:6–14. https://doi.org/10.14456/NUEJ.2022.2.

[11] Rathod APS, Mittal P, Kumar B. Analysis of factors affecting the solar radiation received by any region. 2016 International Conference on Emerging Trends in Communication Technologies, ETCT 2016 2017. https://doi.org/10.1109/ETCT.2016.7882980.

[12] Amaducci S, Yin X, Colauzzi M. Agrivoltaic systems to optimise land use for electric energy production. Appl Energy 2018;220:545–61. https://doi.org/10.1016/J.APENERGY.2018.03.081.

[13] Man A, Chaichana C, Wicharuck S, Rinchumphu D. Predicting sunlight availability for vertical shelves using simulation. IOP Conf Ser Earth Environ Sci 2022;1094:012011. https://doi.org/10.1088/1755-1315/1094/1/012011.

[14] Chaichana C, Man A, Wicharuck S, Mona Y, Rinchumphu D. Modelling of annual sunlight availability on vertical shelves: A case study in Thailand. Energy Reports 2022;8:1136–43. https://doi.org/10.1016/J.EGYR.2022.07.077.

[15] Man A, Chaichana C, Wicharuck S, Wanison R, Rinchumphu D. Optimization of vertical spacing between each row of a vertical shelf to meet minimum sunlight requirement for strawberries. AIP Conf Proc 2024;3086. https://doi.org/10.1063/5.0204711/3294111.

[16] Setiawan D, Azmi MA. Solar Radiation Study of Office Building Shapes at a Bussiness District in South Jakarta. IOP Conf Ser Earth Environ Sci 2021;794:012181. https://doi.org/10.1088/1755-1315/794/1/012181.

[17] Yajima D, Toyoda T, Kirimura M, Araki K, Ota Y, Nishioka K. Agrivoltaic system: Estimation of photosynthetic photon flux density under solar panels based on solar irradiation data using all-climate solar spectrum model. Clean Eng Technol 2023;12. https://doi.org/10.1016/j.clet.2022.100594.

[18] Liemohn MW, Shane AD, Azari AR, Petersen AK, Swiger BM, Mukhopadhyay A. RMSE is not enough: Guidelines to robust data-model comparisons for magnetospheric physics. J Atmos Sol Terr Phys 2021;218:105624. https://doi.org/10.1016/J.JASTP.2021.105624.

[19] Chicco D, Warrens MJ, Jurman G. The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. PeerJ Comput Sci 2021;7:1–24. https://doi.org/10.7717/PEERJ-CS.623/SUPP-1.

[20] Ngamsanroaj Y, Tamee K. Improving model using estimate error for daily inflow forecasting. ECTI Transactions on Computer and Information Technology (ECTI-CIT) 2020;13:170–7. https://doi.org/10.37936/ECTI-CIT.2019132.198508.

[21] Chicco D, Warrens MJ, Jurman G. The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. PeerJ Comput Sci 2021;7:1–24. https://doi.org/10.7717/PEERJ-CS.623/SUPP-1.

[22] Sharma DK, Chatterjee M, Kaur G, Vavilala S. Deep learning applications for disease diagnosis. Deep Learning for Medical Applications with Unique Data 2022:31–51. https://doi.org/10.1016/B978-0-12-824145-5.00005-8.

[23] Hofer M, Strauß G, Koulechov K, Dietz A. Definition of accuracy and precision—evaluating CAS-systems. Int Congr Ser 2005;1281:548–52. https://doi.org/10.1016/J.ICS.2005.03.290.

[24] Deepthi S, Rajesh B, Vyshnavi N, Moni K. Automatic Key Term Extraction from Research Article using Hybrid Approach. Int J Comput Appl 2017;166:17–21. https://doi.org/10.5120/IJCA2017914039.

[25] climate.onebuilding.org n.d. https://climate.onebuilding.org/default.html (accessed October 18, 2024).