

Introducing the Photosynthesis-Stomatal Conductance Coupled Model into Greenhouse Microclimate Studies

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Abstract—This paper introduces the photosynthesis-stomatal conductance coupled model, well known and frequently used in the studies of vegetation-atmosphere interaction, to be incorporated into the studies of modeling greenhouses' microclimate. The use of this model, unlike many of other models in the literature, allows accurate modeling of stomatal conductance for many plant types and under several environmental conditions. It also guarantees the modeling of the photosynthesis process, which is important for microclimate and CO₂ enrichment purposes, due to the direct coupling between photosynthesis and stomatal conductance in this model. Although the many advantages of this model, the many details associated with it may be the reason behind not being used in greenhouse microclimate modeling studies. Thus, this paper comes with an aim of facilitating the use of this model and encouraging modelers of greenhouses' microclimate to use this powerful model by providing them the necessary background for the treatment of the model in a well organized form that contains all the necessary and required information they may need in their use of the model. In this paper, the photosynthesis-stomatal conductance coupled model is introduced by first illustrating briefly the biochemical background of the photosynthesis process and then introducing the accurate biochemical model that represents it. Then the photosynthesis-stomatal conductance coupled model is presented with its analytical solution methodology that gives accurate estimation of the photosynthesis rate and the stomatal conductance. Finally, validation of the model results with available experimental data is performed for a representative crop type under different environmental conditions. This validation proves the accuracy of the model in predicting the photosynthesis rate and in turn the stomatal conductance.

Index Terms—Photosynthesis, stomatal conductance, model, greenhouse, microclimate, CO₂ enrichment.

1 Introduction

In the world we live now where population increases rapidly, the need of food becomes more insistent. Besides to the population increase, the global climatic changes are strongly affecting the open agriculture in a tremendous manner. Consequently, the use of commercial greenhouses as controlled environment places suitable for high quality agriculture is rapidly increasing and is expected to continuously increase in the future [1].

Controlling and managing the microclimate of commercial greenhouses was, and is still, the work of many researchers who investigated several methods for effectively controlling the greenhouses' microclimate; experimentally, theoretically or by both of them [2], [3], [4]. As modeling provides cost-effective tool for many researchers to predict the effect of different microclimate controlling methods on the greenhouses' microclimate before it is actually implemented, the literature is rich with many research works of such modeling efforts [5], [6], [7], [8]. In all of these research works, modeling the interaction between plants and their surrounding environment is of great importance. Plant leaves are exchanging both heat and mass with the surrounding air. This mass transfer is in the form of CO₂ transfer to leaves through the photosynthesis

process and water vapor transfer from leaves' through transpiration. Both of transfers occur through small pores on the leaves surface that are called Stomata. Appropriate modeling of the stomata response to the surrounding environmental conditions is important to adequately represent the inward diffusion of CO₂ from the surrounding air to inside the leaf and the outward diffusion of water vapor to the surrounding air.

The functionality of stomata in exchanging CO₂ and water vapor between leaves and the surrounding air is represented by a mathematical expression called stomatal conductance. Most of the models used for representing the stomatal conductance in the literature depend on relating the plants or stomata response to their locally affecting environmental conditions. This makes most of these models limited to the environmental conditions and crop type that was used in the associated research work.

Abdel-Ghany et al. [9] in their study about managing a greenhouse microclimate using liquid radiation filter in the cover expressed stomatal conductance by an empirical expression that was function of the transmissivity of the greenhouse cover and the incident solar radiation to the plant. This expression was limited to the tomato crop only that was the crop type in their study. Chalabi et al. [10] in their study about the optimal control strategies for carbon dioxide enrichment expressed the stomatal conductance by an empirical relation that was function of the incident photosynthetic photon flux density (PPFD) at the top of the canopy, the canopy light extinction coefficient, and the leaf

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transmission coefficient for the incident light. Impron et al. [11] in their study about the optimization of cover properties to reduce thermal load of greenhouses used an empirical relation that was function of the incident PPFD and the CO₂ concentration inside the greenhouse. Vanthoor et al. [12] in their study about the management of greenhouse microclimate represented the stomatal resistance (the reciprocal of conductance) by a multiplicative model that is applicable to wide range of plant types. The equation they used was function of the minimum stomatal resistance, the incident solar radiation, the CO₂ concentration, and the vapor pressure difference between the leaves and the surrounding air. Although the model they used is applicable to a wide range of plant types, a drawback of the models of the multiplicative type is that they assumes that the response of stomata to each environmental factor is independent of the others, neglecting the interactive effects between these environmental factors, as in [13].

