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Research article

Finding Critical Factors for Developing Dynamic Models to Optimize Greenhouse Solar Dryer's Environmental Conditions

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Abstract

This paper is focused on the formulation of a mathematical model for greenhouse solar dryer systems in the context of determining the principal drivers of efficiency of the solar dryer. The model was built by evaluating the correlation coefficients of each term and only those terms which had high levels of significance were retained. To test this model, experiments were replicated with measurements being taken in the different sections of the greenhouse to provide a large spectrum of the environmental conditions involved. The values of the technical coefficients are predicated on internal air temperature, humidity ratio and weight of the product with fixed scales, avoiding sophisticated complex models prone to overfitting. By using terms with high correlation, the model is less likely to be affected by outliers and total correlation or cross correlation is low, thereby making the model practical. The outcomes of this research, therefore, offer a scientifically viable and a practical approach to enhancing drying processes in greenhouse solar dryer systems.

Keywords: dynamic model; solar dryer greenhouse systems; correlation analysis

1. Introduction

Greenhouses have an ever-growing base in the agriculture market. Several types of greenhouses exist, but the two primary types are crop cultivation greenhouses, which provide a suitable growing environment for plants, and greenhouse solar dryers, designed for the drying of agricultural product.

Cultivation greenhouses are climate-controlled structures tailored to enhance plant growth, with parameters including temperature, humidity and light. Many cultivation greenhouses incorporate new technologies such as hydroponics (Dutch Greenhouses, 2023), vertical farming systems (Eden Green Technology, 2023) and integrated pest management systems (United States Environmental Protection Agency (EPA), 2023) to raise the productivity index while also enhancing sustainability. These controlled environments allow extra-long growing seasons as well as greatly increase crop yields.

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Greenhouse solar dryers are enclosures of a specific architecture that offer proper and efficient drying of crops or other materials using solar energy, as shown in Figure 1. Their main advantage comes from the fact that they are designed to collect as much solar radiation as possible, ensuring optimal crop drying (Mahayothee & Boonrod, 2018). They are also safer than the traditional method of sun-drying.

Figure 1. Solar dryer greenhouse

The idea of greenhouses for growing plants is a well-studied concept with much work done in mathematical modelling to enhance conditions within the greenhouses. These models may include parameters like greenhouse cover temperature, soil temperature, plant temperature and air temperature (Reyes-Rosas et al., 2017) which are important for sustaining the best growing conditions. While the cover temperature affects heat transfer between the inside and outside of the greenhouse, plant temperature regulates its internal humidity. Studies on these models are mostly limited to having temperatures as a major factor (Joudi & Farhan, 2015).

Greenhouse solar dryers are used for drying agricultural product such as fruits, vegetables and herbs. They remove moisture from the product while reducing drying time and increasing the quality of the finished product (Mahayothee & Boonrod, 2018). Existing research on greenhouse solar dryers often simplifies the drying process by considering only one key factor: moisture content (Ahmad & Prakash, 2021). That moisture content is one of the most important parameters and must be taken into consideration is not a point of contention. However, it should not be the only consideration. Some studies incorporate more than two key factors, including air temperature, greenhouse cover temperature, product temperature, floor temperature, relative humidity, and moisture content (Janjai et al., 2011).

Figure 2 represents the interactions between surrounding factors in a greenhouse. Variables that have been specified and illustrated include air temperature outside the greenhouse (T_a), humidity ratio outside the greenhouse (H_a), air temperature inside the greenhouse (T_i), humidity inside the greenhouse (H_i), humidity ratio of product (H_p), wind velocity through greenhouse window (v_w) and installed fan speed (v_f). A detailed description of these interactions and how these can be improved with the aid of an ODE-based model is covered in the next section.

The diagram in Figure 3 illustrates how internal temperature and humidity are affected by sun radiation or an installed fan, and how these factors affect the product's moisture content and measured weight. We use Ordinary Differential Equations (ODE) as the theoretical tool for analyzing dynamic systems shown in Figure 4. The use of ODEs is also effective for modelling the temperature, humidity and other key factors and estimating the interaction of the mentioned key factors during the drying process, which is the basis of the given approach to the development of the optimal drying conditions.

