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Original Research Article

Development of a Decision Support System (DSS) for Greenhouse Ventilation and Cooling Control

Aini Amini Ahmad Shukri[1], Diyana Jamaludin[1, 2]*, Muhamad Saufi Mohd Kassim[1, 2], Muhammad Hazwan Hamzah[1, 2]

[1]Smart Farming Technology Research Center (SFTRC), Faculty of Engineering, Universiti Putra Malaysia Selangor, Malaysia[2]Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang Selangor Malaysia. ainiaminimohdshukri@gmail.com, diyana_upm@upm.edu.my, saufi@upm.edu.my, hazwan@upm.edu.my

*Corresponding author: Jamaludin, D., Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang Selangor Malaysia; diyana_upm@upm.edu.my

Abstract: The confined heat created by the sunlight and ambient temperature is one of the obstacles to greenhouses in the tropics. A conservatory in tropical regions thus requires a proper ventilation and cooling system to provide an ideal greenhouse temperature to support crop production. The main objective of this study is to develop a Decision Support System (DSS) for optimum greenhouse ventilation and cooling control. An equation model to predict the temperature inside was developed by considering heat generation and heat loss inside the greenhouse. The accuracy of the equation model was validated with secondary data from the on-field greenhouse by statistical evaluation metrics. The statistical evaluation proved that the equation model is good with 2.11°C of Root Mean Square Error (RMSE), 6.22% of Percent BIAS (PBIAS) and 0.94 of Nash-Sutcliffe efficiency (NSE) value. A DSS using Microsoft Excel with Visual Basic for Applications (VBA) is developed based on the equation model to provide the ventilation and cooling system information. Input required for the DSS is a climatic condition, dimension and covering greenhouse material. The output of the DSS is the temperature inside the greenhouse, natural ventilation design, forced ventilation, active cooling system design using an evaporative pad and fan, and fogging system. The DSS can be used as an approach for ventilation and cooling design recommendation for the optimum temperature inside the greenhouse.

Keywords: cooling, ventilation, greenhouse, decision support system, equation model

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1. Introduction

One of the methods to reduce the effect of climate variability is crop production under the greenhouse. As for the tropical area, greenhouses are commonly used to protect the growing crop from heavy rain, wind, sunlight, and pests. However, different greenhouse locations frequently result in other environmental conditions and optimum greenhouse requirements. When sunlight penetrates the material of the greenhouse, it will hit any surface inside the greenhouse. The light energy is then converted to heat, making the greenhouse air warmer. The trapping of sunlight radiation and lessened air circulation will lead to microclimate phenomena inside the greenhouse, where the temperature rises. The extra heat forced by direct solar radiation generates a significant increase in the indoor air temperature, which is 20 to 30 degrees Celsius greater than the outside temperature (Shamshiri, 2017). Several types of ventilation and cooling strategies have been studied for a greenhouse. Passive ventilation is based on natural ventilation and could be achieved with vents near the ridge of the roof instead of near the gutter, and the apparent reduction of 18%–22% at the wind speed of 3.0 m/s (Wang & Wang, 2009). A study about the effect of floor area on natural ventilation has proved that if the opening vents are smaller for the wide floor area, it will cause a lousy ventilation rate and rising temperature (Kamaruddin & Al-Shamiry, 2007). The vent area for the combined sidewall and ridge of the greenhouse in tropical climates should be the same, at least 15–20% of the floor area (ASABE, 2008). Active or forced ventilation is based on mechanical systems such as using exhaust fans to bring out the excessive heat inside the greenhouse to the outside environment, or evaporative cooling using pad and fans, misting or fogging method. The fog system helps increase the humidity from 40 -50% to 75% during summer (Ghoulem *et al.*, 2019).

Adequate greenhouse ventilation is crucial in any region with extreme climate situations (Flores-Velazquez *et al.*, 2014). The most design approach to installing greenhouse ventilation and cooling systems is based on the greenhouse dimension. Having proper ventilation and a cooling system is essential to regulate temperature. It optimizes the rate of temperature rise, humidity by transpiration and depletion of the carbon dioxide concentration during a scorching day (Kamaruddin & Al-Shamiry, 2007). Besides, current forced ventilation and cooling systems lead to high operation costs due to electrical energy usage. Therefore, the greenhouse in tropical countries needs a specific design of ventilation and cooling systems based on the greenhouse dimension and outside climate conditions to ensure crops are grown in optimum conditions.