Besides the use of stomatal conductance models that are of limited applicability in many of the research works, these research works often consider the stomatal conductance to model only the outward water vapor transport and neglect the inward CO₂ transport, although stomata is responsible for both of them. Considering the CO₂ transfer (the photosynthesis process) in greenhouses' microclimate studies is not an unnecessary extra, but it is of significant importance as for water vapor transfer. This is because stomata response is strongly affected by the CO₂ concentration. Thus accurate prediction of water vapor transfer requires in turn accurate estimation of CO₂ concentration inside greenhouses which in turn requires modeling of the photosynthesis process. Furthermore, modeling the photosynthesis processes allows estimating the required amount of CO₂ for injection if CO₂ enrichment is required to be applied. The literature contains some greenhouse studies that included the modeling of the photosynthesis process. However, most of these studies considered the photosynthesis models for CO₂ enrichment purposes, not as because photosynthesis modeling is important for the greenhouse microclimate.

Chalabi and Fernandez [14] in their study about estimating the net photosynthesis rate of a tomato crop in a greenhouse expressed the photosynthesis process using two models. The first model was empirical and was function of the respiration rate of the plant, the plant leaf light use efficiency, the canopy light extinction coefficient, the incident PPFD, the transmission coefficient of the leaves, the leaf conductance, the total leaf area index (LAI), and the CO₂ concentration. The second one was mechanistic and was function of the plant biochemical properties (the light saturated potential rate of electron transport, the CO₂ compensation point, the maximum

carboxylation velocity, and the Michaelis-Menten constants for CO₂ and O₂), the intercellular partial pressure of CO₂, and the incident PPFD at the leaf level. They reported that the mechanistic model is more accurate than the empirical one. Isolovich et al. [15] in their study about sub-optimal CO₂ enrichment of greenhouses expressed the photosynthesis rate needed in their model using an empirical equation that was function of the photosynthesis efficiency, the PPFD at the top of the canopy, the leaf conductance to CO₂, the CO₂ concentration in the greenhouse air, the curvature of photosynthesis to temperature response, the temperature at which the gross photosynthesis is maximum, the greenhouse air temperature, the canopy light extinction coefficient, the LAI, the dry weight of the crop, the respiration rate per unit crop mass, and the respiration exponent. Klaring et al. [16] in their study about the CO₂ enrichment in greenhouses expressed the photosynthesis process using an empirical relation that was function of the incident PPFD, the CO₂ concentration of air, the air temperature, and the LAI of the crop. The model they used was originally developed for tomato crop but they used it to estimate photosynthesis rate of cucumber.

From the previous literature, the following can be summarized. Studies that considered the modeling of greenhouses' microclimate use expression for stomatal conductance that are mostly empirical and may be of limited applicability. These studies also use stomatal conductance expressions to model the water vapor transfer only neglecting the important CO₂ transfer. Few studies which used stomatal conductance models that are valid for wide applicability (multiplicative type), however a drawback of these model types is that they neglect the interactive effects between the affecting environmental factors on stomata. Most of the photosynthesis models used are empirical which contain parameter values that may be suitable for the environmental conditions of the study it is used at only and may need adjusting every time the model is used in different conditions. Few studies that considered the mechanistic approach of modeling the photosynthesis process. The mechanistic approach for modeling the photosynthesis process is more accurate than the empirical ones. The modeling of the photosynthesis process is not considered an important part in the greenhouse microclimate studies and it is usually neglected. Thus, it can be concluded that modeling of greenhouses' microclimate will be better improved if the model used for the stomatal conductance becomes applicable for wide range of plant types and at different environmental conditions, and if modeling of the photosynthesis process is also included.

