International Journal of Agriculture Innovations and Research
Volume 14, Issue 3, ISSN (Online) 2319-1473
Manuscript Processing Details (dd/mm/yyyy):
Received: 08/10/2025 | Accepted on: 03/11/2025 | Published: 27/11/2025

Heat Transfer-Based Mathematical Modeling for Predicting Greenhouse Temperatures in Hot Arid Regions

Egbal Elmsaad[1,2*]
[1]Department of Agricultural Systems Engineering, Faculty of Agricultural and Food Sciences, King Faisal University, Saudi Arabia.
[2]Department of Agricultural Engineering, Faculty of Agricultural Sciences, University of Gezira, Sudan.
*Corresponding author email id: egbal456@gmail.com

Abstract – **Greenhouse agriculture has become an essential approach to achieving sustainable food production by allowing precise control of environmental parameters such as temperature, humidity, and solar radiation. However, maintaining optimal internal conditions in hot and arid regions remains a significant challenge due to intense solar loads and high ambient temperatures. This study presents a steady-state mathematical model based on heat transfer principles to predict the internal thermal behaviour of greenhouses operating under such climates. The developed model employs an energy balance approach, integrating factors such as solar radiation, ambient air temperature, relative humidity, ventilation rate, and plant transpiration effects. Experimental validation demonstrated a strong agreement between predicted and measured data, indicating the model's reliability and accuracy. Statistical evaluation showed that the root mean square percent deviation (e) between predicted and observed temperatures ranged from 7.1% to 11.44%, the correlation coefficient (r) varied between 0.95 and 0.99, the mean bias error (MBE) between 0.85 and 2.47, and the root mean square error (RMSE) between 2.34 and 4.91. These findings confirm that the proposed heat transfer-based model effectively simulates greenhouse microclimate conditions, providing a valuable tool for optimizing design and environmental control strategies. The model can be adapted for various crops and climatic zones, contributing to improved greenhouse efficiency and sustainable agricultural practices in arid and semi-arid environments.**

Keywords – **Heat, Temperature, Mass, Greenhouse Technology, Simulation Model.**

I. INTRODUCTION

Agriculture in greenhouses has found global popularity and interest in terms of precise control of environmental factors and the possibility of adjusting them according to the requirements of the grown crop (Mohammed et al, 2025). It has contributed to its quality and increased productivity, and has contributed to the possibility of growing it throughout the year with the optimal and sustainable use of available resources such as water, energy, etc. (Samaranayake et al, 2020) Precise control of the greenhouse environment is achieved by adjusting growth factors such as temperature, light, humidity, and carbon dioxide levels. The internal temperature is considered one of the most important factors that affect good plant growth and increased production. It was found at 7 degrees Celsius to zero degrees Celsius that most of the biological and physiological activities essential for plant growth begin to slow down. For this reason, greenhouse temperatures are constantly controlled through appropriate heating and cooling systems (Cola et al, 2020).

Understanding the greenhouse microclimate and its characteristics is critical to keep it at optimum operating conditions during various periods of plant growth. To build a viable physical model, it is crucial to have an accurate estimation of the solar radiation, mass transfer coefficients, and heat transfer coefficients, as these parameters significantly impact the greenhouse energy and mass balance (Noureddine Choab et al., 2019). A suitable heating or cooling technique must be used for this purpose. Higher inside air temperatures are required for maximum plant growth in cold weathers which can be obtained by maintaining the greenhouse effect or by employing any appropriate heating technology. On the contrary, in relatively hot climates, the greenhouse effect is required solely in a short period that ranges around two to three months while during the rest of months, other suitable cooling systems are needed (Hegazi, et al, 2022).

Areas are characterized by a hot, dry and desert climate, as is the case in the Kingdom of Saudi Arabia and the Gulf Cooperation Council countries, where protected crop areas reached 71,297 hectares in 2014 (FAO, 2021). To reduce temperatures, greenhouses are used to provide effective cooling during hot seasons to bring the internal temperature to normal levels. Suitable for crop growth. Despite this, there is difficulty in controlling traditional cooling processes such as natural ventilation and passive cooling techniques, thus leading to the cultivation of certain types of crops, likewise, in hot areas, relative humidity levels increase inside greenhouses in hot areas, especially at night, as the degree of condensation is high in crop leaves, which leads to fungal and bacterial diseases and botrytis infection (Amani et al, 2020).

Other factors which affect the greenhouse environment include solar radiation, air exchange, wind speed, carbon dioxide concentration, humidity, and relative humidity. (Rasheed, 2017) found that the U-value of PC, PVC, and HG was 9%, 4%, and 15% lower, respectively, than that for PE. The results of an experimental work showed that PE greenhouses under the climatic conditions of the eastern province of Saudi Arabia with 9cm air gap increased the effectiveness of the cooling system by 5.3% and increased the rate of fresh yield of eggplant crop by 32.68%. Ventilation is the main climatic control method of greenhouses. Natural ventilation is used to control the greenhouse climate. It is much cheaper than other systems of ventilation. Cooling is the most effective for lowering air temperature in dry climates and can be used even in humid climates during the hottest part of the day when relative humidity may be significantly below saturation. Misting system effectively reduce heating effect such as heat stress (Almuhanna et al., 2021).

Some previous studies focused on the vertical component of environmental factors inside greenhouses, and most of these studies found a large variation in temperature levels ranging between 4-5 degrees above and below the greenhouse, although these experiments were conducted in small greenhouses (Ogunlowo et al, 2021). (Sˇ alagovicˇ et al, 2024) found that the highest temperatures near the surface were 5 degrees between the coldest and warmest points in the greenhouse, and temperature gradients increased to 14% degrees Celsius with the presence of crops. This result is consistent with (Fatnassi et al, 2021)) In fact, a temperature difference of 6 C° was found near the surface, directly above the crop canopy. (Lee et al, 2012) investigated the distribution of temperature, humidity and photosynthetic photon flux (PPF) in a traditional double-layer air-filled greenhouse used for tomato production. The temperature difference was 3.5°C between a traditional double-layer green house and an air-filled greenhouse and the PPF was lower in the traditional greenhouse (Akpenpuun et al, 2021). Compared the average microclimate coefficients of polyolefin thermal screen (PoTS) and polyolefin-polyethylene thermal screen (PoTSPe) greenhouses used for strawberry cultivation and confirmed that more energy was consumed in PoTS than in PoTSPe. (Cesar et al, 2021) used wireless sensor networks in shaded greenhouses with mechanical and natural ventilation to describe and plot the horizontal and vertical variation in air temperature and relative humidity inside the greenhouse, and concluded that there was horizontal uniformity between the sensors. (Michelet & Blonde, 2018).

Most studies have shown that more than one sensor must be used because the estimate of the energy required in the greenhouse is taken from the average values of the sensors, and some researchers (Ahamed et al, 2018) assumed that the air temperature in the greenhouse is the same in all directions. Therefore, the average values of the sensors do not they are a good representation of the range of scores (Speelman, et al, 2013) In addition, a single sensor must be used to determine, adjust and control the climatic variables inside the greenhouse, and if there is a large difference between the values of the sensors, it cannot estimate the energy demand well and therefore some crops may be exposed to unsuitable climatic conditions (Bojaca et al, 2009) in general, in most cases the mean values are not predicted correctly. Therefore, more studies must be conducted to study and verify the distribution of environmental variables within the greenhouse, and to evaluate the presence of hot spots (Rasheed et al, 2019). Some researchers studied the results of the interaction between air and plants using a highly cultivated portion of greenhouse land with a high density and concluded that heat loss during the day in summer is higher than at night due to higher rates of transpiration, which confirms that crop evaporation in estimating greenhouse energy was positive, while other researchers considered that it was Negatively (Choab et al, 2021).

The decrease in the ambient air temperature (particularly at night) during winter and vice versa in summer can be reported as a problem in Saudi Arabia's greenhouse production industry (Abouda et al, 2012) Computer models of greenhouse environments and crop responses have been successful in explaining major features of crop performance and defining better protected crop environments. There has recently been an increasing argument that models can be of direct use for environmental control (Rezvani et al, 2021). Proper control of the greenhouse environment and nutrients fed the plants can lead to high productivity and product quality of modern greenhouses. It is not surprising therefore, that considerable care is being focused on solving the difficult problems of greenhouse environment control, an area that has become the object of intense research activity (Akmal et al, 2023). In a greenhouse, the air temperature is helpful in controlling the rate of development of plants/crops, such as the leaf unfolding rate, flower development, auxiliary bud development, and flower-forcing time. Air temperature may also be used to control the shape or morphology of the plant to measure this factor, a lot of equipment and labor are required (Jennifer & James, 2019). In many countries, the problem of obtaining early and sustainable vegetable crops is an important economic and social issue, especially in the agricultural sector. The problem is further exacerbated by various weather fluctuations and high temperatures, especially in dry, hot and desert areas. (Rokochynskiy, 2019).

Studying the degree of potential weather effects on crop growth and productivity has become important for agricultural scientists, interested parties, and agricultural practitioners in order to develop the necessary measures to prevent negative climatic and weather phenomena. Computer simulation of such a parameter could be one of the solutions to monitor the environmental factors inside the greenhouse. Although the actual and local climatic conditions play a vital role for the desired location and crop, there is development and evidence achieved by different greenhouse models. Therefore, it is necessary to understand the criteria, standards and performance of greenhouses under the aforementioned conditions. Therefore, a thermal model (taking into account steady-state conditions) based on energy balance must be proposed so that it is easy to understand, apply and adopt the model even for other crops in different climates: humid, dry, hot and coastal areas. Therefore, the proposed model can be adopted for other crops in the humid and dry climate of coastal areas. The validity of the proposed model is verified based on experimental results for its suitability for growing different crops. Performance can be improved by predicting environmental parameters, as it is important for small and marginal farmers, agricultural practitioners and small entrepreneurs. Therefore, the objectives of the present study are: To apply the developed mathematical heat transfer model to simulate temperature in a greenhouse. To validate the developed model by comparing the measured temperature data with the predicted ones.