A decision support system (DSS) interface may provide relevant information in designing the ventilation and cooling systems for the greenhouse. The previous study on developing DSS specific for ventilation and cooling is made by Lee (2010) to allow a wide range of farmers to extend their greenhouse closure efficiently. This DSS helps specify the required cooling, heating, dehumidification capacities and examine the achievable time coverage for a semi-closed greenhouse operation. This study aims to develop a decision support system for optimum greenhouse ventilation and cooling based on the energy balance equation model.

2. Materials and Methods

Figure 1 shows the flow chart of the methodology for developing DSS for greenhouse ventilation and cooling control. The process starts with equation model development based on the heat balance process between elements of the greenhouse, data input which include greenhouse dimension and material detail plus microclimate parameter. The heat balance equation model is then validated and analyzed before embedding it in the DSS as the basis for predicting and designing the greenhouse ventilation and cooling system.

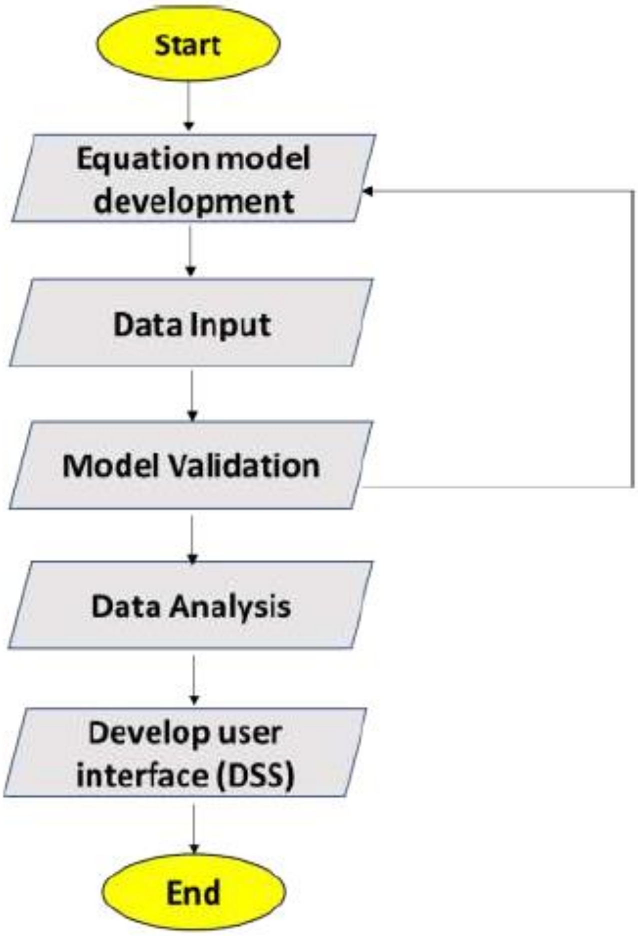

Figure 1. Flow chart for overall process in developing the DSS

2.1. Prediction Equation for Inside Temperature of the Greenhouse

The equation to produce a decision for the ventilation and cooling system was developed based on the heat transfer process inside the greenhouse (Figure 2). The equation is established by considering all three modes of heat transfer that take place inside the greenhouse unit and referring to the ASAE Standards (2008).