Fortunately, there is a model that fulfills the above-mentioned needs. A photosynthesis-stomatal conductance

coupled model is available which couples the photosynthesis rate with the stomatal conductance (thus the naming of coupled model). The use of such model guarantees the modeling of the photosynthesis process in greenhouse microclimate studies as the photosynthesis rate is directly coupled to the stomatal conductance which is an essential term in any greenhouse microclimate model. It also guarantees the accuracy of estimating the stomatal conductance due to the accuracy associated with estimating the photosynthesis rate through well-known mechanistic biochemical model of photosynthesis by Farquhar [17]. In addition, it allows the applicability of the stomatal conductance model for many plant types as the photosynthesis rate of the plant types can be calculated in terms of its biochemical properties which are available in for many of the plant types [18].

Although this coupled model is frequently used in vegetation-atmosphere interactions studies [19], [20], [21], [22], authors of the present work believe that the many details of this model may be the reason that discourages other research from using such powerful model. Thus, the aim of this paper is to facilitate to modelers of the greenhouse microclimate the treatment of photosynthesis-stomatal conductance coupled model so that it becomes the common model in the future greenhouse microclimate studies. This will be achieved by introducing a brief introduction about the photosynthesis process which forms the background of the most famous photosynthesis model in the world; the Farquhar model which is considered in this paper. It will then introduce the photosynthesis-stomatal conductance coupled model and the solution methodology of determining the photosynthesis rate and the stomatal conductance.

2 The photosynthesis process

Photosynthesis is the biochemical process in green plants in which complex organic compounds are synthesized from carbon dioxide coming from atmospheric air and water coming from soil using energy obtained from the sunlight. This process is performed through series of reactions that are classified to light dependent reactions and light independent reactions. Definitions given in the following sub sections (2.1–2.5) explain some of the biochemical aspects of the photosynthesis process that are fundamental for the understanding and treatment of the mechanistic biochemical model used in the present study [23].

2.1 Light dependent reactions

They are reactions stimulated by solar radiation energy transported by photons in the visible spectrum (light). In these reactions; chlorophyll absorbs energy of the light photons, they become excited, and flow of electrons occur.

These electrons are incorporated in Reduction-Oxidation reactions that produce the so-called NADPH and ATP chemical compounds. The NADPH is a reducing agent that helps in reducing CO₂ to sucrose, and ATP is an energy carrier that provides enzymes and other molecules by the sufficient energy they need for their reactions.

2.2 Light independent reactions

They are a set of slower, enzyme-catalyzed reactions that use the chemical energy compounds produced during the light dependent reactions to convert carbon dioxide to sucrose. Fig. 1 shows the coupling between the light dependent reactions and the light independent reactions.

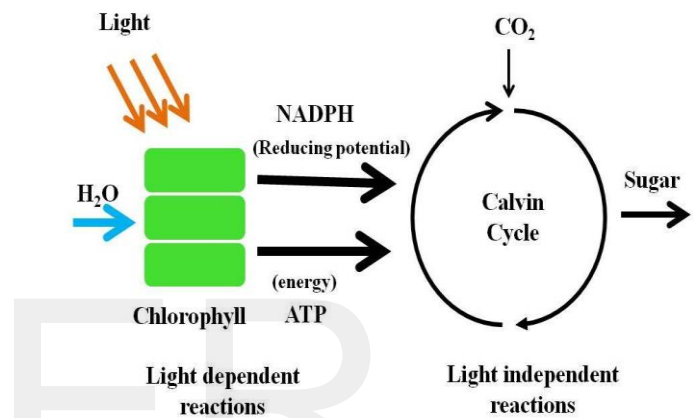


Fig. 1 Coupling between light dependent reactions and light independent reactions [23]

The light independent reactions occur in a cycle known as Calvin cycle or Photosynthetic Carbon Reduction cycle (PCR). This PCR cycle is composed of three stages that are carboxylation stage, reduction (Triose-P production) stage, and the regenerative stage, respectively. Fig. 2 shows the stages of the PCR cycle.