II. MATERIALS AND METHODS

2.1. *Modelling Heat Transfer in the Greenhouse*

A mathematical model was tested to study the thermal performance of a greenhouse. To develop the model, energy balance equations were derived to predict environmental conditions. The model was developed based on specific assumptions, such as considering steady-state conditions while neglecting the storage capacity of the greenhouse's covered plants, heat capacity, and absorption capacity, as well as the radiative heat exchange between the greenhouse wall and roof. The thermal properties of the plants were assumed to be uniform throughout the greenhouse. The research was conducted at the King Faisal University Training and Research Station. The experimental site was located at 25.3°N and 49.6°E. Parameters introduced into the model included ambient air temperature and solar radiation incident on different surfaces of the greenhouse-oriented north and south. Plant temperature and input parameters were included based on the greenhouse climate and conditions.

The mathematical heat transfer model was based on the following assumptions: When doing the energy balance, the following are major components in the greenhouse mathematical modelling of the greenhouse and cannot be ignored: Thermal environment solar radiation absorbed by the various component surfaces constitutes the major heat term and therefore it must be considered, and Evapo-transpiration is an essential component of energy balance and it is a major cooling mechanism of greenhouse crop canopies, and moreover, heat lost by cooling and ventilation of greenhouses is an important factor.

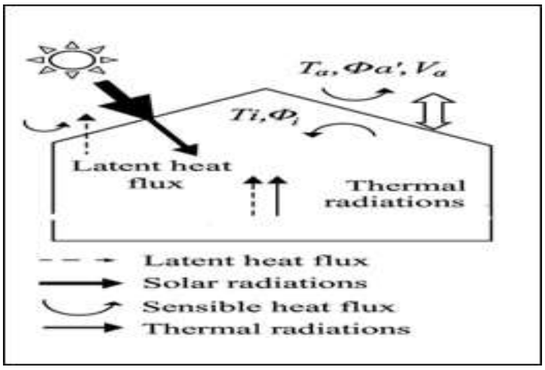

Fig. 1. Greenhouse energy balance components

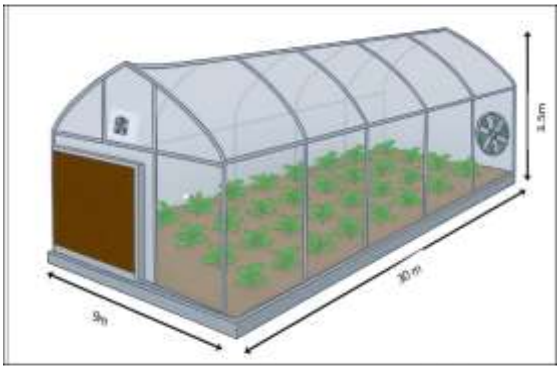

Fig. 2. Schematic diagram of the experimental.

Fig. 3. External and internal of the experimental greenhouse.

2.2. *The Model Analysis:*

The following equations were derived for model analysis performance.

2.1. *Solar radiation:*

It is known that the surface of a greenhouse is sloping, so the incident solar radiation is determined using the hourly horizontal solar radiation, which is the radiation present and available on the surface of each cover of the greenhouse, and the total incident solar radiation on the surface of the greenhouse and each cover consists of the used solar radiation, the solar radiation, and the reflected solar radiation from the ground. Using the equation given by (1) and (2) (Gadhesaria et al., 2020).

$$S_i(t) = I_b R_b I_d R_d + (I_b + I_d)\rho R_r \tag{1}$$

$$S_t = \sum S_i(t) A_i \tag{2}$$

At any time, the beam radiation ratio on an inclined surface to a horizontal surface (R_b) can be determined as

$$Rb = \frac{\cos\theta_i}{\cos\theta_z} \tag{3}$$

The transmittance of solar radiation through a greenhouse cover depends on the refractive index, irradiance, thickness, and extinction coefficient of the cover. Equation (4) was mainly used to calculate the hourly incidence angle of the ray radiation on the greenhouse cover, and according to Fresnel's and Bouguer's laws the transmittance of direct radiation through the greenhouse cover was determined. For the radiation reflected from the soil and isotropic radiation (Al-Helal, et al, 2020).

Which the θ_i and θ_z can be calculated as:

$$\begin{aligned} cos(\theta i &= sin(\phi) * (sin(\delta) * cos(\beta i) + cos(\delta) * cos(\gamma i) * cos(\omega) * sin(\beta i) + cos(\phi) * cos(\delta) \\ &* cos(\omega) * cos(\beta i) - sin(\delta) * cos(\gamma i) * sin(\beta i) + cos(\delta) * sin(\gamma i) * sin(\omega) * sin(\beta i) \end{aligned} \tag{4}$$

$$\theta_z = cos^{-1}[\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega] \tag{5}$$

The view factors of inclined surface to the ground and to the sky were determined as:

$$Rr = \frac{1-cos\beta}{2} \tag{6}$$

$$Rd = \frac{1+cos\beta}{2} \tag{7}$$

The distribution of solar radiation depends on the size and shape of the greenhouse. In the northern hemisphere, during winter, most of the solar radiation of an east-west-oriented greenhouse falls on the south wall and is transmitted into the greenhouse through the cover. Partial energy entering the greenhouse is distributed as shortwave reflected radiation or longwave radiation in the surrounding air. Some studies have taken this portion of solar radiation into account when thermally modelling a greenhouse [Gupta et al., 2012]. To calculate the radiation losses from the north wall, introduced the concept of Fn. Radiation losses from these parts were also present. To calculate these radiation losses, a total solar fraction (F_t) was proposed [Gadhesaria et al., 2020]. In this research, a three-dimensional shadow analysis in Auto-CAD was used to determine F_n and F_t, and radiation losses from the north wall and other parts were also determined. Using the equations (1, 8,9,10) and the concepts of F_t and F_n, the total available solar radiation per hour was calculated (Amani et al., 2020).

$$I_i = \left(\frac{cos(\theta)}{sin(h)}\right)I_b + \left(\frac{1+cos(\beta)}{2}\right)I_d + r\left(\frac{1-cos(\beta)}{2}\right)(I_b + I_d) \tag{8}$$

Where: i is *EW, WW, NW, SW, SR, NR*. θ is the zenith angle of sun on an inclined surface; h is the altitude angle of the sun with vertical;β is the slope of the surface with horizontal.

$$Q_p = \tau_{sc}S_t\left[(1-F)\left(1+\rho_{sc}\rho_{sp}\right) + \rho_{sc}(F-F_n) + \rho_w F_n\right] \tag{9}$$

$$Q_c = \tau_{sc}S_t\left[(1-F)\left(1+\rho_{sp}\rho_{sc}\right) + (F-F_{NW})\left(1+\rho_{sp}\rho_{sc}\right) + \frac{1}{\tau_{sc}}\right] \tag{10}$$

$$Q_w = F_n\tau_{sc}S_t \tag{11}$$

Total solar fraction *F* is the ratio of the total radiation loss from the greenhouse to the total solar radiation transmitted into the greenhouse. 4 The value of *F* will be higher during the winter months because of the low elevation angle of the sun. Therefore, *F* will be higher in the winter months and the losses will be higher. To minimize the losses, a model has been developed to calculate the total solar fraction because it measures all solar radiation losses into the greenhouse. These losses are mostly from the north wall/roof and the east-west wall. The fraction that falls on the north wall F_n is the most significant compared to the other face. It is assumed that the solar radiation entering the greenhouse is reflected doubly between the greenhouse plants, the canopy and the PCM NW. However, the total solar radiation incident on the plants, the canopy and the north wall PCM is approximately given by (Fertahi et al, 2024).

2.3. *Energy Balance Equations for Greenhouse Components:*

The various components of a greenhouse absorb incident solar radiation, and the remainder is lost through the cover to the outside. Some assumptions were made and calculated as heat energy balance equations. The equations were defined as follows:

2.3.1. *Greenhouse Cover:*

$$Q^s{}_c + Q^c{}_{a,c} + Q^c{}_{i,c} + Q^r{}_{sky,c} + Q^r{}_{p.c} + Q^r{}_{w,c} = 0 \tag{12}$$

$$\alpha_{sc}Q_c + h^c{}_{a,c}\frac{h_c}{A_g}(T_a - T_c) + h^c{}_{i,c}\frac{A_c}{A_g}(T_i - T_c) + h^r{}_{sky,c}\frac{A_c}{A_g}\left(T_{sky} - T_c\right)$$
$$+h^r{}_{p,c}\frac{A_p}{A_g}\left(T_p - T_c\right) + h^r{}_{w,c}\frac{A_w}{A_g}(T_w - T_c) = 0 \tag{13}$$

$$T_{sky} = 0.0552 \text{ x } (T_a + 273.16)^{1.5} - 273.16 \tag{14}$$

Where: Q^s (Wm^{-2}) is the solar radiation absorbed by the cover; $Q^c{}_{a,c}$ (Wm^{-2}) are the convective heat transfer between cover and respectively the outside and inside air of the greenhouse. $Q^r{}_{sky,c}$ (Wm^{-2}) and $Q^r{}_{p,c}$. (Wm^{-2}) and $Q^r{}_{w,c}$ (Wm^{-2}) is the net thermal radiation between the cover and respectively the sky, the plants and the PCM NW Eq. can be written.

$$I_j = I_{bj}R_{bj} + I_{dj}R_{dj} + R_{rj}(I_{bj} + I_{dj}) \tag{15}$$

$$Fn = \sum_j F_{nj} \tag{16}$$

2.3.2. *Greenhouse Plants:*

The energy balance of the plants surface in the model condition is:

$$Q^{s}{}_{p} + Q^{r}{}_{c,p} + Q^{r}{}_{w,p} = Q^{c}{}_{p,i} + Q^{1}{}_{p.i} \tag{17}$$