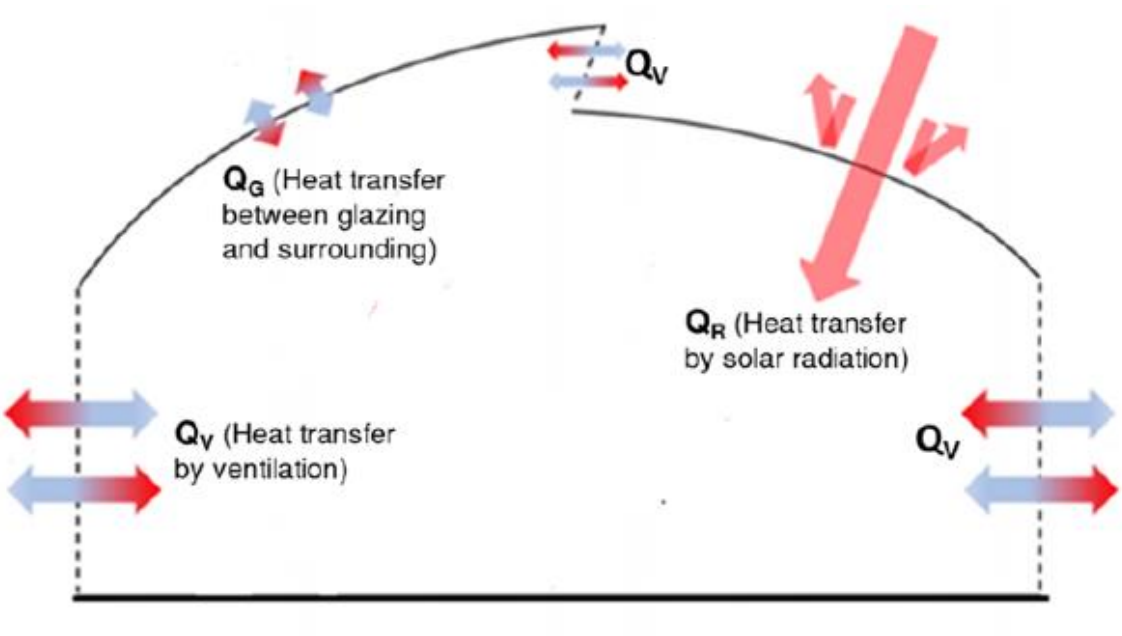

Figure 2. Heat transfer within the greenhouse structure. Adapted from McCartney (2018)

The conduction inside the greenhouse refers to heat transfer between the covering materials of the greenhouse, which depends on the heat transfer coefficient of the covering material (W/m^2 °C), exposed glazing area (m^2), and temperature inside (°C) and outside (°C) the greenhouse (Equation 1). Meanwhile, the convection process (Equation 2) refers to the movement of air inside the greenhouse, which depends on pad efficiency (%), the temperature inside (°C), ventilation rate (m^3/s), air density (kg/m^3) and specific heat of the air (kJ/kg °C). These factors were affected by the cooling pad efficiency, air flow rate and density, respectively. Radiation is represented by the material transmissivity properties and solar radiation factor (Equation 3). In general, the heat inside the greenhouse is generated via solar radiation from the sun. Heat conduction is caused by the greenhouse material and loss due to the installed ventilation and cooling system that implements conduction and convection mechanisms (Equation 4). These factors depend on the transmissivity of the covering material

(%), solar radiation intensity (W/m^2), and greenhouse area (m^2). From this consideration, the equation model was developed as stated in Equation 5:

Conduction heat transfer, $Q_G = UA_g(T_i - T_o)$ Equation 1

Convection heat transfer, $Q_V = [VC_p\rho(T_i - T_o)]$ Equation 2

Radiation heat transfer, $Q_R = [\tau\ IA_f]$ Equation 3

Heat transfer balance =0

$Q_R \pm Q_G \pm Q_V = 0$ Equation 4

Heat gain = Heat loss

$[\tau IA_f] + UA_g(T_i - T_o) = [VC_p\rho(T_i - T_o)]$ Equation 5

$$\mathbf{T_i = T_0 - \left[\frac{\tau IA_f}{UA_g - (VC_p\rho)}\right]}$$

Transmissivity of greenhouse glazing (τ) and heat transmission coefficient (U) values are as in Table 1, while specific heat (C_p) and air density (ρ) were obtained based on standard value. All these data were used in the interface as the critical parameters. For greenhouse floor area (A_f), glazing area (A_g), ventilation rate (V), pad efficiency (ŋ), solar radiation intensity (I), and temperature inside (T_i) were obtained from the output calculated from the interface based on the input parameter by the user.

Table 1. Transmissivity and heat transmission coefficient value for a different type of glazing material.