2.2.1 Carboxylation stage

It is a biochemical reaction in which a CO₂ molecule from inside the leaf attaches to a CO₂ acceptor molecule known as RuBP in the presence of an enzyme called Rubisco. This reaction yields compound known as PGA.

2.2.2 Reduction stage

It is the stage in which ATP and NADPH compounds produced in the light dependent reactions are consumed to reduce PGA to a Triose-phosphate (Triose-P). This Triose-P is the compound used in the production of sucrose and other metabolites that are exported to all parts of the plant or used in the leaves.

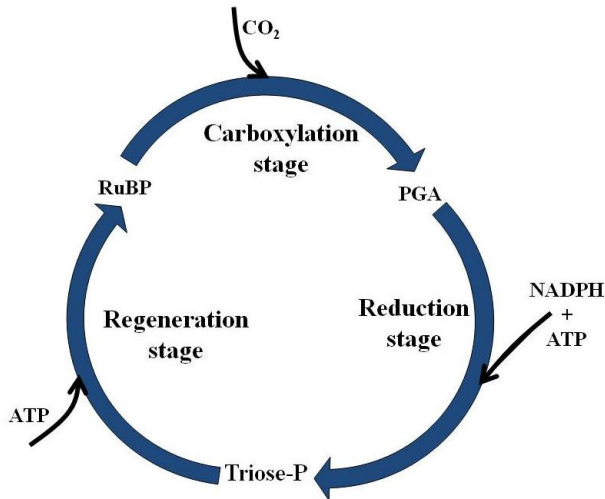


Fig. 3 Stages of Calvin cycle [13].

2.2.3 Regeneration stage

In this stage, ATP compounds are also consumed in a series of reactions in which the remaining Triose-P is used to regenerate RuBP. This regenerated RuBP represents the fresh amount of RuBP needed for use in the carboxylation stage. Thus, the cycle closes and continues.

2.3 Respiration

On the contrary to photosynthesis, CO₂ is released to atmosphere in a process called respiration. This respiration is of two types that are cellular respiration and photorespiration.

2.4 The CO₂ compensation point

It is the CO₂ concentration at which the photosynthesis rate is equal to the respiration rate (cellular respiration and photorespiration); leading to no net uptake of CO₂.

3 The mechanistic biochemical model of photosynthesis

The Calvin cycle described in the previous section shows that the photosynthesis process is composed of three stages that are Carboxylation stage, reduction stage and regeneration stage. These stages are organized in a cyclic way as the output of one stage is the input to the next stage. Thus if any of the three stages has a delay in delivering its output to the next stage, the photosynthesis process will stop at this delayed stage until it provides its output to the next stage, and so on.

The mechanistic biochemical model developed by Farquhar [17] and used in the present study stands upon this fact. This model considers three potentials of photosynthesis that represent the three stages of Calvin cycle. These potentials are RuBP Saturated (or Rubisco Limited) rate A_c , the RuBP regeneration (or electron transport) limited rate A_j , and the sucrose export limited rate A_{ph} . These potential

represents the carboxylation stage, regeneration stage, and reduction stage of the Calvin cycle, respectively.

The model considers that the rate of photosynthesis is the minimum of three potentials of the model. This corresponds to considering the slowest stage of Calvin cycle. Each of the three potentials represents the (gross) photosynthesis rate or the total CO₂ transferred to the leaf inside. It does not consider CO₂ that is lost from the leaf due to respiration. The net assimilation rate is defined as the difference between the photosynthesis rate and the respiration rate. This rate is expressed by:

$$A_n = \min \{A_c, A_j, A_{ph}\} - R_d \quad (1)$$

Where $A_{n,leaf}$ is the leaf net assimilation rate and R_d is the respiration rate.