Where: Q^{s}_{p} (Wm^{-2}) is the solar radiation by the plants; $Q^{r}_{c,p}$ (Wm^{-2}) and $Q^{r}_{w,p}$ (Wm^{-2})are the net thermal radiation between the plants and respectively the cover and PCM NW; $Q^{c}_{p,i}$ (Wm^{-2}) is the sensible heat transfer between the plants and inside air of greenhouse; $Q^{l}_{p,i}$ (Wm^{-2}) is the latent heat transfer between the plants and the inside air of greenhouse. Eq. can be written as:

$$\alpha_{sp}Qp + h^{r}{}_{c,p}\frac{A_c}{A_g}\left(T_c - T_p\right) + h^{r}{}_{w,p}\frac{A_w}{A_g}\left(T_w - T_p\right) = \rho_a C_a LAI\frac{T_p - T_i}{T_a} + \frac{\rho_a C_a x LAI}{\gamma}\frac{[\ell^{*}(Tp) - \ell_i]}{\Gamma_a + \Gamma_s} \tag{18}$$

The incident and partially transmitted sunlight on the surfaces of plants leads to an increase in the temperature of the plants. The energy balance equation for plants inside the greenhouse can be written as follows (Shethi, 2009).

$$\alpha\tau S_t(1 - F_t) = M_p C_p\frac{dT_p}{dt} + A_p h_{pr}(T_p - T_r) + A_p h_r(T_p - T_r) \tag{19}$$

$$h_{pr} = h_p + \left|\frac{0.016h_p[P(T_p) - \gamma_r P(T_r)]}{T_p - T_r}\right| \tag{20}$$

$$h_p = 2.8 + 3(\upsilon) \tag{21}$$

$$h_r = F_{pr}\varepsilon_p\sigma(T\frac{2}{p} + T\frac{2}{r}(T_p + T_r) \tag{22}$$

$$P(T) = [exp\,9\,20.386 - \frac{5132}{T}]x133.3 \tag{23}$$

In the following empirical formula, which accurately relates the saturated vapor pressure of water to the temperature between 0 and 60 degrees Celsius, the saturated vapor pressure is calculated $e^{*}\ (T_p)$:

$$\ell^{*}(T_p) = 0.06108\,exp\left[\frac{17.27T_p}{T_p + 237.3}\right] \tag{24}$$

From the characteristics of the air flow in the greenhouse and the leaf length, the aerodynamic resistance r_a (s/m) of the plants was derived as follows:

$$r_a = \frac{I_f\rho_a C_a}{N_u K_a} \tag{25}$$

The stomatal resistant r_s(s/m) of the plants is derived from a simple empirical relation with global radiation. It was expressed in the following Eq.

$$r_s = 200x\left[1 + exp\left(0.05\left(50 - Q_p\right)\right)\right] \tag{26}$$

2.3.3. *Soil Layer*

The solar radiation received by the floor of the greenhouse is a small amount compared to the soil surface. The surface area of the greenhouse through which heat energy will be transferred as mentioned in assumption was calculated by the following equation in steady state:

$$\alpha_g(1 - \rho)\tau S_t = h_a A_g(T_{z=0} - T_i) + h_b A_g(T_{z=0} - T_0) \tag{27}$$

$$T(x \to \infty) = \overline{T}_a \tag{28}$$

The floor of the greenhouse receives the incident and transmitted rays in varying quantities. The energy bala-

-nce equation in the steady state can be written as follows (Gadhesaria et al 2020):

$$\alpha_g(1-\alpha_p)\tau S_t(1-F_t) = A_g h_g(T_g - T_0) + A_g h_g(T_g - T_r) \tag{29}$$

2.3.4. *Greenhouse Air:*

Greenhouse air temperature is an important factor for plant growth, as well as for energy exchange between the air and all greenhouse components, such as soil, plants, equipment, greenhouse structure, and energy leaked or transferred through the greenhouse cover, door, and ventilation system. Therefore, the energy balance equation for greenhouse air can be written as follows, Adeleke et al, 2024.

$$A_p h_{pr}(T_p - T_r) + A_g h_g(T_g - T_r) + (1-\alpha_g)(1-\alpha_p)(1-F_t)\tau S_t + \rho_c F_t \tau S_t +$$

$$Q_p = M_a C_a\left(\frac{dT_r}{dt}\right) + U_{tc}A_c(T_r - T_a) + h_d A_d(T_r - T_a) + E_v \tag{30}$$

$$Ev = 0.33NV(T_r - T_a) \tag{31}$$

Equations (32) and (34) were determined using Equation (29). An equation for the indoor air temperature (T_r) was determined by neglecting the heat capacity of the indoor air and replacing Equation (34) with Equation (30) with some mathematical simplifications.

$$T_g = \frac{[\alpha_g(1-\alpha_p)\tau S_t(1-F_t) + A_g h_b(T_0 - T_r)}{A_g(h_a + h_b)} \tag{32}$$

$$T_g - T_r = \frac{\alpha_g(1-\alpha_p)\tau S_t(1-F_t)A_g h_b(T_0 - T_r)}{A_g(h_a + h_b)} \tag{33}$$

$$A_g h_a(T_g - T_r) = [(\alpha_g(1-\alpha_p)\tau S_t(1-F_t) + (A_g h_b(T_0 - T_r))]H_g \tag{34}$$

$$T_r = \left[\frac{1}{A_p(h_{pr} + h_r) + Z}\right][(A_p T_p h_{pr} + UA_g T_0 + Q_p + T_a(A_c U_{tc} + A_d h_d + 0.33NV)$$

$$+\tau S_t(F_t \rho c + \alpha ge H_g(1-F_t)(1-\alpha_g) * (1-\alpha_p) * (1-F_t)))] \tag{35}$$

Where:

$$H_g = \frac{A_g h_a}{A_g(h_a + h_b)}, \quad H_p = \frac{A_{phpr}}{A_{phpr} + Z} \tag{36}$$

$$(UA)_{pa} = \left[\frac{1}{A_p(h_{pr+hr}} + \frac{1}{Z}\right]^{-1}, (UA)_g \frac{A_g h_a A_g h_b}{A_g h_a + A_g h_b} \tag{37}$$

$$\alpha_1 = (\rho_c F_t) + (\alpha_{ge}(1-F_t)H_g) + \alpha_{peff} \tag{38}$$

$$\alpha_{peff} = (1-\alpha_g) * (1-\alpha_p)(1-F_t) \tag{39}$$

2.3.5. *The Plant Temperature Inside the Greenhouse*

The first-order equation for the plant temperature (T_p) is determined by substituting the expression for the indoor air temperature (T_r) into Equation (35) (, Michelet & Blonde, 2018):

$$\frac{dTp}{dt} + aTp = f(t) \tag{40}$$

$$a = \frac{(UA)pa}{MpCp} \tag{41}$$

$$f(t) = \left(\frac{1}{MpCp}\right)(p\tau St(1 - Ft)Hp[(UA)gT0 + (\tau St \propto 1) + Ta(AcUc + Adhd + 0.33NV)] + Qp) \tag{42}$$

Assuming that the values of heat transfer, temperature and total solar radiation are constant for a time interval (*t = 1h*), this is the general solution (Stieglitz & Platzer, 2024).

$$Tp = \left(\frac{f(t)}{a}\right)(1 - e - at) + Tp0e - a \tag{43}$$

Equation (39) shows the temperature of plants inside the greenhouse. The mean plant temperature can be written and using the mean value theorem for integrals as follows:

$$Tp = \frac{1}{t}\int_0^t Tpdt \frac{[\propto p(1-Ft)+Hp\propto 1]\tau St+Hp(UA)gT0+HpTa(AcUc+Adhd+0.33NA)+HpQp}{(UA)pa} \tag{45}$$

2.3.6. *Determination of Evapo-Transpiration in Greenhouse*

There are several methods by which the evapotranspiration rate in greenhouses can be determined, such as integration methods or energy balances, including vortex coupling, aerodynamic techniques, and the Bowen method. These methods have been studied and detailed, including energy balances, mass and heat transfer, turbulent mixing, aerodynamics, and the Bowen ratio method. The Penman-Monteith equation can therefore be used to estimate the evapotranspiration rate in a greenhouse. In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to calculate evaporation from an open water surface from standard solar climatological records. Some researchers and studies have developed additional methods, such as vegetated surfaces, by incorporating resistance factors. There are two types of resistance: aerodynamic resistance (r_a), which describes the upward resistance of the vegetation cover and includes the friction of air flowing over the vegetated surface. Surface resistance (r_s), which describes the resistance to vapor flow through the stomatal openings, the total leaf area, and the soil surface. (Mass and Energy balance in a greenhouse (Juwawa, 2017). Evaporation from crops inside greenhouses is the main source of vapor, along with evaporation from wet and humid surfaces. It is removed through condensation and ventilation using the following equation:

$$E\text{-}C\text{-}V = 0 \tag{46}$$

Where: *E* is the crop transpiration, *C* and *V* is the vapor removed by condensation and ventilation respectively. The amount of water vapor contained in a parcel of air depends a lot on the temperature of the greenhouse air. Relative humidity and vapor pressure deficit quantify the “drying power” of air that is the amount of vapor that air at a given temperature is able to absorb. The temperature when vapor starts to saturating is called dew point which is also a measurement of humidity. Penman-Monteith Method: for determining transpiration form of the combination equation is as follows:

$$\lambda E_T = \frac{\Delta(R_n - G) + \rho_a C_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{47}$$

$$ET = \frac{0.408\Delta(Rn - G)\_\lambda\frac{900}{T+273}u_2(es - ea)}{\Delta + \gamma(1 + 0.34u_2)} \tag{48}$$