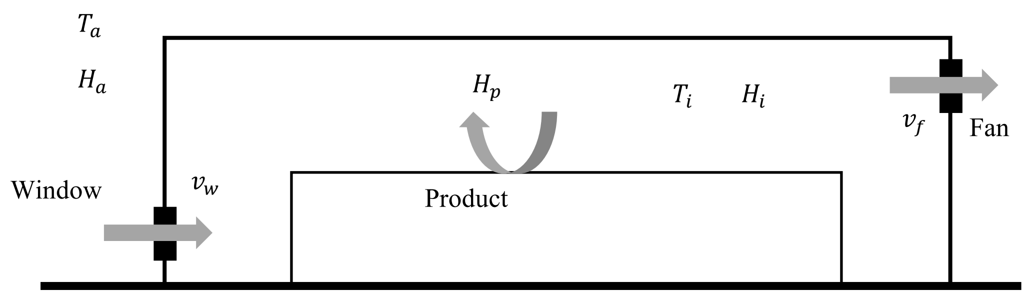

Figure 2. The interactions between surrounding factors in greenhouse

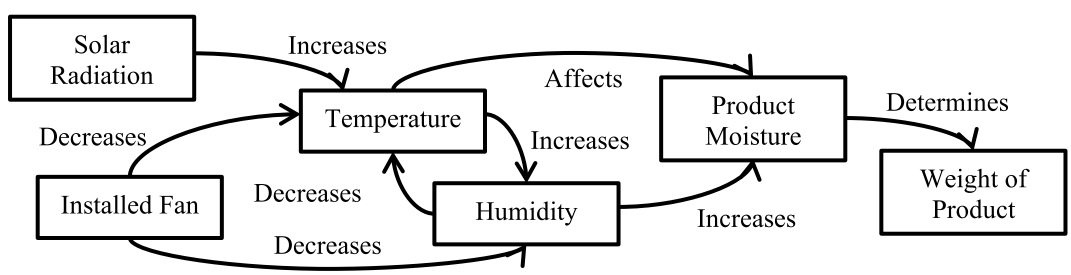

Figure 3. Dynamic model of key factors' interactions in the drying process

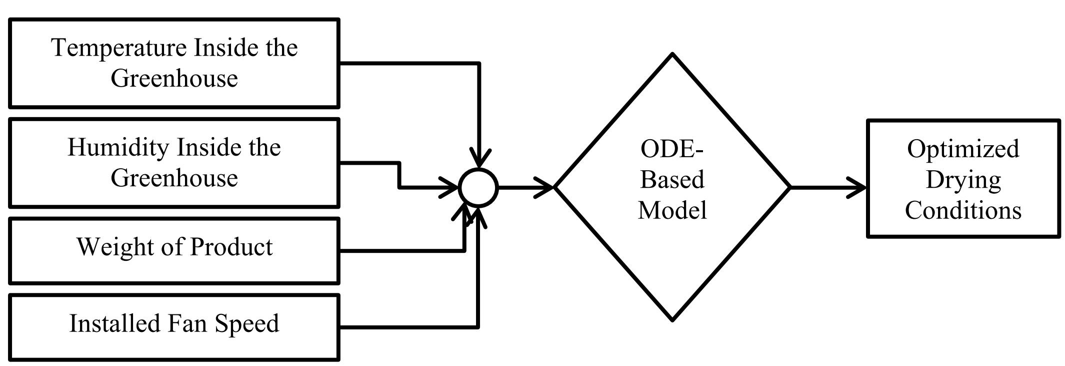

Figure 4. Diagrammatic representation of the ODE-based modeling process for solar greenhouse drying

This research defines and examines key factors essential for the construction of dynamic models associated with solar dryer greenhouse. The first empirical results reveal that temperature is an important factor in cultivation greenhouses. However, humidity within the greenhouse affects the drying rate and quality of the product. Because of this, attention should be given to these two factors simultaneously. We try to combine the model for cultivation greenhouse with the model for solar dryer greenhouses to create a more comprehensive model for the latter. In other words, the two types of models can be integrated to provide a simple yet more comprehensive picture of the drying scenario taking into account various surrounding factors.

2. Materials and Methods

The researchers identified key factors from the literature review. These factors are interconnected, as depicted in Figure 3. Consequently, we define the mathematical model using the following variables: air temperature inside the greenhouse, air humidity ratio inside the greenhouse and weight of the product. Table 1 lists the variables and their corresponding subscripts used in the model

The coefficients of the model are shown in Table 2. These values were derived from sources included in the Table. Some of the coefficients depend on individual greenhouses, including the area of the greenhouse in m^2, areas for drying product in the greenhouse in m^2, the height of the greenhouse in m, and frequency of air changes in an hour, which is equivalent to the data collection period. These dependent coefficients will not be included in the Table 1.

2.1 Air temperature inside the greenhouse

Air temperature inside the greenhouse can be considered using the energy balance when computing the sensible heat fluxes. Fourier’s Law and its application are well-established principles and important in heat flux (Testbook, 2024). Fourier’s law in its differential form can be written as:

$$q = k\frac{d}{dt}T_i(t)$$

where q is the heat flux density (Wm^{-2}), k is the conductivity of the material ($Jm^{-2}{}^\circ\mathrm{C}^{-1}$) and $\frac{d}{dt}T_i(t)$ is the air temperature inside the greenhouse gradient (°Cs^{-1}).

The rate of change of the inside air temperature $\frac{d}{dt}T_i(t)$ in the above energy balance equation is estimated by the exchange between the air and related components of the greenhouse (Reyes-Rosas et al., 2017), which can be written as:

$$\boldsymbol{\frac{d}{dt}T_i(t) = \frac{q_{s,c}}{k_c} + \frac{q_{s,floor}}{k_{floor}} + \frac{q_{inf}}{k_g} + \frac{q_{co,i-p}}{k_p + k_g} + \frac{q_{co,i-c}}{k_p + k_g} + \frac{q_{v_w,a-i}}{k_g} - \frac{q_{v_f,i-a}}{k_g}}$$

where k is the conductivity of the material ($Jm^{-2}{}^\circ\mathrm{C}^{-1}$).