3.1 RuBP saturated (RubisCo limited) rate

This potential represents the first stage of the Calvin cycle. It deals with the carboxylation of RuBP by CO₂ in the presence of Rubisco. Farquhar expressed this potential by:

$$A_c = \frac{(C_i - \Gamma) V_{c,max}}{C_i + K_c (1 + O_2 / K_o)} \quad (2)$$

where $V_{c,max}$, Γ , K_c & K_o are biochemical properties that are plant type dependent and temperature dependent. The term $V_{c,max}$ represents the maximum rate of Rubisco activity for carboxylation, Γ is the CO₂ compensation point, R_d is the cellular respiration which is taken as $0.015 V_{c,max}$ [24]. The terms K_c and K_o are the Michaelis-Menten constants of carboxylation and oxygenation. The terms C_i & O_2 are the CO₂ and O₂ concentrations in the intercellular air space inside the leaf, respectively.

3.2 RuBP regeneration limited rate

This potential represents the regeneration stage of Calvin cycle in which RuBP is regenerated to be available for the carboxylation stage. This potential is expressed by:

$$A_j = \frac{(C_i - \Gamma) J}{4C_i + 8\Gamma} \quad (3)$$

where J is known as the electron transport rate potential.

As described in sections 2.1 and 2.2, the regeneration stage needs the ATP chemical compound that is generated from the light dependent reactions in which flow of electrons occur. This explains the dependency of the RuBP regeneration potential on the electron transport potential. The rate of the electron transport J can be expressed as:

$$J = \frac{J_{max} + J_i - \sqrt{(J_{max} + J_i)^2 - 4\theta J_i J_{max}}}{2\theta} \quad (4)$$

where J_{max} is the maximum (biochemical capacity limited) potential of the electron transport rate, J_i is the light limited potential of electron transport rate, and θ is an empirical curvature factor (0.7 is a good average value [25]).

The light limited potential J_i is expressed by:

$$J_i = \varphi I \quad (5)$$

where I is the incident flux of photons in the visible spectrum of solar radiation which is usually named as photosynthetic photon flux density (PPFD). It is the rate of

absorbed visible radiation (from the incident solar radiation) by the plant leaves but in the units of $\mu\text{mol photon/m}^2\cdot\text{s}$, not W/m^2 . A conversion factor of ($1 \text{ W/m}^2 = 4.6 \mu\text{mol photon/m}^2\cdot\text{s}$) is used for this unit conversion [24].

The term φ is the efficiency of energy conversion for electron transport and is expressed by:

$$\varphi = 0.5 \alpha_{\text{leaf,vis}} (1-f) \quad (6)$$

where $\alpha_{\text{leaf,vis}}$ is the absorbance of leaves to visible radiation and f is the fraction of absorbed PPF unavailability for photosynthesis. This parameter is plant type-specific and typically ranges from 0.05 to 0.5.

3.3 Sucrose export limited rate

This potential expresses the reduction stage of Calvin cycle and is related to the export and use of the products of photosynthesis. This rate can be simply expressed in terms of maximum rate of carboxylation by:

$$A_{\text{ph}} = V_{\text{c max}}/2 \quad (7)$$

From the previous, it is obvious that in order to estimate the photosynthesis rate, the following is required. The biochemical properties ($V_{\text{c max}}$ and J_{max}) which are available for 109 plant types of the C3 species [18]. The properties Γ , K_c & K_o which are usually taken as the same values for any plant type of the C3 species as in [26]. The absorbed visible radiation and it can be easily obtained from any canopy radiation model [27]. All these parameters are obtainable and can be considered as direct inputs. The only thing that remains and needs to be determined is the CO_2 concentration inside the leaf, C_i .

4 The photosynthesis-stomatal conductance coupled model

In 1988, John T. Ball [28] introduced an empirical model for stomata conductance that couples the stomata conductance with photosynthesis rate. This model type is more accurate than the multiplicative type as it takes into its account the response of stomata to all environmental conditions represented in the photosynthesis rate term. This model is expressed as:

$$g_{s,wv} = m_{wv} \frac{A_n \cdot rh_s}{C_s} + b_{wv} \quad (8)$$

where $g_{s,wv}$ is the stomatal conductance for water vapor transfer, m_{wv} is a coefficient that depends on the plant type and ranges from 8-16 [25], rh_s is relative humidity at leaf surface, C_s is CO_2 concentration at leaf surface, and b_{wv} is value of stomatal conductance when $A_{n,\text{leaf}} = 0.0$ and is taken as $0.01 \text{ mol/m}^2\cdot\text{s}$ [25].