Where: R_n is the net radiation, (*MJ/m²/day*), related to solar radiation R_s , *G* is the soil heat flux (MJ/m²/day), often small during daytime, (e_s- e_a) is the vapor pressure deficit of air, ρ_a is the mean air density at constant pressure, C_p is the specific heat of air, Δ represents is the slope of the saturation vapour pressure temperature, γ is the psychometric constant (*kPa/°C*), u_2 = wind speed at 2 m height (m/s), increased by forced ventilation and

r_s and r_a are the bulk surface and aerodynamic resistances respectively. Transpiration in a greenhouse is generally from the understanding that the rate of transpiration depends on the amount of radiative energy absorbed by the canopy, R_A, and on the vapour pressure deficit, $D = e_s(T)-e$, $e_s(T)$ being the saturated pressure vapour deficit (mb) at temperature. The transpiration is expressed by means of Penman-Monteith formula extended to the whole canopy considered (big leaf).

$$TR = \frac{\Delta}{\Delta+\gamma^*} \bullet \frac{RA}{\lambda} \bullet \frac{\rho aCa}{\lambda} \bullet \frac{raD}{\Delta+\gamma^*} \tag{49}$$

Where: TR = transpiration rate ($kgm^{-2}s^{-1}$), RA = radiation absorbed by the canopy (Wm^{-2}), λ = latent heat of vaporization (Jkg^{-1}), $\rho_a c_p$ = volumetric heat capacity of air (Jm^{-3} °C^{-1}).

$$\gamma *= \gamma(1+\frac{ra}{rs}) \tag{50}$$

γ being the psychometric constant, r_a and r_s (ms^{-1}) respectively the aerodynamic and stomatal conductance of the canopy to water vapor transfer. The psychometric constant ($kPaK^{-1}$) is depended on pressure and latent heat of vaporization.

$$\gamma = \frac{Pcp}{0.622\lambda} \tag{51}$$

ƛ in $kJkg^{-1}$ is given by the relationship below, where P is the pressure (kPa), ƛ = 10000(2501-2.3617)

$$P = 101.3[\frac{293-0.0065EL]5.26}{293} \tag{52}$$

Where P is the barometric pressure in *kPa,* calculated from elevation (E_L) in m above sea level Δ = slope of the water vapor saturation curve

$$\Delta = \frac{4098es}{(T+273.3)2} \tag{53}$$

in (kPa°c^{-1}) and e_s in kPa and T in °C, the saturation vapor pressure of the air when the number of water molecules condensing equals the number evaporating from a flat surface of water with both the air and water vapor at some temperature, T. An equation for the saturation vapor pressure (e_s) over water at temperature, T, (C°) was given as:

$$es = 0.6108\exp\left(\frac{17.27T}{(T+273.3)2}\right) \tag{54}$$

In greenhouse conditions, r_a = 200 sm^{-1} was chosen as a representative value of leaf aerodynamic resistance (Hopwood et al, 2024).

2.3.6. *Ventilation Inside the Greenhouse (Forced Ventilation):*

With forced ventilation, the ventilation rate Q is mechanically controlled, often based on greenhouse climate parameters like temperature and humidity. Dependence on Temperature & Relative Humidity as: Ventilation control systems typically adjust Q to maintain optimal temperature T_{in} and relative humidity RH inside the greenhouse. A simple control relationship can be

$$Q = Q_{max} \times f\,(T_{in}, RH) \tag{55}$$

Where: Q_{max} = maximum ventilation capacity (m^3/s), $f\,(T_{in}, RH)$ = control function increasing ventilation with rising temperature and humidity. For example, ventilation might increase linearly above a temperature threshold

$T_{set}: Q = \{Q_{min},\ T_{in} \leq T_{set};\ \{Q_{min+}k_v(T_{in} - T_{set}),\ \ Tin > Tset$

Where: k_v is a proportional gain for ventilation increase. Similarly, ventilation can be triggered to reduce humidity when RH exceeds a set point RH_{set}. In greenhouse energy balance models, the ventilation term is added into account for both sensible heat exchange and latent heat exchange moisture loss and both heats as modelled as:

$$Q_{vent} = T_v * \rho * C_p * (T_a - T_e) \tag{56}$$

Here the ventilation rate (T_v) and the discharge coefficient (C_d) are given by:

$$T_v = \left(\frac{A_{vent}}{2}\right)(C_d)\sqrt{C_w * V_e + Ts_v} \tag{57}$$

$$e_{\frac{1_0}{w_0}} = F^{-0.5}{}_0F_0 = 1.75 + 0.7e^{-\left[\frac{1_0}{w_0}\right]/32.5} \tag{58}$$

2.3.6.1. *Sensible Heat:*

The sensible heat balance of the air is described by the following Eq.

$$Q^c{}_{p,i} + Q^c{}_{c,i} + Q^c{}_{w.i} + Q^c{}_{a,i} = 0 \tag{59}$$

Where $Q^c{}_{p,i}$, $Q^c{}_{c,i}$ and $Q^c{}_{w,i}$ are the convective heat transfer between inside air and respectively the plants, the cover the greenhouse wall, $Q^c{}_{a,i}$ represent the sensible heat transfer between inside and the outside air due to leakage or ventilation. Eq. can be written as:

$$h^c{}_{p,i}\frac{A_p}{A_g}(T_p - T_i) + h^c{}_{c,i}\frac{A_c}{A_g}(T_c - T_i) + h^c{}_{w,i}\frac{A_w}{A_g}(T_w - T_i) + h^c{}_{a,i}(T_a - T_i) = 0 \tag{60}$$

Where $h^c{}_{a,i}$ is the sensible heat transfer coefficient between the inside air and the outside air calculated using the equation of Fuchs et al. 22.

$$h^c{}_{a,i} = \frac{\rho_a C_a x N x V}{3600 x A_g} \tag{61}$$

In this study, air is renewed hourly to express the leakage rate where N and the relationship between N and V_a that was experimentally established by tracer gas technology for a low-cost plastic greenhouse, and this expression was given by Baille et al. 20200123.

$$N = 0.29 \ x\ V_a + 0.76 \tag{62}$$

2.3.6.2. *Latent Heat:*

Transpiration is the only source of water vapor under non-condensing conditions, so the latent heat balance of greenhouse air is described by the following equation:

$$Q^l{}_{p,\,i} = Q^l{}_{i,\,a} \tag{63}$$

Where $Q^1{}_{p,\,i}$ (Wm^{-2}) is the latent heat between plants and the inside air; $Q^1{}_{a,\,i}$ (Wm^{-2}) represent the latent heat transfer between the inside air and outside air due to leakage or ventilation. Eq. can be written as:

$$\frac{\rho_a C_a x LAI}{\gamma}\frac{[\ell^*(T_p) - \ell_i]}{r_a + r_s} = \frac{h^c{}_{i,a}}{\gamma}(\ell_i - \ell_a) \tag{64}$$

The ventilation inside the greenhouse affected by different factors such as : solar radiation R_s so R_n increases with solar radiation and higher R_n increases energy available for ET, increasing water loss.in the morning R_s is low → lower ET; midday R_s peaks → ET peaks; evening R_s declines → ET decreases. Temperature T, affects vapor pressure deficit *es*, higher temperature increases *ese* (saturation vapor pressure), enhancing ET if humidity is low. Inside greenhouse temperature is elevated by solar radiation and ventilation effectiveness. Relative humi--dity RH; $RH = ea/es \times 100\%$. High RH reduces vapor pressure deficit, decreasing ET. Ventilation lowers indoor humidity by exchanging moist air with drier outside air, increasing ET. Plant Type and Stomatal Conductance, Plants have species-specific crop coefficients K_c adjusting ET from reference values. Some plants regulate transpiration via stomatal closure under stress. ET- K_c *x* ET_0 is the reference ET (e.g., from Penman-Monteith).

2.4. *Heat Transfer by Conduction and Convection*

Conduction and convection are two of the major heat transfer phenomena in greenhouses. Heat transfer through the processes of conduction and convection in transparent and non-transparent envelopes can be calculated as follows.

$$Q_t = (U_t A_t + U_n A_n) \times (T_i - T_{\circ}) \tag{65}$$

2.4.1. *Convective Heat Transfer Coefficients:*

Empirical equation that were used to calculate the convective coefficient are 26.

$$h^{c}{}_{a,c} = 0.95 + 6.67 V^{0.49}{}_{a} \text{ with } V_a < 6.3\text{m/s} \tag{66}$$

$$h^{c}{}_{i,c} = \frac{N_u K_a}{L_c},\ h^{c}{}_{i,p} = \frac{N_u K_a}{L_f},\ h^{c}{}_{i,w} = \frac{N_u K_a}{L_w} \tag{67}$$

Correlation developed by Monteith 27 based on convection regime and the type of air flow inside the greenhouse are used for computation of the Nusselt number. Depending on the types of greenhouse envelopes, two different approaches have been applied to the estimation of the overall conduction and convection heat transfer coefficient. The overall heat transfer coefficient for transparent surfaces and non-transparent surfaces can be given as Cheilytko et al, 2024).

$$U_t = [\frac{1}{h_i} + N_c \times \frac{l_c}{k_c} + (N_c - 1) \times \frac{1}{h_a} + \frac{1}{h_{\circ}}]^{-1} \tag{68}$$

$$U_n = [\frac{1}{h_i} + \sum \frac{k}{\Delta x} + \frac{1}{h_{\circ}}]^{-1} \tag{69}$$