The solar radiation absorbed by the greenhouse cover, $\boldsymbol{q_{s,c}}$, can be calculated using the following equation:

Table 1. The nomenclature of the dynamic model

Alphabetic symbols	
A	Area (m^2)
c_p	Specific heat (Jkg^{-1}℃$^{-1}$)
$\tilde{h}$	Thickness (m)
h_{co}	Convection heat transfer coefficient (Wm^{-2}℃$^{-1}$)
h_v	Ventilation heat transfer coefficient (Wm^{-2}℃$^{-1}$)
H	Humidity ratio (%)
I	Solar radiation (Wm^{-2})
k	Conductivity (Jm^{-2}℃$^{-1}$)
L	Length (m)
N	Number of air changes per hour (h^{-1})
q_{co}	Convection heat transfer (Wm^{-2})
q_{inf}	Infiltration heat transfer (Wm^{-2})
q_s	Solar radiation absorption (Wm^{-2})
q_v	Ventilation heat transfer (Wm^{-2})
R	Relative humidity (%)
T	Temperature (℃)
V	Velocity (ms^{-1})
W	Weight of product (g)
Greek symbols	
α	Absorption of solar radiation (–)
ρ	Density (kgm^{-3})
Subscripts	
a	Ambient
c	Greenhouse cover
$concrete$	Concrete
f	Installed fan
$floor$	Greenhouse floor
g	Greenhouse
i	Inside the greenhouse
p	Product
w	Wind outside the greenhouse
$i-a$	Between the inside and outside greenhouse
$i-c$	Between the inside greenhouse and greenhouse cover
$i-p$	Between the inside greenhouse and product

Table 2. The coefficients of the dynamic model

Parameters	Symbol	Value	Source
Polycarbonate specific heat ($Jkg^{-1}°C^{-1}$)	$c_{p,c}$	1200	(The Engineering ToolBox, 2013)
Polycarbonate sheet thickness (m)	$\tilde{h}_c$	0.006	(Mahayothee & Boonrod, 2018)
Polycarbonate absorption of solar radiation	α_c	0.001	(Zapałowicz & Garnysz-Rachtan, 2022)
Polycarbonate density (kgm^{-3})	ρ_c	1200	(The Engineering ToolBox, 2013)
Concrete specific heat ($Jkg^{-1}°C^{-1}$)	$c_{p,concrete}$	750	(The Engineering ToolBox, 2003)
Concrete density (kgm^{-3})	$\rho_{concrete}$	1850	(The Engineering ToolBox, 2003)
Concrete absorption of solar radiation	$\alpha_{concrete}$	0.6	(The Engineering ToolBox, 2009)
Air specific heat ($Jkg^{-1}°C^{-1}$)	$c_{p,a}$	1005	(Joudi & Farhan, 2015)
Air density (kgm^{-3})	ρ_a	1.2	(Joudi & Farhan, 2015)

$$\boldsymbol{q_{s,c} = \alpha_c I_a}$$

where α_c is the absorption coefficient of the greenhouse cover (Table 2) and I_a is the outside solar radiation (Wm^{-2}).

The solar radiation absorbed by the greenhouse floor, $q_{s,floor}$, can be calculated using the following equation:

$$q_{s,floor} = \alpha_c I_i (1 - \alpha_{floor})$$

where I_i is the inside solar radiation (Wm^{-2}) and α_{floor} is the floor absorption. Since the greenhouse floor is concrete, then $\alpha_{floor} = \alpha_{concrete} = 0.6$ (Table 2).

The infiltration through the greenhouse, q_{inf}, can be calculated as:

$$q_{inf} = \rho_a c_{p,a} \tilde{h}_g \frac{N}{3600} \left(T_i(t) - T_a(t)\right)$$

where ρ_a is the air density (kgm^{-3}), $c_{p,a}$ is the specific heat of air ($Jkg^{-1}°C^{-1}$), $\tilde{h}_g$ is the thickness of greenhouse (m), and N is the number of air changes per hour (h^{-1}).

The energy transferred between the air inside the greenhouse and product by convection, $q_{co,i-p}$, is expressed as:

$$q_{co,i-p} = h_{co,i-p} \left(T_i(t) - T_p(t)\right)$$

where $T_p(t)$ is the temperature of product (℃).

The energy transferred between the air inside the greenhouse and the greenhouse cover by convection, $q_{co,i-c}$, is expressed as:

$$q_{co,i-c} = h_{co,i-c}\big(T_i(t) - T_c(t)\big)$$

where $T_c(t)$ is the cover temperature (℃). While T_c can influence mitigating temperatures inside the greenhouse, we have left it out of the model due to data inaccessibility. Most literature specifically targets moisture content. This simplification does not detract from the model while making it easier and more practical for greenhouse operators to use without having to install more instruments. Thus, despite excluding T_c from the model, it is still effective for estimating the drying conditions in the greenhouse.

The energy transferred by ventilation between the air inside and outside greenhouse elements, q_v, can be expressed as:

$$q_{v_w,i-a} = h_{v_w,i-a}\big(T_i(t) - T_a(t)\big),$$
$$q_{v_f,i-a} = h_{v_f,i-a}\big(T_i(t) - T_a(t)\big).$$

Empirical relations reported in the literature to estimate the heat transfer coefficients between air temperature and the different surfaces following from (Fatnassi et al., 2013):

$$h_{co,i-p} = \tilde{y}_1\left(\frac{\left|T_i(t) - T_p(t)\right|}{L_p}\right)^{\tilde{y}_2};$$

and from (Abdel-Ghany & Kozai, 2006):

$$h_{v_w,i-a} = \tilde{y}_3 + \tilde{y}_4 v_w^{\tilde{y}_5}(t),$$

$$h_{v_f,i-a} = \tilde{y}_6 + \tilde{y}_7 v_f^{\tilde{y}_8}(t).$$

Given that the parameters $\tilde{y}_2$, $\tilde{y}_5$ and $\tilde{y}_8$ lead to the term $h_{co,i-p}$, $h_{v_w,i-a}$ and $h_{v_f,i-a}$ yielding imaginary numbers, we have set $\tilde{y}_2 = \tilde{y}_5 = \tilde{y}_8 = 1$ to avoid these errors and ensure the model's practical applicability.