Type of glazing Material	Transmissivity of greenhouse glazing,τ	Heat transmission coefficient, U (W/m2 ˚C)
Glass	0.90	6.2
Polycarbonate	0.75	6.5
Acrylic	0.86	3.2
Polyethylene	0.88	6.3

Sources: ASABE (2008) & Hanan (1978)

2.2 Natural Ventilation and Active Cooling System Design

As for the natural ventilation system, the optimum percentage of roof openings was calculated based on the range percentage of openings proposed by ASABE (2008), which is 15–20% of the floor area. The forced ventilation and cooling system considered in this study were exhaust fans, evaporative fan-and-pad systems and fog systems. The DSS's ventilation and cooling properties output is the recommended parameter to control the temperature inside the greenhouse. The ventilation and cooling systems were strategized in the user interface based on the input to be inserted in the specific formula.

The specific formula for the design of the ventilation and cooling system for the greenhouse, such as the exhaust fan size, number, evaporative pad length, height and the creation of the fogging system, were obtained according to the standard of the National Greenhouse Manufacturers Association (NGMA) USA specifically for summer ventilation and cooling and Good Agricultural Practice.

2.3 *Secondary Data*

The secondary data is a supporting database to validate the equation model with the actual greenhouse condition. For this data, the greenhouse was assumed to operate without any cooling systems to evaluate the deviation between the actual temperature inside and the value retrieved from the model. The greenhouse solar dryer data from MARDI were obtained, such as the type of greenhouse, its dimension, the temperature outside and inside the greenhouse and solar radiation value. The type of this greenhouse is the even-span type which covers by polycarbonate with a size of 1.25 m, 1.7 m, and 16.4 m for height, width and length, respectively. The datasets were recorded for each hour within 9 days from January 19th to January 27th 2018. The average datasets by the hour were determined and applied for validating the statistical evaluation metrics in analyzing the accuracy of the equation model. The value for average, maximum and minimum values for secondary data were tabulated in Table 2.

Table 2. The average value of radiation, the temperature inside and outside of the Solar Dryer Greenhouse at MARDI

	Radiation, I (W/m^2)	**Temperature Outside, To (°C)**	**Temperature Inside, T_i (°C)**
Minimum	0.00	22.7 2	24.1
Maximum	646.11	38.1	46.5
Average	130.95	27.3	30.5

2.4 *Statistical Evaluation Metrics*

The value temperature inside (T_i) from the calculation is validated with the actual temperature from secondary data. To evaluate the equation model, the statistical evaluation metrics proposed by Moriasi *et al.* (2015) were performed to see the reliability of the model value. In their paper, they stated that there are three categories to assess: error-index, bias and agreement index. Table 3 explains each type in detail and indicates that each value to define the model is good.

Table 3: Description of statistical evaluation matrices used in the analysis

Statistical Evaluation Metrics	Formula	Indication
1. Error Index: Root Mean Square Error (RMSE)	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P)^2}$	• The ideal value for RMSE is 0 • If the value is approaching zero, it means the model equation capable of predicts as same as the actual data. • The RMSE tends to give more weight to the bigger error compared to the smaller error.
2. Bias Percent BIAS (PBIAS)	$\frac{\sum_{i=1}^{N}(O_i - P)}{\sum_{i=1}^{N} O_i} \times 100$	• The ideal value for PBIAS is 1. • If the value is 1, the expected percentage error by the predicted model data is zero to the actual data. • The positive percent indicates the predicted data underestimate the actual data. • The negative percent indicates the predicted data overestimate the actual data.
3. Index agreement Nash Sutcliffe efficiency (NSE)	$1 - \frac{\sum_{i=1}^{N}(P - Oi)}{\sum_{i=1}^{N}(Oi - \bar{O})^2}$	• The ideal value for NSE is 0. • If the NSE value is 0, it means the predicted data is perfect to the actual data

O_i = Actual data of the temperature inside (°C)

P = Predicted data of the temperature inside (°C)

$\bar{O}$ = Average value for actual data of the temperature inside (°C).

2.5 *User Interface Development*

The decision support system was implemented on a commonly used software: Microsoft Excel Macro-Enable Worksheet (Microsoft 365 Version 2107) with Visual Basic for Application (VBA). Three main sections were created: cover section, type of greenhouse input and DSS in an Excel file. The user interface was developed from the equation development to provide optimum numerical iteration and calculation.