2.4.2. *Radiative Heat Transfer Coefficients:*

The radiative heat transfer coefficients and geometrical shape factors are calculated using equations are given by:

$$h^{r}{}_{sky,c} = \sigma \varepsilon_c \left(T^2{}_{sky} + T^2{}_{c}\right)\left(T_{sky} + T_c\right) \tag{70}$$

$$h^{r}{}_{p,c} = \sigma\left(T^2{}_{p} + T^2{}_{c}\right)\left(T_p + T_c\right)\left[\frac{1}{F_{pc}} + \frac{1}{\varepsilon_p} - \frac{A_p}{A_c}\left(\frac{1}{\varepsilon_c} - 1\right)\right]^{-1} \tag{71}$$

$$h^{r}{}_{w,c} = \sigma(T^2 w + T^2{}_{c})(T_w + T_c)\left[\frac{1}{F_{wc}} + \frac{1}{\varepsilon_w} - \frac{A_w}{A_c}\left(\frac{1}{\varepsilon_c} - 1\right)\right]^{-1} \tag{72}$$

$$h^{r}{}_{w,p} = \sigma\left(T^2 w + T^2{}_{p}\right)\left(T_w + T_p\right)\left[\frac{1}{F_{wp}} + \frac{1}{\varepsilon_w} - \frac{A_w}{A_p}\left(\frac{1}{\varepsilon_p} - 1\right)\right]^{-1} \tag{73}$$

The thermal resistance of air gaps depends on several factors, including temperature difference, heat flow direction, orientation, thickness, and the emissivity of the surrounding surface. The air gap for greenhouse covers ranges from 8 to 12 mm, depending on the cover type, with emissivity ranging from 0.2 to 0.9 mm. The thermal resistance of a 13 mm thick air gap ranges from 0.45 to 0.13 mm, for an emissivity range of 0.2 to 0.82 (Urzędowski et al, 2024).

2.5. *Additional Energy Requirements*

The parameters considered for model development and experiments were based on the local climate and greenhouse climate (A_c, A_g, A_p, A_d, M_p, T_0, and ΔH. This study aimed to explore the energy use in a greenhouse to maintain a suitable plant temperature (approximately 29°C). Based on the hourly solar radiation data available to the greenhouse, the additional thermal energy required was determined using Equation 57, as well as the ambient air temperature, hourly changes in solar radiation at the horizontal surface, and some other parameters.

$$Qp = (\frac{1}{H_p})((T_p(UA_0)p_a - [\alpha_p(1 - F_t) + H_p\alpha 1]\tau S_t - H_p(JA)_g T_0 - H_p T_a(A_c U_{tc} + At_{hd} + 0/33NV) \qquad (74)$$

2.6. *Experimental Details*

The experiment was carryout in the even span greenhouse type with dimensions of 30m×9m×3.5m was used for conducting the experimental work. It is made of galvanized pipe with aluminium extrusion. The greenhouse was cooled by an evaporative cooling system (Fan and Pad). The wetted pad was fixed along the greenhouse in western side the pad dimensions were 300mm thickness, 9m width and 2m length, while the exhaust fans model YNP-1380, Size 1530mm, voltage 220-380V customized, power: 1500W, Frequency:50/60Hz, motor rotational speed1400 Rpm, were installed along the opposite side. Cucumber (*Cucumis sativus*) was grown as an experimental crop was planted from the beginning of the experiment, it took 56 days to harvest. It was harvested several times since it was planted in drip irrigation lines, the distance between each plant and the other is 40 cm. To measure the indoor temperature of the greenhouse and the ambient temperature, (Temperature and Humidity Sensor (operating conditions range:40°C to 105°C, accuracy ± 0.1°C - India) was used for a specified 24-hour period. This means that readings were taken every hour and averaged. The humidity was also measured using the same sensor (Temperature and Humidity Sensor (operating conditions range: 0% to 100% RH accuracy ± 1.5% RH-India). Plant temperature was also measured using (SKF TKTL 31 Infrared Thermometer, -64°C Min, +1600°C Max, 1 °C Accuracy, °C and °F Measurements, Taiwan, Province of China), a solar radiation also was measurement used (Solar radiation meter model TM-207, Range: 2000 W / m^2, accuracy: +/- 10W / m^2), Barcelona-Spain). Steady-state measurements were used to analyze the indoor environment of the treatments and compared with experimental values to validate the developed model.

III. RESULTS AND DISCUSSIONS

To verify and compare the results with the experimental results, hourly experimental measurements of plant and indoor air temperatures, humidity, and ventilation, and evapotranspiration were made in the greenhouse, using the same orientation, dimensions, and plastic cover as the current model. Using similar entry criteria to those used in the experiment, it was concluded that the model allows for a more accurate and reliable simulation of the climatic parameters inside the greenhouse. Figure 4 shows the experimental and calculated values of ambient air temperature (Ta) and solar radiation (St), as well as the measured and calculated temperature values. A significant increase in both plant temperature (Tp) and greenhouse temperature (Tr) was observed, starting at 10:00 AM and peaking at 14:00. The experimental plant temperature was 3 to 4 °C higher than the ambient air temperature during the day, and 2 to 3°C higher at night. This temperature difference during the day is attributed to the solar radiation intensity exceeding the required temperature. To maintain the optimal plant temperature, excess heat within the greenhouse must be dissipated. During the night, the greenhouse cover maintained an internal temperature approximately 2 to 3°C higher than the ambient air temperature. These temperature variations were considered in the model, and the greenhouse temperature was approximately (4-2) °C higher than the ambient air temperature during the day and (3-1) °C higher in the evening. These results are consistent with those from (Lopez-cruz et al,2018), which may be due to the assumptions made in the mathematical model.

The model can be further improved by removing these assumptions. Table 2 was shown the statistical analysis of the root mean square percent deviation (e), a coefficient of correlation (r), mean bias error (MBE), and the root mean square error between the predicted and experimental values verified these. From the values indicated in the Figure 4. a, b, c, d, and 5 it has been shown that the root mean square percent deviation (e) among the experimental and predicted values of enclosed air and plant temperatures for both naturally and forced ventilated greenhouses varied from 7.1 to 11.44, coefficient of correlation (r) varied from 0.95 to 0.99, mean bias error (MBE) varied from 0.85 to 2.47, and root mean square error (RMSE) varied from 2. 34 to 4.91.

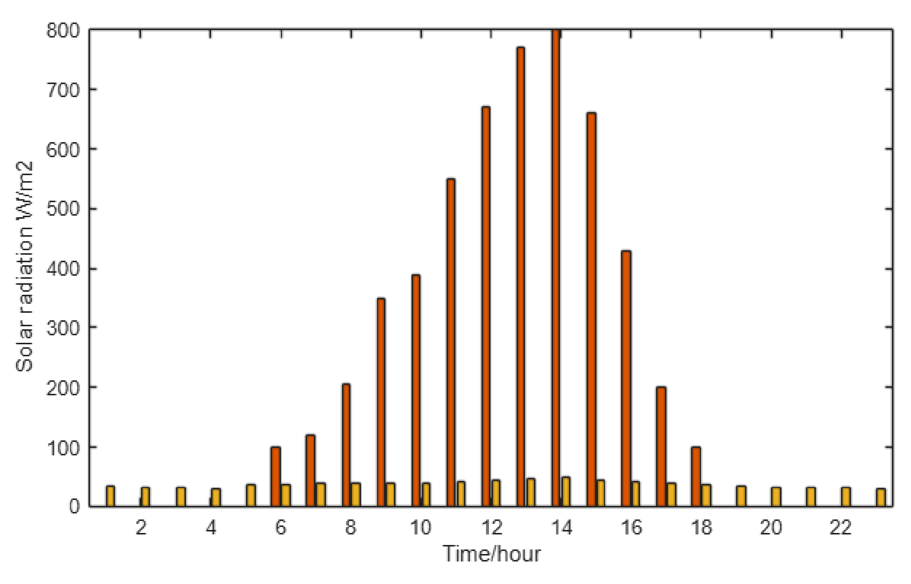

Fig. 4. Average of variation of ambient temperature C° and solar radiation w/m^{2}for 30 days.

During the afternoon hours, indoor air temperatures are at their highest, with the greatest radiation loss occurring during the evening and morning hours. Excess solar energy lost to the surrounding environment during the day can be prevented through ventilation or a thermal storage system integrated into the greenhouse. The latter is the ideal option for reducing excess heat consumption. In this climate, storage units absorb only available heat and release it when needed. Based on the expected air temperatures for the plants and greenhouses, the crops to be grown indoors can be selected. Additionally, heating or cooling requirements are based on the estimated air temperature to minimize fluctuations in the thermal environment reported that by (Chen et al, 2025).