The conductivity of the material (Jm^{-2}°C^{-1}) can be calculated as:

$$k_c = \rho_c c_{p,c}\tilde{h}_c, \qquad k_{floor} = \rho_{floor} c_{p,floor}\tilde{h}_g,$$

$$k_g = \rho_a c_{p,a}\tilde{h}_g, \qquad k_p = \rho_p c_{p,p}\frac{A_p}{A_g}\tilde{h}_p,$$

where the value of coefficients can be found in Table 2.

The equation of derivative of air temperature inside the greenhouse can be written as:

$$\frac{d}{dt}T_i(t) = \frac{q_{s,c}}{k_c} + \frac{q_{s,floor}}{k_{floor}} + \frac{q_{inf}}{k_g} + \frac{q_{co,i-p}}{k_p + k_g} + \frac{q_{v_w,a-i}}{k_g} - \frac{q_{v_f,i-a}}{k_g}. \tag{1}$$

2.2 The greenhouse's internal air humidity ratio

The rate of moisture accumulation in the air inside the dryer is the rate of moisture inflow from the entry of ambient air minus the rate of moisture outflow from the exit of air from the dryer, plus the rate of moisture removal from the product inside the dryer (Janjai et al., 2011) which can be written as:

$$\rho_a V_g \frac{d}{dt}H_i(t) = A_{in}\rho_a H_{in}(t)v_{in}(t) - A_{out}\rho_a H_{out}(t)v_{out}(t) + V_p\rho_p \frac{d}{dt}M(t). \tag{2}$$

From the basic formula of the relationship between the humidity ratio and relative humidity (The Engineering ToolBox, 2004), we have $H = \frac{0.622e}{P-e}$ where e is vapor pressure where $e = \frac{R}{100} \times e_s$, e_s is saturation vapor pressure at temperature T, R is relative humidity, and P is the total atmospheric pressure.

Consider Magnus-Tetens equation (Bolton, 1980), $e_s = 6.112\exp\left(\frac{17.67T(t)}{T(t)+243.5}\right)$. Then,

$$H(t) = \frac{0.622R(t)\left(6.112\exp\left(\frac{17.67T(t)}{T(t)+243.5}\right)\right)}{100P - 6.112R\exp\left(\frac{17.67T(t)}{T(t)+243.5}\right)}.$$

Since the above equation is exceedingly difficult to transform to a function of R, we will convert the data into the value of humidity ratio.

Equation (2) involves H_{in} and H_{out}. However, at the steady state, it is common to assume $H_{in} = H_i$ and $H_{out} = H_a$.From equation (2), we get

$$\frac{d}{dt}H_i(t) = \frac{A_w\rho_a H_i(t)v_w(t)}{\rho_a V_g} - \frac{A_f\rho_a H_a(t)v_f(t)}{\rho_a V_g} + \frac{V_p\rho_p \dot{M}(t)}{\rho_a V_g}.$$

Since $W(t) = V_p\rho_p$, then

$$\frac{d}{dt}H_i(t) = \frac{A_w\rho_a H_i(t)v_w(t)}{\rho_a V_g} - \frac{A_f\rho_a H_a(t)v_f(t)}{\rho_a V_g} + \frac{W(t)}{\rho_a V_g}\cdot\frac{d}{dt}M(t). \tag{3}$$

The thin layer drying equation for banana is written as (Janjai et al., 2011):

$$\frac{M(t) - M_e(t)}{M_o - M_e(t)} = A(t)\exp(-\mathrm{B}(t)t).$$

We get

$$M(t) = A(t)\exp(-B(t)t)\left(M_o - M_e(t)\right) + M_e(t) \tag{4}$$

where M_o is the initial moisture content of product (%), M_e is the equilibrium moisture content of product (%),

$$A(t) = 1.5035 + 0.5054R_i(t) - 0.0132T_i(t) - 2.1417R_i^2(t) + 0.0001T_i^2(t),$$

$$B(t) = 0.1874 + 0.1920R_i(t) - 0.0064T_i(t) - 0.7978R_i^2(t) + 0.0008T_i^2(t).$$

The formula for the equilibrium moisture content of product varies, depending on the kind of product; the equilibrium moisture content of bananas, $M_e(t)$, is

$$M_e(t) = 74.6602 - 1.144T_i(t) + 37.0722R_i(t) + 0.0012T_i^2(t)\ , +51.5537R_i^2(t).$$