To express stomatal conductance for the CO_2 transfer g_s , equation (8) must be divided by 1.6 which is the molecular diffusivities ratio between water vapor and CO_2 . Thus, g_s can be obtained as:

$$g_s = m \frac{A_n \cdot rh_s}{C_s} + b \quad (9)$$

Where $m = m_{wv}/1.6$ and $b = b_{wv}/1.6$

It is obvious that in order to determine the stomatal conductance, the following is required. The relative humidity at the leaf surface rh_s , the CO_2 concentration at the leaf surface C_s , and the photosynthesis rate A_n which needs C_i to be determined. In the following section, the solution methodology to the above coupled equation is presented.

5 Analytical Solution of the photosynthesis-stomatal conductance coupled model

The solution of this coupled model can be performed either numerically or analytically. However, Baldocchi in his paper [29] reported that the numerical solution becomes unstable at some environmental conditions and he introduced an analytical methodology that we present here. In order to estimate the photosynthesis rate, Baldocchi considered only the first the two potentials of the photosynthesis process given by equations (2 and 3). The reason behind neglecting the third potential (equation 7) is the rare dependency of the photosynthesis process on it. Baldocchi then expressed the two potentials in the following form:

$$A_n = \frac{aC_i - ad}{eC_i + b} \quad (10)$$

Where a , e , and b are parameters representing their corresponding ones in each of the two equations of the photosynthesis potentials e.g.: (for the light saturation potential, $a=J$, $e=4.0$ and $b=8\Gamma$).

The estimation of the photosynthesis rate requires the determination of C_i . In order to get it, Baldocchi performed some mathematical operations to get C_i in terms of already known parameters. Considering that the supply of CO_2 by mass transfer to the plant leaves' stomata is in an equilibrium with the consumption of this supplied CO_2 through the photosynthesis process, the following equation can be written:

$$A_n = m_{\text{CO}_2} = \delta g_{\text{total}} (C - C_i) = \delta g_{\text{bl}} (C - C_s) = \delta g_s (C_s - C_i) \quad (11)$$

where m_{CO_2} is the mass transfer rate of CO_2 from the greenhouse air to the carboxylation sites inside the plant leaves. The term g_{total} is the total mass transfer conductance (the equivalent conductance to boundary layer conductance g_{bl} and the stomatal conductance g_s). The boundary layer conductance g_{bl} can be obtained by considering the heat and mass transfer analogy for any appropriate convective heat transfer correlation depending on the convection conditions (free, forced, or mixed) [30], [31]. The term C is the CO_2 concentration in the greenhouse air. The parameter δ is to define whether the plant leaf is amphistomatous (stomata are on one side of the leaf and thus $\delta=1.0$) or hypostomatous (stomata are on both sides of the leaf and thus $\delta=2.0$).

Considering amphistomatous leaf ($\delta=1.0$), then C_i can be expressed as:

$$C_i = C_s - \frac{A_n}{g_s} \quad (12)$$

Both of C_s and g_s are unknown. Beginning with C_s , it can be expressed as:

$$C_s = C - \frac{A_n}{g_{bl}} \quad (13)$$

The only unknown in the above equation is A_n (or implicitly C_i), provided that both of g_{bl} and C are known or can be directly calculated.

As g_s can be determined using equation 9, the term C_s of equation 13 will be introduced in equations 9 and 12. Then, equation 9 will be used to substitute for term g_s in equation 12. This makes equation 12 expressed in terms of the known parameters ($C, g_{bl}, m, r_h, s,$ and b).

Substituting back by C_i in equation 10 and performing many mathematical manipulations, a cubic expression of A_n will result that is function of ($C, g_{bl}, m, r_h, s,$ and b) besides (a, b and e) that are all known. This cubic expression has three roots. Baldocchi reported that the third root (in his original paper) is the one that represents the photosynthesis rate (The full mathematical derivation can be checked in the original reference for all details).