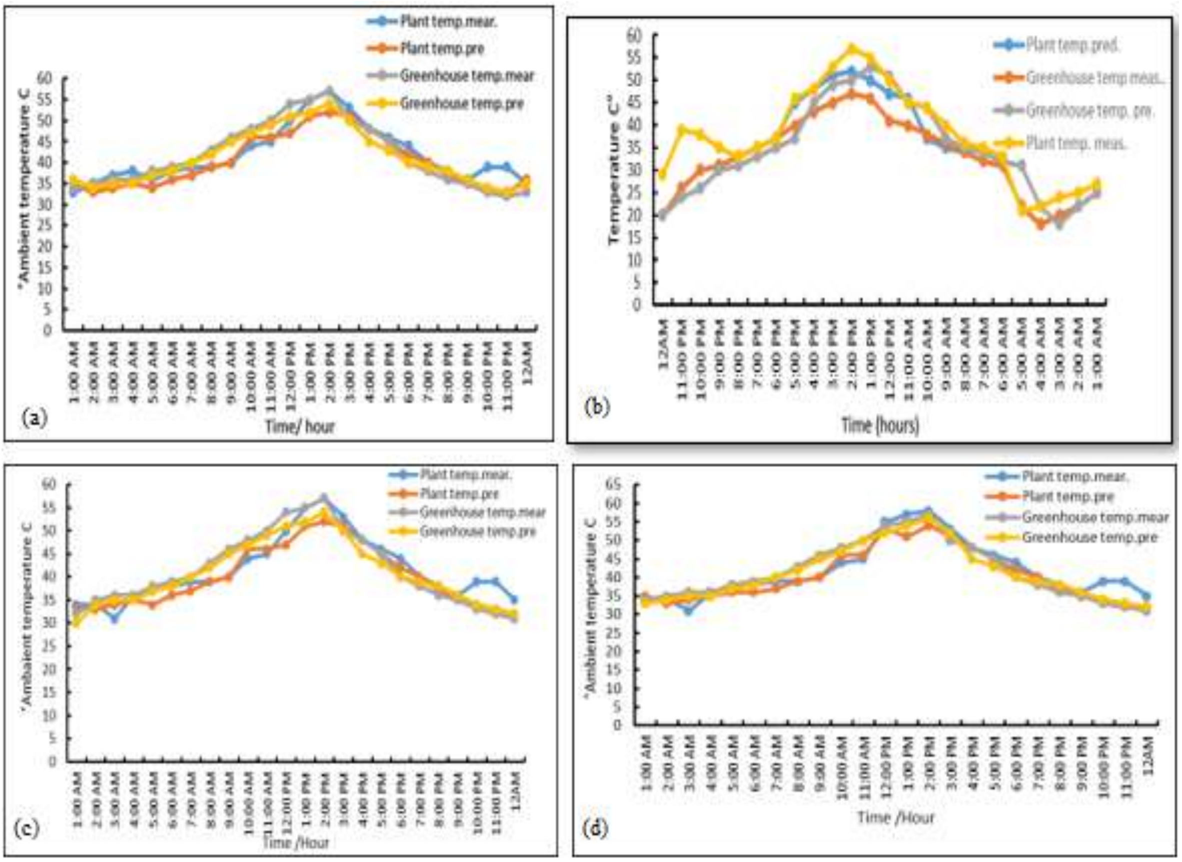

Fig. 5. a, b, c, d. Average of temperature inside the greenhouse, plant, and ambient air for the four weeks.

Table 2. Internal temperatures of greenhouse error analysis.

Statically Analysis	First Week	Second Week	Third Week	Forth Week
e_r	7.1	11.1	8.99	9.76
e_p	10.78	11.44	10.78	9.55
r_r	0.95	0.97	0.99	0.97
r_p	0.95	0.95	0.99	0.98
MBE_r	0.85	2.47	1.86	1.93
MBE_p	0.47	0.46	0.48	0.26
$MBSE_r$	2.79	4.91	4.32	4.21
$MBSE_p$	2.34	2.26	2.31	2.43

Figures 6.a, b. were shown the hourly variation in the relative humidity of the ambient air and inside the forced-ventilated greenhouse during the study period, which proved that the relative humidity inside the greenhouse was higher than the ambient air by an amount of. During the daytime hours and also in the evening periods by an amount of. These air changes were incorporated into the model. The relative humidity inside the greenhouse at night can reach 80 to 90%, which is very high compared to the optimal level of 55 to 60%. In this case, it is necessary to raise the temperature to lower the humidity, and it is also higher than the humidity outside. Several factors affect humidity; for example, solar radiation increases it, while ventilation helps to reduce it, this agrees with (Lianhua et al, 2022).

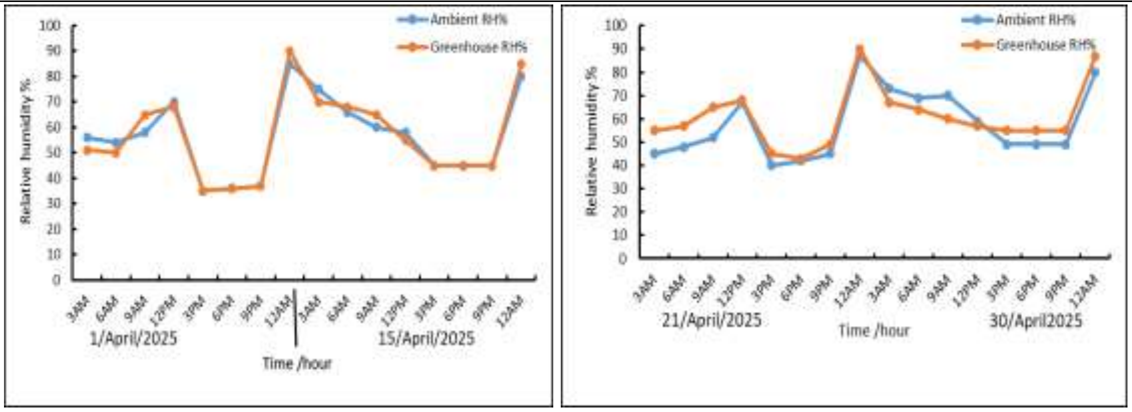

Fig. 6. a, b. Average of relative humidity inside the greenhouse, and ambient air for the four weeks.

The ventilation rate inside a greenhouse plays a fundamental and crucial role in maintaining the balance of mass and energy, thus significantly influencing the internal environment of the greenhouse. This allows farmers to cultivate crops under optimal conditions, thereby improving productivity (Mahesh et al, 2022). In the morning, lower temperature and solar radiation result in lower ET; ventilation rate might be moderate to maintain minimal heat loss but supply fresh air. In the afternoon/evening, increased temperature and solar radiation increase *ET*; forced ventilation rates increase to cool the air and reduce humidity. Managing forced ventilation based on temperature and humidity sensors optimizes water use (through *ET*) and energy consumption. Plants contribute to microclimate dynamics via transpiration, influencing humidity and temperatu--re indirectly. The ventilation rate was determined using the water vapor balance method in Equation (44); the transpiration limit was evaluated using the Penman-Monteith method as applied by (Urzędowski et al,2024; Hopwood et al, 2024). To verify this, it was compared with sap flow measurements, as shown in the figure. The relationship between transpiration rates derived from sap flow, which were determined using the Penman-Monteith formula using data for 1-30 April 2025, is shown in the figure 7.

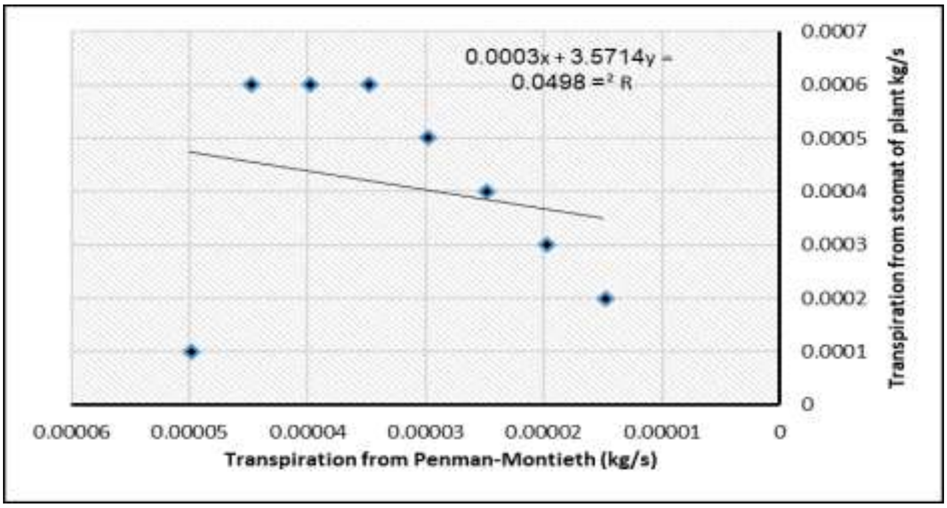

Fig. 7. The relation between transpiration obtained from plant and Penman-Monteith on days 1-30 April 2025.

Figure 8 shows that there is a good agreement between the stomatal resistance measured on the plant and the one simulated in the model to determine the transpiration values from Equation 41b. Statistical analysis showed no statistically significant differences between the predicted and simulated values at the 5% significance level this result in line with Wei et al, 2018.

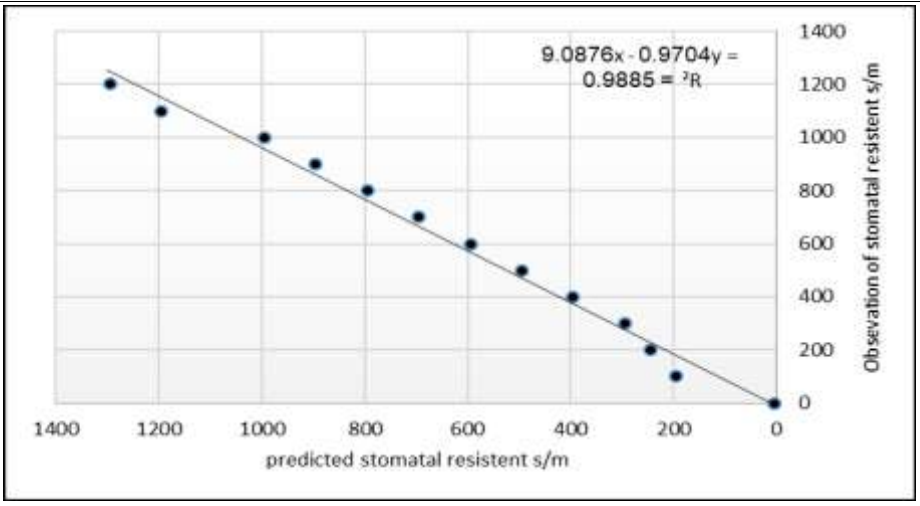

Fig. 8. The relation between predicted and observation from plant and models on days 1-30 April 2025.

Figure 9 shows the estimated additional heat energy requirements for greenhouses with natural and forced ventilation. Based on the observed readings, there is no need to increase the heat requirements from 10:00 a.m. to 6:00 p.m. Rather, heat must be drawn from the greenhouse to maintain the desired plant temperature. For greenhouses with forced ventilation, additional energy requirements were lower during the midday hours this agree with (Sapounas et al, 2020).