From equation (4), we get

$$\boldsymbol{\frac{d}{dt}M(t) = j_1 + (j_2 + tj_3)\, exp(-B(t)t)}$$

where $j_1 = j_1(\dot{T}, T\dot{T}, \dot{R}, R\dot{R})$,

$j_2 = j_2(T, R, T^2, R^2, TR, T^2R, R^3, T^3, TR^2, T^2R^2, R^4, T^4, \dot{T}, T\dot{T}, \dot{R}, R\dot{R}, R\dot{T}, T^2\dot{T}, R^2\dot{T}, TR\dot{T}, T^3\dot{T}, TR^2\dot{T}, T\dot{R}, T^2\dot{R}, R^2\dot{R}, TR\dot{R}, T^2R\dot{R}, R^3\dot{R}, T^5, R^5, T^6, R^6, TR^3, TR^4, T^2R^3, T^2R^4, T^3R, T^3R^2, T^4R, T^4R^2)$,

and $j_3 = j_3(T, R, T^2, R^2, TR, T^2R, R^3, T^3, TR^2, T^2R^2, R^4, T^4, \dot{T}, T\dot{T}, \dot{R}, R\dot{R}, R\dot{T}, T^2\dot{T}, R^2\dot{T}, TR\dot{T}, T^3\dot{T}, TR^2\dot{T}, T\dot{R}, T^2\dot{R}, R^2\dot{R}, TR\dot{R}, T^2R\dot{R}, R^3\dot{R}, T^2R\dot{T}, R^3\dot{T}, T^2R^2\dot{T}, R^4\dot{T}, T^4\dot{T}, T^3\dot{R}, TR^2\dot{R}, T^2R^2\dot{R}, R^4\dot{R}, T^4\dot{R}, T^3R\dot{T}, TR^3\dot{T}, T^3R^2\dot{T}, TR^4\dot{T}, T^5\dot{T}, T^3R\dot{R}, TR^3\dot{R}, T^2R^3\dot{R}, R^5\dot{R}, T^4R\dot{R})$

with $T = T_i$ and $R = R_i$. To simplify the expression of terms, we approximate the exponential decay function, $\exp(-Bt)$, by the method of asymptotical expansion as a rational function of $\frac{R_i}{T_i}$. Hence,

$$\frac{d}{dt}M(t) = j_1 + (j_2 + tj_3)\frac{R_i}{T_i}. \qquad (5)$$

Substituting equation (5) in equation (3), we have

$$\frac{d}{dt}H_i(t) = \frac{A_w\rho_a H_i(t)v_w(t)}{\rho_a V_g} - \frac{A_f\rho_a H_a(t)v_f(t)}{\rho_a V_g} + \frac{W(t)}{\rho_a V_g}\cdot\left[j_1 + (j_2 + tj_3)\frac{R_i}{T_i}\right]. \qquad (6)$$

2.3 Weight of product

The relationship between the weight of a dried product and the weight of the same product after it has absorbed moisture as published in Trautmann & Richard (1996) can be expressed as:

$$M(t) = \frac{W_d - W(t)}{W(t)} \times 100 \qquad (7)$$

where $\boldsymbol{M(t)}$ is the moisture content of product at time t (%), $\boldsymbol{W_d}$ is the weight of dry product (g), and $\boldsymbol{W(t)}$ is the weight of product at time $\boldsymbol{t}$ (g). From equation (7), we get

$$\frac{d}{dt}W(t) = -\frac{W(t)^2}{100W_d} \times \frac{d}{dt}M(t). \tag{8}$$

Substitute equation (5) in equation (8), then

$$\frac{d}{dt}W(t) = -\frac{W(t)^2}{100W_d} \times \left[j_1 + (j_2 + tj_3)\frac{R_i}{T_i}\right]. \tag{9}$$

2.4 Correlation analysis

From equation (1), we assume all coefficients y_i are unknown parameters belonging to the set of positive integers, denoted as $i \in \{1,2,3,\ldots,8\}$. Therefore,

$$\begin{aligned}\frac{d}{dt}T_i(t) = y_1 I_a + y_2 I_i + y_3\,\big(T_i(t) - T_a(t)\big) + y_4\big|T_i(t) - T_p(t)\big| \\ + (y_5 + y_6 v_w)\big(T_i(t) - T_a(t)\big) - \big(y_7 + y_8 v_f\big)\big(T_i(t) - T_a(t)\big).\end{aligned} \tag{10}$$

However, equations (6) and equation (9) for the air humidity ratio and the weight of product involve too many parameters to estimate. To simplify the model, we examine the correlations between variables by conducting an experiment at the Maesom Banana solar dryer greenhouse, located in Bang Krathum, Phitsanulok, Thailand (Figure 5).

Figure 5. Maesom Banana solar dryer greenhouse, Bang Krathum, Phitsanulok, Thailand (ETE, 2022)

The greenhouse measures 20.8 m in length, 9.2 m in width, and 3.25 m in height. Data collection was carried out at four key positions within the greenhouse (Figure 6). At position 1 (front), we measured the ambient air temperature (T_a), ambient air relative humidity (R_a), and ambient solar radiation (I_a). At position 2 (near the window), we recorded the wind velocity through the window (v_w). At position 3 (middle section), we measured the inside air temperature (T_i), product temperature (T_p), inside air relative humidity (R_i), inside solar radiation (I_i), and the weight of product (W). Finally, at position 4 (back, near the fan), we measured the wind velocity through the installed fan (v_f). The variables we collected are summarized in Table 1.