3. Results and Discussions

This section comprises the analysis of the predicted temperature generation inside the greenhouse based on the energy balance model as in Equation 5 and DSS for ventilation and cooling control. The environmental data set value from the MARDI Solar Dryer Greenhouse was used to evaluate the model's accuracy and reliability in predicting the actual greenhouse operation.

3.1 Comparison between Predicted and Actual Temperature Inside

Figure 3 shows the average temperature outside (T_o) and inside (T_i) MARDI greenhouse and the predicted T_i acquired from the equation model in one complete day. The temperature rises gradually from 9 am to 1pm and decreases from 3 pm until midnight.

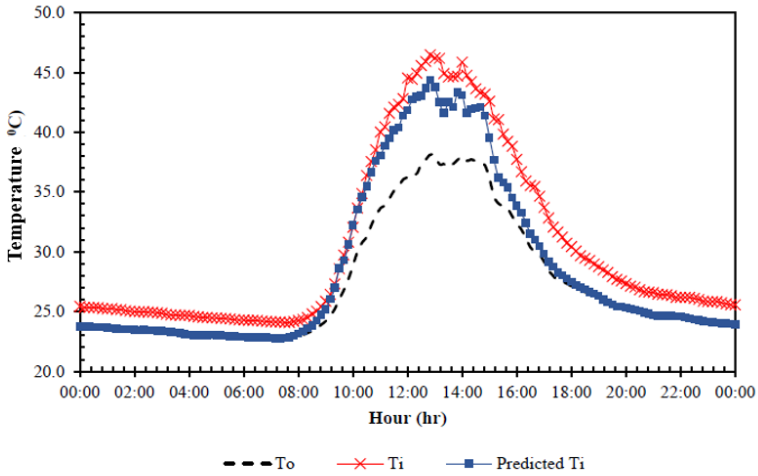

Figure 3. Description of statistical evaluation matrices used in the analysis

From the plot, the temperature pattern showed a similar trend between the predicted and actual values of Ti. This indicates that the energy balance equation model used to predict the temperature inside the greenhouse based on the heat transfer process is reliable. Similar observations were reported by Gadhesaria *et al.* (2020) in their study about the validation of thermal analysis and experimental environmental conditions inside the greenhouse in a tropical wet and dry climate. The average for actual Ti was recorded at 31.0°C while the predicted values were at 29.0°C. The highest Ti was achieved at the same time as the real data recorded at 46.5°C while indicated at 44.4°C at 12:50 pm. This is due to higher solar radiation transmission. The observation is supported by a study by Abdel-Ghany and Kozai (2005), which is solar radiation around 12:19–1:00 pm provides the maximum solar radiation transmission into the greenhouse. At midday, the T_o fluctuated during 1:00 pm.

3.2. Statistical Evaluation Metrics

The statistical evaluation metrics were performed based on RMSE, PBIAS, and NSE to evaluate the performance measures of the model developed with the real-time greenhouse operation. Table 4 provides the result from the statistical evaluation metrics for the equation model for predicted and actual T_i datasets. The RMSE indicates an error for expected and actual T_i data. RMSE value calculated at 2.11°C. Statistically, the model can produce a line of best fit similar to the experimental datasets if the RMSE value is closer to 0. However, the RMSE score is considerably high, indicating that the T_i value predicted via the model would scatter far from the line of best fit, as shown in Figure 4. Nevertheless, the RMSE value is still acceptable as the difference is in a smaller range of 2.28. Mobtaker *et al.* (2018) developed a dynamic model based on an energy balance equation to predict air temperature inside a single-span greenhouse with RMSE using the dynamic model is 2.82°Cwhile the energy equation model used in this DSS produces a smaller RMSE value at 2.11°C.