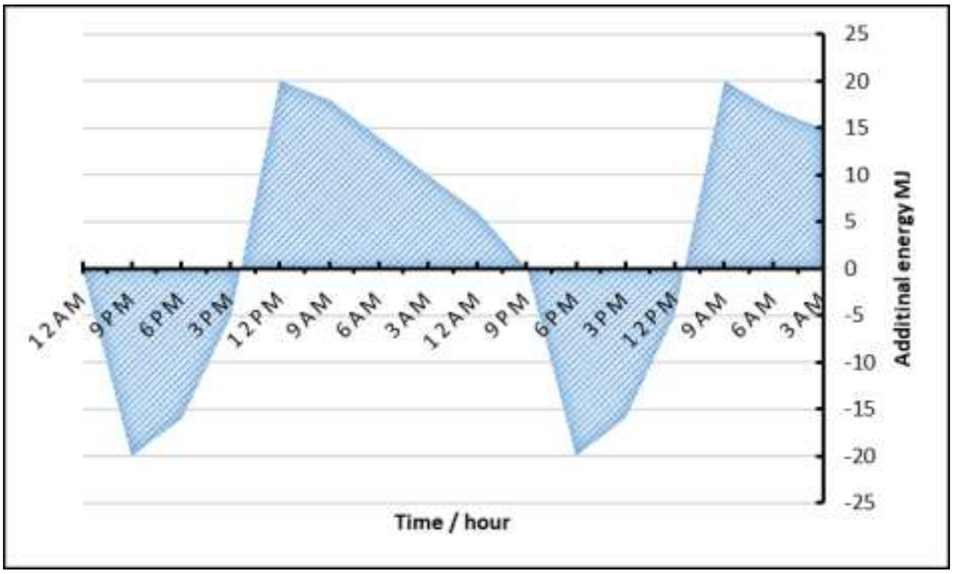

Fig. 9. Hourly estimated values of additional thermal energy requirement for forced ventilated greenhouses during study period 1-30 April 2025.

IV. CONCLUSIONS

This research presents a robust and validated steady-state heat transfer model tailored for greenhouse environments in hot arid regions, with a specific focus on the climatic conditions of Saudi Arabia. The model was developed using an energy balance approach and calibrated against experimental data collected at the College of Agricultural and Food Sciences, King Faisal University. It integrates critical environmental and operational parameters-ambient temperature, solar radiation, relative humidity, ventilation type, and plant characteristics-to simulate the internal thermal behaviour of greenhouses with high precision.

The statistical evaluation of the model revealed strong agreement between predicted and observed values. The root means square percent deviation (e) ranged from 7.1% to 11.44%, the coefficient of correlation (r) varied from 0.95 to 0.99, mean bias error (MBE) ranged from 0.85 to 2.47, and root mean square error (RMSE) ranged from 2.34 to 4.91. These metrics confirm the model's reliability and its capability to capture the dynamic thermal interactions within naturally and mechanically ventilated greenhouses.

Beyond its predictive accuracy, the model offers practical implications for greenhouse design and management. It serves as a decision-support tool for optimizing ventilation strategies, improving microclimate control, and enhancing crop productivity while minimizing energy and water consumption. Its adaptability to different crops and climatic zones makes it a valuable asset for agricultural engineers, researchers, and practitioners aiming to implement sustainable and efficient greenhouse systems.

Future work may focus on extending the model to dynamic simulations, integrating real-time climate data, and coupling it with automated control systems to further improve precision agriculture applications. Additionally, incorporating crop-specific physiological responses and economic performance indicators could enhance its utility in commercial greenhouse operations.

Nomenclature:

A area (m^2).

A_i area of roofs and walls (m^2).

C specific heat (J/kg K).

E_v heat transfer through ventilation (W).

F_n ratio of solar fraction falling on the north wall over the total incoming radiation at the same.

F_{pr} shape factor between greenhouse room and plant.

F_t ratio of the transmitted solar radiation falling on roof/walls inside the greenhouse to the total transmitted solar radiations inside the greenhouse at the same time.

h_a convective heat transfer coefficient between the greenhouse floor and inside air (W/m^2 K).

h_b bottom heat transfer coefficient between the greenhouse floor and the ground beneath (W/m^2 K).

h_d heat transfer coefficient from the greenhouse door to the ambient air (W/m^2 K).

h_p convective heat transfer coefficient between plant and inside air (W/m^2 K).

h_{pr} convective and evaporative heat transfer coefficient from the plant to the inside air.

H_r radiation heat transfer coefficient between plant and inside air (W/m^2 K).

I_b beam radiation (W/m^2).

I_d diffuse radiation (W/m^2).

M total mass (kg).

P partial vapor pressure at saturation (pa).

Q_p additional energy rate (W).

R_b the ratio of beam radiation on the tilted surface to that on a horizontal surface.

R_d view factor of tilted surface to the sky.

R_r view factor of tilted surface to the ground.

$S_{i(t)}$ total solar radiation on various walls and roofs (W/m^2).

S_t total solar radiation falling on the greenhouse cover (W).

T temperature (◦C).

t time (s).

U_{tc} overall heat transfer coefficient of the greenhouse cover (W/m^2 K).

U_{tw} overall heat transfer coefficient of the north wall (W/m^2 K).

V volume of greenhouse (m^3).

V wind velocity (m/s).

Greek

α_g ground absorptivity of solar radiation.

α_p plant absorptivity of solar radiation.

β slope of the surface with horizontal (degree).

γ surface azimuth angle (degree).

γ_r relative humidity.

δ declination angle of the sun (degree).

ε emissivity.

θ_i incidence angle (degree).

θ_z zenith angle (degree).

ρ ground reflectivity.

ρ_c north wall reflectivity.

ρ_w greenhouse cover reflectivity.

σ Stefan Boltzmann constant (W/m^2 K^4).

τ greenhouse cover transmissivity.

ω “hour angle (degree)”.

ϕ latitude angle of a location (degree).

Subscript

a ambient.

c greenhouse cover.

d greenhouse door.

g greenhouse ground/soil.

p plant.

r room air, *w* north wall.

REFERENCES

[1] T.D. Adeleke, Q.O. Ogunlowo, Na, W-H., Rabiu, A. Adesanya, M.A., Dutta, P., Zakir, E., Ogundele, O. M., Kim, H-T and Lee, H-W. Review of Temperature Management Strategies and Techniques in the Greenhouse Microenvironment. University Journal of Engineering and Technology [AUJET] .2023, 6, 2, pp.126 - 147 2714.

[2] S. Ahamed, Guo, H, Tanino. A quasi-steady state model for predicting the heating requirements of conventional greenhouses in cold regions. Inf. Process. Agric.2018, 5, pp. 33–46. [Google Scholar] [CrossRef]

[3] D. Akmal, T. Madumarov. G. Abdulkhayeva, G., Akmal S., Sultaniyaz, B. Environmental aspects and microclimate in greenhouses in the republic of Uzbekistan. E3S Web of Conferences. 2023, 389, 04002.

[4] T.D. Akpenpuun, Na, W.H.; Ogunlowo, Q.O.; Rabiu, A.; Adesanya, M.A.; Addae, K.S.; Kim, H.T.; Lee, H.W. (2021) Effect of glazing configuration as an energy-saving strategy in naturally ventilated greenhouses for strawberry (Seolhyang sp.) cultivation. J. Agric. Eng. 52, 1–24. [Google Scholar] [CrossRef]

[5] L. Al-Helal, A. Alsadon, M. Shady, M., Ibrahim,A., Abdel-Gany,A. Diffusion Characteristics of Solar Beams Radiation Transmitting through Greenhouse Covers in Arid Climates 2020.

[6] S. Abbouda, E. Almuhanna, A. Al-Amri. Effect of using double layers of polyethylene cover with air gap on control environment inside greenhouses. Engineering Sustainable Future,2012. 121341057. doi:10.13031/2013.42044.

[7] E.A., Almuhanna, G. R., Gamea, O. E., Osman, F. M., Almahdi. Performance of roof mounting misting fans to regulate heat stress in dairy cowsheds. Journal of Thermal Biology, 2021, (99): 99, 102984.

[8] M. Amani, S, Foroushani, M. Sultan, M. Bahrami. Comprehensive review on dehumidification strategies for agricultural greenhouse applications. Appl. Therm. Eng. 2021, 181, 115979. [Google Scholar] [CrossRef]

[9] Baille, A., Kittas, C., Katsoulis. Influence of whitening on greenhouse microclimate and crop energy partitioning b Agricultural and Forest Meteorology 107 (2001) 293–306.

[10] C.R. Bojacá, R. Gil, S. Gómez, A. Cooman, E. Schrevens. Analysis of greenhouse air temperature distribution using geostatistical methods. Trans. ASABE, 2009. 52, 957. [Google Scholar] [CrossRef]

[11] Z. Cesar, M. Leal, C, Branquinho, M. Miranda. Wireless sensor network to identify the reduction of meteorological gradients in greenhouse in subtropical conditions. J. Agric. Eng, 2021. 52, pp1–8. [Google Scholar] [CrossRef]

[12] A. Cheilytko, P. Schwarzbozl,.R. Broeske. Analytical Determination of Nusselt Numbers for Convective Heat Transfer Coefficients in Channel Macroporous Absorbers. Materials,2024, 17, 2738. https://doi.org/10.3390/ma17112738

[13] H. Chen., X. Lium., J. Liu, F. Wang, C. Wang. Radiative cooling applications toward enhanced energy efficiency: System designs, achievements, and perspectives. The Innovation, 2025. https://doi.org/10.1016/j.xinn. 100999

[14] N Choab, A. Allouhi, A. Maakoul, T. Kousksou,. S. Saadeddine, A, JamilE. effect of Greenhouse Design Parameters on the Heating and Cooling Requirement of Greenhouses in Moroccan Climatic Conditions. IEEE Access, 2021, 9, pp 2986–3003. [Google Scholar] [CrossRef]

[15] G. Cola, L. Mariani, Toscano, D. Romano, D. Ferrante. A. Comparison of Greenhouse Energy Requirements for Rose Cultivation in Europe and North Africa. Agronomy, 2020, 10, 422. [Google Scholar] [CrossRef]

[16] FAO. Unlocking the Potential of Protected Agriculture in the Countries of the Gulf Cooperation Council—Saving Water and Improving Nutrition; FAO, 2021, Cairo, Egypt. [Google Scholar]

[17] H. Fatnassi, T. Boulard, C. Poncet, N. Katsoulas, T. Bartzanas, M. Kacira, M., H. Giday, L. Lee. Computational Fluid Dynamics Modelling of the Microclimate within the Boundary Layer of Leaves Leading to Improved Pest Control Management and Low-Input Greenhouse. Sustainability, 2021, 13(15), 8310; https://doi.org/10.3390/su13158310.