It can be concluded that the photosynthesis rate can now be determined in terms of parameters that are all known and directly substituted. Once the photosynthesis rate is calculated, g_s is then estimated by back substitution in equation 13 then equation 9.

The only thing that may be not clear how to determine it is r_h, s . This term is expressed and estimated as in [32] as follows:

$$r_h, s = e_s / e_{sat}(T_{leaf}) \quad (15)$$

where e_s is the water vapor pressure at leaf surface and $e_{sat}(T_{leaf})$ is the saturation water vapor pressure of the at leaf temperature. The term $e_{sat}(T_{leaf})$ can be determined from direct expressions as in [25]. In order to determine the e_s term, the equilibrium between the water vapor transfer by transpiration from inside the leaf to the leaf surface through stomata, and then from the leaf surface to the bulk air through the boundary layer is considered. This equilibrium can be expressed mathematically as:

$$g_{s, wv}(e_{sat}(T_{leaf}) - e_s) = g_{bl, wv}(e_s - e_{air}) \quad (16)$$

where e_{air} is the water vapor pressure of the greenhouse air.

Equation 16 can be rearranged in terms of e_s as:

$$e_s = [e_{sat}(T_{leaf}) g_{s, wv} + e_{air} g_{bl, wv}] / (g_{bl, wv} + g_{s, wv}) \quad (17)$$

Thus, e_s can now be determined based on the easily obtainable values of $e_{sat}(T_{leaf}), g_{s, wv}, e_{air},$ and $g_{bl, wv},$ and in turn equation 15 can be easily determined. After performing the above calculations, the photosynthesis rate and the stomatal conductance are obtained. Thus, they can be incorporated in any greenhouse microclimate study.

6 Results and Discussion

In the section, the results of solving the photosynthesis-stomatal conductance coupled model is presented. A FORTRAN computer code is written to execute the processes and sequence of the previous calculations. The program is tested to estimate the photosynthesis rate of the cucumber crop, as a crop type commonly used in commercial greenhouses. Table 1 shows the inputs used for the model.

Table 1 Parameters of the biochemical model used in validation and their values

Property	Value	Units	Reference
V_{cmax0}	50	$\mu\text{mol m}^{-2} \text{s}$	[18]
J_{max0}	$2.1 V_{cmax0}$	$\mu\text{mol m}^{-2} \text{s}$	[26]
K_C	267	ppm	
K_O	179000	ppm	
Γ	38.6	ppm	
O_2	21000	ppm	
f	0.15	-----	
θ	0.7	-----	[25]
m_{wv}	12	-----	
b	0.0175	$\text{mol/m}^2 \cdot \text{s}$	

The program is used to estimate the photosynthesis rate of cucumber under different environmental conditions of CO_2 concentration, solar irradiance, leaf temperature, and air relative humidity. Fig. 3 (a, b, and c) shows a comparison between the model prediction of photosynthesis rate with the corresponding experimental ones. Each of these figures shows the variation of the photosynthesis rate with the absorbed solar radiation by the plant leaf. Fig. 3a shows this variation when the CO_2 concentration was 350 ppm, the temperature of the plant leaf was 28°C , and the relative humidity of air was 75%. The absorbed solar radiation in this figure is expressed as photosynthetic active radiation, $\mu\text{mol/m}^2 \cdot \text{s}$ [33]. Fig. 3b and Fig. 3c show the variation when the CO_2 concentration was 1300 ppm and when the plant leaf temperature was 20°C and 30°C , respectively [34].

It can be seen from fig.3 that the model is able to accurately predict the photosynthesis rate under different environmental conditions which guarantees the ability of the model to also predict the stomata response under the different environmental conditions.