Table 4. Statistical analysis for equation model of the predicted and actual dataset

Statistical Analysis	Optimal Value	Computed Value
RMSE	0.0	2.11°C
PBIAS	0.0	6.22%
NSE	1.0	0.94

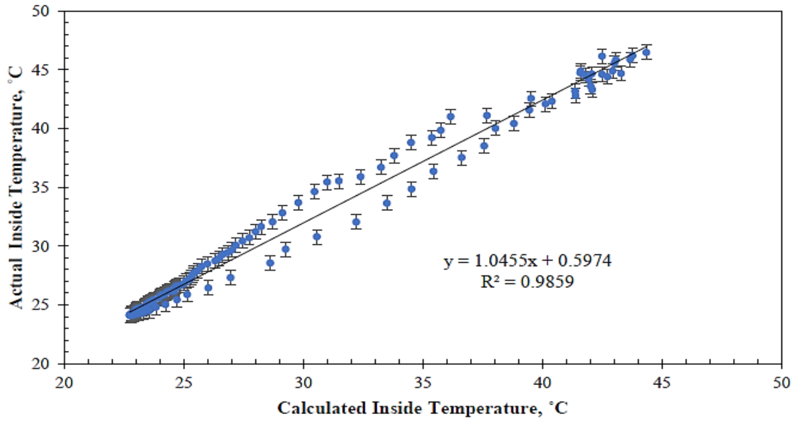

Figure 4. Scatter plot graph of actual inside temperature versus calculated/predicted inside temperature

The plot showed regression analysis performed between two datasets and may be expressed mathematically as Equation 6:

$$\text{Actual } T_i = 1.046(\text{Predicted } T_i) + 0.597;\ R^2 = 0.986 \qquad \text{Equation 6}$$

Although the R^2 value is closer to 1, the value does not reflect the model accuracy because the scatter plot visualizes that the actual T_i value is only relative to the best-fit line at a lower temperature region. The higher temperature value in the graph showed significant deviations from the line of best fit, especially in the 30°C to 40°C. The result is supported by a previous study by Jamaludin (2009) in predicting T_i of the empty greenhouse. It shows that the higher temperature value points (above 30°C) deviate from the best-fit line. However, overall, the equation model gives an R2 value of 0.996, indicating that the calculated values are parallel to the measured values. Therefore, the equation model (Equation 6) is reliable in reflecting the actual T_i. Next, the PBIAS value computes at 6.22%. According to Moriasi *et al.* (2007), this value indicates that the expected percentage error by the predicted model falls below 10% from the real-time experimental data sets. This is a good score because the significant value between optimal and computed PBIAS is only 6.22. Lastly, the NSE score shows 0.94, with a difference of 0.06 from the optimal value, as shown in Table 4. This score reflected a 0.06 error variance ratio between theoretical and experimental values, respectively. It shows the equation model is good because the predicted data is almost perfect to the actual data. Based on the three tests computed, the model developed is justified as reliable in predicting and simulating the T_i generated inside the greenhouse with known environmental factors and greenhouse parameters.

3.3. Decision Support System (DSS) For Ventilation and Cooling Control

This section covers the development of DSS for Greenhouse Ventilation and Cooling Validations based on the energy balance model. The interface has three sections: the cover section, the type of greenhouse input and DSS. Figure 5 shows the cover section with detail of the developer and version of the DSS.

Figure 5. The cover section in the user interface**.**

In the 2nd section, users can select three designs for the greenhouse in the type of greenhouse section: gable, flat arch and hoop greenhouse. The design selection will prompt the users to key in the greenhouse dimension parameters. Figure 5 shows the 3rd section of DSS, the interface's central part, comprising the combination of input and output arguments. Users shall plug in the environmental parameter inputs under the Climate parameter tab, as shown in Figure 6. Users must plug in temperature values outside the greenhouse (To) and solar radiation (I) based on data collected from their sensor or Meteorological Data. These inputs are the significant parameters to enable DSS to strategize the ventilation and cooling system inside the greenhouse. Next, the Greenhouse Covering Material selection allows users to select any of the four common materials used to construct the greenhouse facility. The section of greenhouse covering materials relates to the heat transfer properties across the materials, such as transmissivity and heat transmission coefficient, which impacted the predicted T_i value. Based on the input value by users, the DSS then continue to compute the optimum design for ventilation and cooling of the greenhouse.