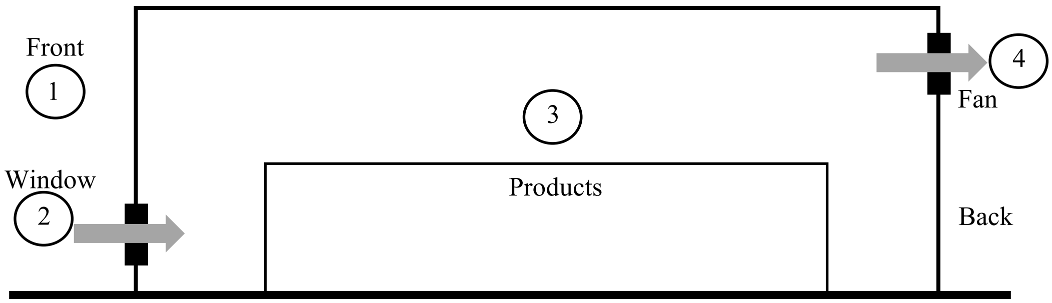

Figure 6. The data collection positions

Note that these correlations cannot be used for all greenhouses and must be recalculated based on the individual greenhouse studied.

For the air humidity ratio, starting with equation (6) and the presence of multiple variable terms, we opt to examine the correlation of each term with respect to $\dot{H_i}$. To do so, we calculate the correlation coefficient, r, between each term and $\dot{H_i}$ using the data collected. The result correlation is presented in Table 3.

We begin by selecting the terms in Table 3 that have a correlation coefficient (r) greater than 0.8. This allows us to eliminate many terms, leaving us with 8 terms; $WR^3\dot{T}T^2$, $WR^3\dot{T}T$, $WR^2\dot{T}T$, $WR^2\dot{T}T^2$, $WR\dot{T}T$, $WR^2\dot{T}$, $WR\dot{T}T^2$, $WR\dot{T}$ and $WR^3\dot{T}$. Since this selection is for choosing the term of $\frac{d}{dt}H_i(t)$, and the remaining terms do not include H_i, we will focus on R. We then choose the terms that include R, R^2 and R^3. These terms are $WR^3\dot{T}T^2$, $WR^2\dot{T}T$, and $WR\dot{T}T$.

We assume all coefficients y_i are unknown parameters belonging to the set of positive integers, denoted as $i \in \{9,10,11,\ldots,14\}$. Equation (6) can be simplified using only high correlation terms as:

$$\begin{aligned}\frac{d}{dt}H_i(t) = {} & y_9 H_i(t) v_w(t) - y_{10} H_a(t) v_f(t) \\ & + [(y_{11} + y_{12}t) + y_{13} t R_i(t) \\ & + y_{14} t R_i(t)^2 T_i(t)]\, W(t) R_i(t) T_i(t) \\ & \cdot \Big[y_1 I_a + y_2 I_i + y_3 \left(T_i(t) - T_a(t)\right) + y_4 \left|T_i(t) - T_p(t)\right| \\ & + \left(y_5 + y_6 v_w(t)\right)\left(T_i(t) - T_a(t)\right) \\ & - \left(y_7 + y_8 v_f(t)\right)\left(T_i(t) - T_a(t)\right)\Big]. \end{aligned} \quad (11)$$

We proceed to simplify equation (9) by selecting each term in equation (5) in the same manner as discussed for simplifying equation (9). We calculate the correlation coefficient, r, between each term and $\dot{W}$. The calculated correlations are shown in Table 4.

We begin by selecting the terms in Table 4 which have a correlation coefficient (r) greater than 0.7. This allows us to eliminate many terms, leaving us with only 5 terms: W^2T^3R, W^2T^2R, W^2T^4R, $W^2T^3R^2$, and W^2T^5R. Among these, we choose 3 terms that have the highest correlation coefficient. They are W^2T^3R, W^2T^2R, and W^2T^4R.

Table 3. The correlation, r, between each term and ($\dot{H}_i$)