[18] S. Fertahi. Sh. Rehman, Kh. Lahrech, A. Samaouali.AA Review of Comprehensive Guidelines for Computational Fluid Dynamics (CFD) Validation in Solar Chimney Power Plants: Methodology and Manzanares Prototype Case Study. Fluids, 2024, 9(11), 251; https://doi.org/10.3390/fluids9110251.

[19] M. Fuch. Conductive Heat Transfer in Thermal Bridges. Encyclopedia, 2022, 2(2), pp 1019- 1035; https://doi.org/10.3390/encyclopedia2020067

[20] G. Gadhesaria, C. Desai, R. Bhatt, B. Salah, B. Thermal Analysis and Experimental Validation of Environmental Condition Inside Greenhouse in Tropical Wet and Dry Climate. Sustainability, 2020, 12(19), 8171; https://doi.org/10.3390/su12198171.

[21] R. Gupta, G.N. Tiwari, A. Kumar, Y Gupta, Y. Calculation of total solar fraction for different orientation of greenhouse using 3D-shadow analysis in Auto-CAD. Energy Build., 2012, 47, 27–34. [CrossRef]

[22] A.Hegazi,, M. Farid, A. Subiantoro,S. Norris. Sustainable cooling strategies to minimize water consumption in a greenhouse in a hot arid region. Agricultural Water Management, 2022, 274, 107960. https://doi.org/10.1016/j.agwat.2022.107960.

[23] W. Lee, Sim, Y., Kim, S. Characteristics of Temperature, Humidity and PPF Distribution by Covering Method and Environmental Control in Double Covering Greenhouse. J. Bio-Environ. Control, 2021, 21, 1–11. [Google Scholar]

[24] L. Hopwood., Lopez-Reyes, Z., Bantan, A., Vietti., Al-Shahrani, D., Al-Harbi, A., Qaryouti, D., Davies, P., Tester, M., Wing, R, Waller, R. Benchmarking techno-economic performance of greenhouses with different technology levels in a hot humid climate. Biosystems Engineering, 2024, 244, 177-199.

[25] K, Jennifer, F. James, E. Timing of a Short-Term reduction in temperature and irradiance affects growth and flowering of four annual bedding plants. Horticulture,2019, 5(1), 15; https://doi.org/10.3390/horticulturae5010015

[26] C. Juwawa. Mass and Energy balance in a greenhouse. International Journal of Research in Medical and Basic Sciences, 2017, 3, 2, 1-31. ISSN: 2455-2569.

[27] D. Lianhua, N. Shaofeng, N., Angui Li., F. Xianglin, L. Minqiang, L. Anjing. Indoor air temperature and humidity variation of a greenhouse base on field test: A case study in Shandong. E3S Web of Conferences 356, 03032.EDP sciences published.,2022. https://doi.org/10.1051/e3sconf/202235603032.

[28] M. Mahesh., K. Singh, K.Sharma, P. Vishnu. Impact of ventilation rate and its associated characteristics on greenhouse microclimate and energy use. Arabian Journal of Geosciences,2022, 15:288. https://doi.org/10.1007/s12517-022-09587-1

[29] S. Michelet, B. Blonde, (2018). A model for leaf temperature decoupling from air temperature. Agricultural and Forest Meteorology, 2018, 262: 354-360. DOI: 10.1016/j.agrformet.2018.07.012.

[30] A. A. Mohamed, M. Sayed Ahmed, E, Fathy.; Y, Rizk.; Designing Sustainable Greenhouse is the Future of Agriculture. Pharos Engineering Science Journal (PESJ),2025, 02, 2025 Digital Object Identifier 10.21608/pesj.2025.376059.1029.

[31] H.G Mobtaker, A. Iabshirchi, Y, S.F. Ranjbar, M. Matloobi. Solar energy conservation in greenhouse: Thermal analysis and experimental validation. Renew. Energy, 2016, 96, 509–519. [CrossRef]

[32] C. Noureddine, A. Allouhi, A. El Maakoul, T. Kousksou, S. Saadelddine, L. Abdel,ajid. Review on greenhouse microclimate and application: Design parameters thermal modeling and simulation, climate controlling technologies. Solar Energy,2019, 191, pp 109-137. https://doi.org/10.1016/j.

[33] O. Ogunlowo, T. Akpenpuun, N. Wook-Ho, A. Rabiu, A., Adesanya, K. Addae, K., Hyeon-Tae, L. Hyun-Woo. Analysis of Heat and Mass Distribution in a Single- and Multi-Span Greenhouse Microclimate,2021.

[34] A. Rasheed, J. Lee, H. Lee. Development of a model to calculate the overall heat transfer coefficient of greenhouse covers. Spanish Journal of Agricultural Research, 2017, 15 (4): pp 208 -219.

[35] A. Rasheed, W. Lee, W., Kim, H. Lee. (2019). Efficiency of Different Roof Vent Designs on Natural Ventilation of Single-Span Plastic Greenhouse. Prot. Hortic. Plant Fact.,2019, 28, pp 225–233. [Google Scholar] [CrossRef]

[36] M. Rezvani, R. Redmond, A. Ibrahim, K. Siva. Greenhouse Crop Simulation Models and Microclimate Control Systems, A Review.2021 DOI: 10.5772/intechopen.97361

[37] A. Rokochynskiy, P. Volk, N. Frolenkova, N., Prykhodko, N., Gerasimov, I. O. Pinchuk. Evalu-ation of climate changes and their accounting for developing the reclamation measures in western Ukraine. Scientific c Review Engineering and Environmental Sciences, 2019,28(1), pp 3-13. https://doi. org/10.22630/PNIKS.2019.28.1.1

[38] J.Sˇ alagovicˇ D. Vanhees D, Verboven P, Holsteens K, Verlinden B, Huysmans M, Van de Poel B and Nicolai B (2024) Microclimate monitoring in commercial tomato (Solanum Lycopersicum L.) greenhouse production and its effect on plant growth, yield and fruit quality. Front. Hortic. 2024,3:1425285. doi: 10.3389/fhort.2024.1425285

[39] P. Samaranayake, W. Liang, Z-H. Chen, D. Tissue, Y. Lan. Sustainable Protected Cropping: A Case Study of Seasonal Impacts on Greenhouse Energy Consumption during Capsicum Production. Energies,2020, 13, 4468. [Google Scholar] [CrossRef]

[40] A. Sapounas, N. Katsoulas, B. Slager, B., Bezemer, C. Lelieveld. Design, Control, and Performance Aspects of Semi-Closed Greenhouses. Agronomy, 2020, 10(11), 1739; https://doi.org/10.3390/agronomy10111739

[41] V.P. Shethi. On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. Sol. Energy, 2009, 83, pp 21–38. [Google Scholar] [CrossRef]

[42] P. Speelman, M. McGann. How mean is the mean? Front. Psychol, 2013, 4, pp 1–12. [Google Scholar] [CrossRef][Green Version]

[43] Stieglitz, W. Platzer. Heat Transfer. Chapter.Solar Thermal Energy Systems,2024, pp 243–363

[44] A. Urzędowski, A. Sachajdak., S. Arkadiusz, Z. Jacek. CFD and Statistical Analysis of the Impact of Surface Physical Parameters on the Thermal Resistance of Layered Partitions in ETICS Systems. Energies, 2024, 18(1), 107; https://doi.org/10.3390/en18010107

[45] Z. Wei, T. Du, X. Li,F. . Fang,F.,F. Liu. Simulation of Stomatal Conductance and Water Use Efficiency of Tomato Leaves Exposed to Different Irrigation Regimes and Air CO2 Concentrations by a Modified "Ball-Berry" Model. Sec. Plant Biophysics and Modeling, 2018,9. | https://doi.org/10.3389/fpls.2018.00445.

AUTHOR'S PROFILE

Dr. Egbal Mohammed Ahmed Yousif Elmsaad, Assistant professor at Department of Agricultural Engineering, Faculty of Agricultural Sciences, University of Gezira P.O. Box 20 Wad Madani, Sudan. Mobiles: :00249 918320687 +966563491107. B.Sc. (Honorus)-Class II, Division 1 (Sept.2001) Major: Mechanization Option Faculty of Agriculture, University of Gezira, Wad Madani, Sudan. M.Sc. (June. 2008). Major: Agricultural Engineering & Control environment in Agricultural building. Dept. of Agricultural Engineering, University of Gezira, Wadmedani, Sudan. Ph.D. (Feb. 2013). Major: Control Environment in Agricultural Building Protected Agriculture (Green houses). University Sains Malaysia, Penang., Malaysia. Major: Agricultural Structures. Now I am working at King Faisal University, KSA. Collage o f Agric. And Food Sciences, Depart. Of Agric. Systems Engineering, from 2017 until now.