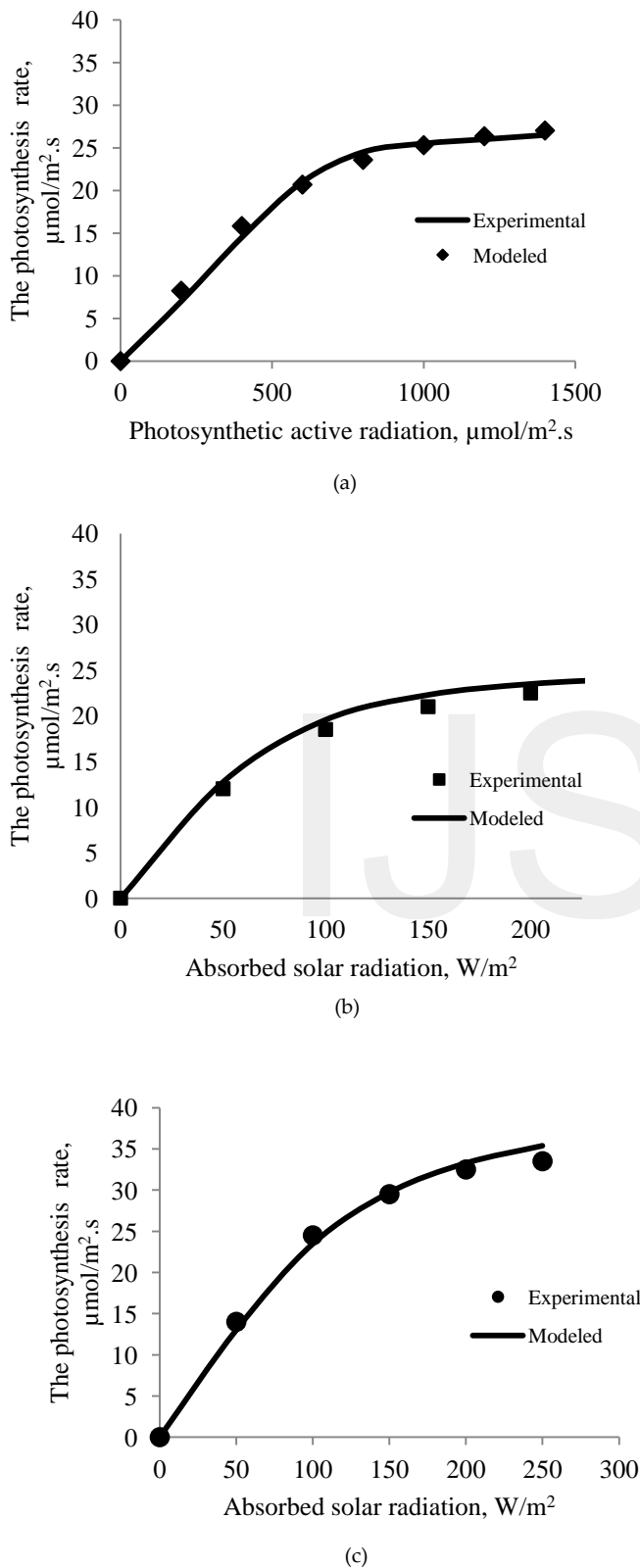


Fig. 3 Comparison between the experimental measurements and the numerical predictions of photosynthesis rates under different environmental conditions of CO_2 concentration, leaf temperature, and absorbed solar radiation.

7 Conclusion

In this work, a photosynthesis-stomatal conductance coupled model is introduced to be incorporated in greenhouse microclimate modeling studies. The paper briefly introduced the biochemical background behind the most famous and accurate mechanistic model of photosynthesis by Farquhar. It then presented the biochemical model in its mathematical form. The photosynthesis-stomatal conductance coupled model is then presented. The analytical methodology for solving this coupled model developed by Baldocchi is then presented and illustrated. The coupled model is solved and its numerical predictions of photosynthesis rate for cucumber crop is then validated with the corresponding experimental ones at different environmental conditions of leaf temperature, air relative humidity, solar radiation and CO_2 concentration. There is very good agreement between the experimental and predicted results which reveals the accuracy of the photosynthesis model in predicting the photosynthesis rate and guarantees an accurate estimation of the stomatal conductance that is strongly coupled to it.

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