Variables	r	Variables	r	Variables	r
$H_i v_w$	0.1478	WR^5	0.2108	$WR^5\dot{T}/T$	0.7479
$H_a v_f$	−0.2411	WR^5T	0.3455	$WR^5\dot{T}$	0.7882
WR	0.1691	WR^6/T	0.0918	$W\dot{R}$	0.2058
WRT	0.3076	WR^7/T	0.0880	$WR\dot{R}/T$	0.1728
WRT^2	0.3580	$W\dot{T}$	0.7931	$WR\dot{R}$	0.2076
WRT^3	0.3374	$WT\dot{T}$	0.7953	$WR\dot{R}T$	0.2356
WRT^4	0.2954	$WR\dot{T}/T$	0.7681	$WR\dot{R}T^2$	0.2537
WRT^5	0.2496	$WR\dot{T}$	0.8031	$WR\dot{R}T^3$	0.2615
WR^2/T	0.0696	$WR\dot{T}T$	0.8145	$WR^2\dot{R}/T$	0.1726
WR^2	0.2031	$WR\dot{T}T^2$	0.8048	$WR^2\dot{R}$	0.2079
WR^2T	0.3479	$WR\dot{T}T^3$	0.7787	$WR^2\dot{R}T$	0.2378
WR^2T^2	0.4294	$WR\dot{T}T^4$	0.7403	$WR^2\dot{R}T^2$	0.2595
WR^2T^3	0.4389	$WR^2\dot{T}/T$	0.7668	$WR^2\dot{T}T^2$	0.8204
WR^3/T	0.0856	$WR^2\dot{T}$	0.8053	$WR^3\dot{T}/T$	0.7624
WR^3	0.2150	$WR^2\dot{T}T$	0.8225	$WR^3\dot{T}$	0.8025
WR^3T	0.3579	WR^4/T	0.0923	$WR^2\dot{R}T^3$	0.2718
WR^3T^2	0.4558	WR^4	0.2158	$WR^3\dot{R}/T$	0.1717
WR^3T^3	0.4906	WR^4T	0.3549	$WR^3\dot{R}$	0.2068
WR^3T	0.3579	$WR^2\dot{T}T^2$	0.8204	$WR^3\dot{R}T$	0.2378
WR^3T^2	0.4558	$WR^3\dot{T}/T$	0.7624	$WR^4\dot{R}/T$	0.1699
WR^3T^3	0.4906	$WR^3\dot{T}$	0.8025	$WR^4\dot{R}$	0.2045
WR^4/T	0.0923	$WR^3\dot{T}T$	0.8229	$WR^4\dot{R}T$	0.2358
WR^4	0.2158	$WR^3\dot{T}T^2$	0.8257	$WR^5\dot{R}/T$	0.1672
WR^4T	0.3549	$WR^4\dot{T}/T$	0.7559	$WR^6\dot{R}/T$	0.1637
WR^5/T	0.0937	$WR^4\dot{T}$	0.7965		

Here, we also assume all coefficients y_i are unknown parameters belonging to the set of positive integers, denoted as $i \in \{15,16,17,18,19\}$. Hence, equation (9) can be simplified as,

$$\frac{d}{dt}W(t) = (y_{15} + y_{16}t)W(t)^2T(t)^2R(t) + (y_{17} + y_{18}t)W(t)^2T(t)^3R(t) + y_{19}W(t)^2T(t)^4R(t). \quad (12)$$

The equations (10), (11), and (12) still contain unknown parameters. However, initial parameters are provided in Table 2. Using these initial parameters, the model can then be applied to determine the remaining parameters specific to the greenhouse in which this model will be used.

Table 4. The correlation, r, between each term and ($\dot{W}$)

Variables	r	Variables	r	Variables	r
W^2R	−0.4715	$W^2T^3R^3$	−0.6735	$W^2T^4R\dot{T}$	−0.4041
W^2R^2	−0.3955	W^2T^4R	−0.7503	$W^2R\dot{R}/T$	0.0526
W^2R^3	−0.3231	W^2T^5R	−0.7041	$W^2R^2\dot{R}/T$	0.0254
W^2R^4	−0.2577	$W^2\dot{T}$	−0.3334	$W^2R^3\dot{R}/T$	0.0008
W^2R^5	−0.2004	$W^2R\dot{T}/T$	−0.2672	$W^2R^4\dot{R}/T$	−0.0206
W^2R^2/T	−0.2356	$W^2R^2\dot{T}/T$	−0.2564	$W^2R^5\dot{R}/T$	−0.0385
W^2R^3/T	−0.1803	$W^2R^3\dot{T}/T$	−0.2479	$W^2R^6\dot{R}/T$	−0.0530
W^2R^4/T	−0.1315	$W^2R^4\dot{T}/T$	−0.2412	$W^2\dot{R}$	0.1016
W^2R^5/T	−0.0895	$W^2R^5\dot{T}/T$	−0.2360	$W^2R\dot{R}$	0.0689
W^2R^6/T	−0.0537	$W^2R\dot{T}$	−0.3194	$W^2R^2\dot{R}$	0.0378
W^2R^7/T	−0.0235	$W^2R^2\dot{T}$	−0.3071	$W^2R^3\dot{R}$	0.0096
W^2TR	−0.6467	$W^2R^3\dot{T}$	−0.2967	$W^2R^4\dot{R}$	−0.0151
W^2TR^2	−0.5642	$W^2R^4\dot{T}$	−0.2880	$W^2TR\dot{R}$	0.0863
W^2TR^3	−0.4817	$W^2R^5\dot{T}$	−0.2808	$W^2TR^2\dot{R}$	0.0529
W^2TR^4	−0.4047	$W^2T\dot{T}$	−0.3727	$W^2TR^3\dot{R}$	0.0218
W^2TR^5	−0.3351	$W^2TR\dot{T}$	−0.3591	$W^2TR^4\dot{R}$	−0.0058
W^2T^2R	−0.7531	$W^2TR^2\dot{T}$	−0.3462	$W^2T^2R\dot{R}$	0.1025
$W^2T^2R^2$	−0.6838	$W^2TR^3\dot{T}$	−0.3345	$W^2T^2R^2\dot{R}$	0.0690
$W^2T^2R^3$	−0.6078	$W^2T^2R\dot{T}$	−0.3851	$W^2T^3R\dot{R}$	0.1156
W^2T^3R	−0.7762	$W^2T^2R^2\dot{T}$	−0.3725	$W^2T^3R^2\dot{R}$	0.0845
$W^2T^3R^2$	−0.7318	$W^2T^3R\dot{T}$	−0.3992		