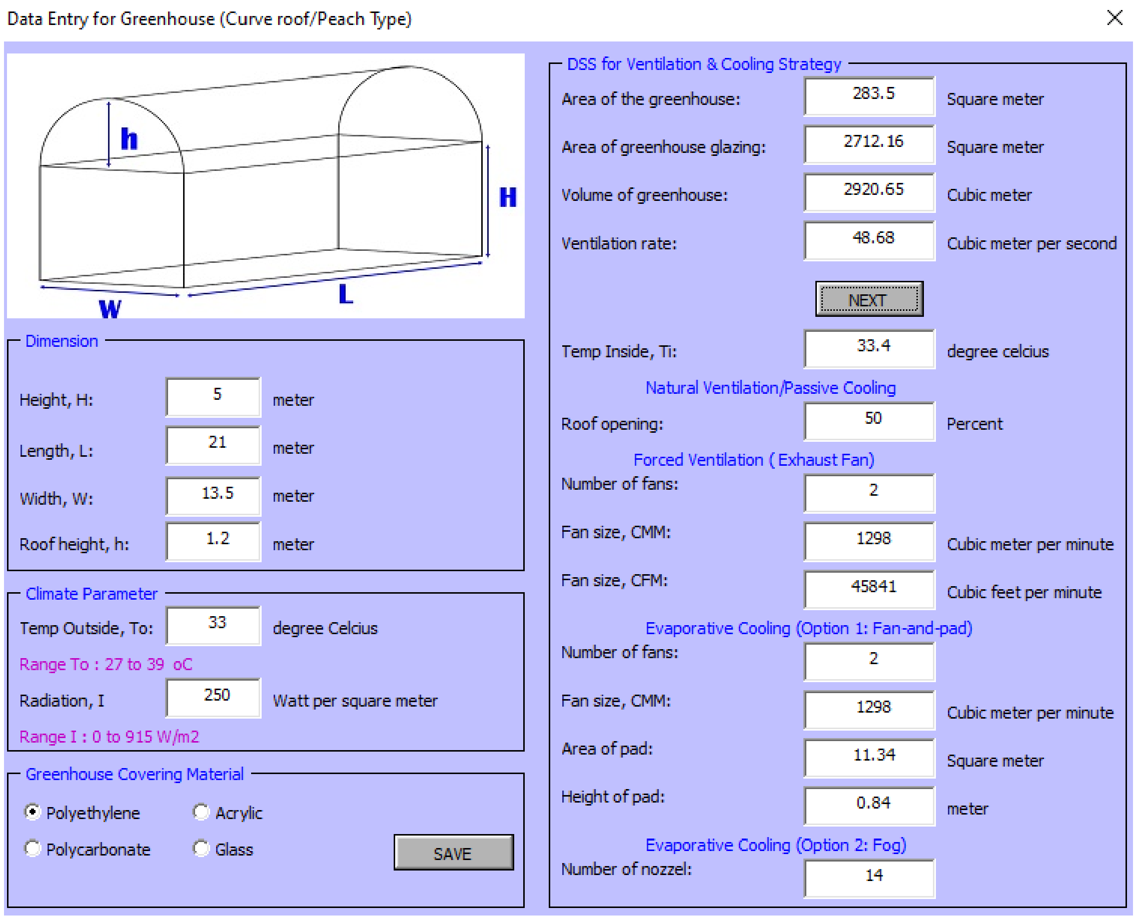

Figure 6. The DSS section. Comprises the combination of input and output parameters

4. Conclusions

The energy balance analysis allows the development of a model equation to describe the energy conservation inside the greenhouse areas. The inclusion of all modes of heat transfer, i.e., conduction, convection and radiation inside the equation model allows the user to predict the temperature inside by plugging in the temperature outside and solar radiation as input. Graphical analysis between T_i indicated via equation model and actual condition T_i from the results shows a similar temperature pattern reflected that the model generated capable of providing actual operating conditions for greenhouse unit. In addition, the statistical evaluation metrics on RMSE, PBIAS and NSE resulted in a 10% and lower deviation between experimental and computed T_i values. The user interface developed by the application of the DSS can be used as an approach to design the greenhouse ventilation and cooling system using the model as a basis. In this interface, the users can create the desired T_i value for the greenhouse by plugging in the input parameters such as greenhouse dimensions, materials and environmental aspects. Recommended numbers and sizes of ventilation and cooling systems provided by the DSS can help users design and purchase wisely.

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