3. Results and Discussion

Heat and temperature are related, and the majority of greenhouse literature employs heat flow theory to examine the rate of temperature change. Heat flux is another tool we use to analyze heat exchange between various components. These include solar radiation that is absorbed by the floor and cover of the greenhouse, infiltration through the greenhouse, energy transferred by conduction between the air inside the greenhouse and the product, as well as between the air inside the greenhouse and the cover, and ventilation between the inside and outside of the greenhouse through windows and fans. Unfortunately, due to data inaccessibility, we do not consider the terms of energy transmitted by conduction between the air inside the greenhouse and the greenhouse cover. Since most greenhouses only have temperature sensors inside and outside, adding more sensors would be necessary to monitor the temperature under the greenhouse cover. Nevertheless, since the product's temperature is correlated with its color, which impacts the product grade, the model continues to account for energy transmitted by conduction between the air inside the greenhouse and the product.

The rate of humidity change is considered by examining the flow of humidity; this includes the humidity that enters the greenhouse through the windows and the humidity released from the product, which is then ventilated out by the installed greenhouse fan. While the terms for inflow and outflow of humidity present no complications, the humidity from the product is more complex, as detailed in equation (6) because of the term of moisture content.

Most solar dryer greenhouse models include an equation for the moisture content of the product. However, since recording moisture content data is more challenging than measuring the weight of the product, we decided to use an equation for the rate of product weight change instead of the rate of moisture content change. This equation is calculated based on the moisture content equation, as described in equation (8).

The equations from the rate of change of humidity and weight have the same issue: they contain terms that include moisture content. To prevent this model from becoming overly complex and overfitting on this specific dataset, we conducted a correlation analysis to identify three of the available terms; this method simplifies the analysis and computations and generally enhances the performance of the model (Hastie et al., 2009). We selected terms with a condition based on a correlation coefficient: terms in Table 3 have a correlation greater than 0.8, and terms in Table 4 have a correlation greater than 0.7. We selected terms from Table 3 that have a correlation coefficient greater than 0.8, and by taking variables R, R^2, and R^3, we managed to reduce to only three terms instead of the total eight terms in the model. Similarly, from Table 4, we get three terms having a better value of a correlation coefficient above 0.7 from a total of five terms. Using these, the final model is expressed as in the previous section, which can be summarized as

$$\frac{d}{dt}T_i(t) = y_1 I_a + y_2 I_i + y_3\left(T_i(t) - T_a(t)\right) + y_4\left|T_i(t) - T_p(t)\right| + (y_5 + y_6 v_w)\left(T_i(t) - T_a(t)\right) - \left(y_7 + y_8 v_f\right)\left(T_i(t) - T_a(t)\right),$$

$$\begin{aligned}\frac{d}{dt}H_i(t) = {} & y_9 H_i(t) v_w(t) - y_{10} H_a(t) v_f(t) \\ & + [(y_{11} + y_{12} t) + y_{13} t R_i(t) + y_{14} t R_i(t)^2 T_i(t)] W(t) R_i(t) T_i(t) \\ & \cdot \Big[y_1 I_a + y_2 I_i + y_3\left(T_i(t) - T_a(t)\right) + y_4\left|T_i(t) - T_p(t)\right| \\ & + \left(y_5 + y_6 v_w(t)\right)\left(T_i(t) - T_a(t)\right) - \left(y_7 + y_8 v_f(t)\right)\left(T_i(t) - T_a(t)\right)\Big],\end{aligned}$$

$$\frac{d}{dt}W(t) = (y_{15} + y_{16} t) W(t)^2 T(t)^2 R(t) + (y_{17} + y_{18} t) W(t)^2 T(t)^3 R(t) + y_{19} W(t)^2 T(t)^4 R(t).$$

where all coefficients y_i are unknown parameters belonging to the set of positive integers, denoted as $i \in \mathbb{Z}^+$.

We then created a model that does not have too many complex equations, which means making the model more useful and more practical to apply. Further, with fewer terms, the chances of increasing multicollinearity are minimized resulting in more accurate measures and less chance of error given the scarcity of data. This approach enhances the ability of the model to concentrate on variables, making it more efficient and usable.

4. Conclusions

This paper proposes a mathematical model for solar dryer greenhouse systems. The objective was to design a dynamic model with important key factors that directed the performance of the model. To achieve this, we calculate the correlations between the rate of each variable and its corresponding right hand side terms then select only the terms with high correlation. The final model was found using data collected from Maesom Banana solar dryer greenhouse, Bang Krathum, Phitsanulok, Thailand. It incorporates essential key predictive factors such as air temperature inside the greenhouse, humidity ratio inside the greenhouse and weight of product. Due to the lack of complex layers and the prevention of overfitting, the model remains versatile, easy to analyze in terms of relationships between inputs and outputs, and computationally inexpensive. The operation uses a high correlation analysis for the selection of terms and thus minimizes multicollinearity. Moreover, this approach improves the model's usability and makes the key practical outputs match the needs of greenhouse operators by allowing them to fine-tune the drying processes as required.

In summary, this study helps to enhance the design of solar dryer greenhouse systems and presents an exemplary and effective approach among the current studies. Future work should be oriented towards augmenting the experiments done and making modifications to the model. Further, the model should be applied to different greenhouse surrounding factors and drying processes other than those used in this study.

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6. Conflicts of Interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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