JOURNAL OF ENGINEERING SCIENCES

Volume 10, Issue 1 (2023)

Sokolov S. (2023). Optimization of greenhouse microclimate parameters considering the impact of CO_2 and light. Journal of Engineering Sciences, Vol. 10(1), pp. G14-G21, doi: 10.21272/jes.2023.10(1).g2

Optimization of Greenhouse Microclimate Parameters Considering the Impact of CO_2 and Light

Sokolov S.[1][0000-0001-8707-4616]

[1] Sumy State University, 2, Rymskogo-Korsakova St., 40007 Sumy, Ukraine

Article info:
Submitted: March 9, 2023
Received in revised form: May 5, 2023
Accepted for publication: May 12, 2023
Available online: May 16, 2023

***Corresponding email:**
s.sokolov@ksu.sumdu.edu.ua

Abstract. The most critical parameters of the microclimate in greenhouses are air and soil temperature, air and soil moisture, plant illumination, and carbon dioxide (CO_2) concentration in photosynthesis. New energy sources and resource-efficient management of microclimate parameters in greenhouses can be utilized to reduce greenhouse crop cultivation costs and increase profits. As the plant mass increase depends on photosynthesis, which involves the formation of glucose in the plant chloroplasts from water and carbon dioxide under the influence of light radiation, the saturation of greenhouses with carbon dioxide has become popular in recent decades. However, insufficient light slows down the process of glucose formation, while excessive light intensity negatively affects photosynthesis. Based on the experimentally proven Van Henten model of plant growth and using the MATLAB environment, a methodology was proposed, and the dependence between CO_2 concentration and leaf lettuce illumination power required for maximum photosynthesis was determined. It is equal to 0.57 ppm/(W/m^2). Such dependence should be considered when designing control systems to reduce resource and energy costs for greenhouse crop cultivation while ensuring maximum yield.

Keywords: greenhouse gas, illumination, greenhouse effect, photosynthesis, energy efficiency, process innovation.

1 Introduction

The increasing population on Earth has led to a rise in demand for food products. However, using only natural conditions for crop cultivation is becoming insufficient. Therefore, the issue of growing crops in artificial conditions such as chambers and greenhouses is becoming more pressing. This allows for the cultivation of exotic crops and protects plants from adverse external climatic conditions in the winter and spring periods. The latest instruments and technologies expand the possibilities of achieving high yields. There are several directions in the pursuit of increasing yields, from developing genetically modified varieties, new disease and pest control methods and creating optimal conditions for plant growth. These achievements are effectively realized during plant cultivation in greenhouses. Additionally, creating favorable conditions for plants during greenhouse farming not only contributes to an increase in the yield of crops but also affects their quality. Such plant growth improvement is due to maintaining specific microclimate parameters in the greenhouse.

Most of the scientific research is focused on studying the impact of various factors on plant growth. These studies primarily identify qualitative dependencies, optimize control parameters, and various mathematical models. An essential task of horticultural engineering is optimal control of the microclimate parameters of the greenhouse. Such a task should not be based on intuition and results obtained from numerous experiments during plant cultivation. Instead, it should rely on certain principles of scientific optimization theory. Applying the optimal control theory allows for determining strategies for controlling microclimate parameters in greenhouse farming.

It should be noted that plant growth occurs through photosynthesis, which is a chemical reaction involving the formation of sugars from carbon dioxide and water in the presence of light. This reaction occurs in the leaves of plants, which are like small factories that use energy from the sun to produce food. Therefore, understanding the factors influencing photosynthesis is crucial for optimizing plant growth in greenhouses.

2 Literature Review

The process by which plants form sugars from water and carbon dioxide in the presence of light in chloroplasts is referred to as photosynthesis. During this process, free oxygen is released into the atmosphere. Despite its lack of color and odor, carbon dioxide is essential for maintaining life on Earth, with its concentration in the atmospheric air being approximately 0.004 % by volume or 400 parts per million (ppm). Although plants consume carbon dioxide during photosynthesis and release it during respiration, they consume much more gas than they exhale, creating a deficit of CO_2 in the air that limits the potential for further growth. The concentration of CO_2 in the air is not constant and depends on numerous factors, such as season, time of day, the presence of plants, water bodies, industrial enterprises, transportation, people, and animals, among others. Nevertheless, in the open air, the concentration of carbon dioxide varies only slightly.

A different state is characteristic of enclosed spaces, where during the day, while photosynthesis occurs, the concentration of CO_2 rapidly decreases, limiting glucose formation and slowing down plant growth. Experimental studies [1] confirm increased carbon dioxide consumption during photosynthesis, as 400 g of CO_2 is expended for every kilogram of cucumber harvest. Article [2] has shown a decrease in carbon dioxide concentration in greenhouse premises during the day by almost 2.0 times to 150-200 ppm. At night, the concentration of CO_2 rapidly increases due to the absence of the photosynthesis process in the absence of light and plant respiration, during which plants consume oxygen and release carbon dioxide. At this time, plants are already lacking oxygen, which can also harm their life processes. However, even in a closed environment, there is enough oxygen for plant respiration at night, and the problem remains only with carbon dioxide during photosynthesis in the daytime.

Increasing CO_2 concentration during the daytime to 800-1000 ppm has a favorable effect on crop yield. The study [3] considered the impact of carbon dioxide concentration on plant growth. A quantitative increase in biomass was found, and qualitative factors such as increased oxidative stress resistance of plants and increased concentration of minerals and vitamins in vegetables and fruits were improved. The review article on the influence of increasing carbon dioxide concentration on plants [4] concluded a 30 % increase in biomass for plants with C3 photosynthesis and a 10 % increase for plants with C4 photosynthesis with only a doubling of CO_2 concentration. However, research [2] found that the yield of C3 photosynthetic plants increased by 40-100 %, and C4 photosynthetic plants increased only by 10-25 %. Such differences in the effect of increasing carbon dioxide concentration on growth are due to different mechanisms of photosynthesis (C3, C4, CAM photosynthesis) [5]. Results of studies during pea cultivation [6] confirm a significant increase in plant mass with C3 photosynthesis with increased CO_2 concentration.

It should be noted that more than 90% of all plants in the world carry out C3 photosynthesis [5] without going into detail on the mechanisms of photosynthesis. Only four crops, i.e., corn, millet, sorghum, and sugarcane, have C4 photosynthesis. For other plants, increasing CO_2 concentration significantly affects their development.

Further increases in carbon dioxide concentration initially led to an increase in yield, but after a certain optimum, it harmed their development. It should be noted that such dependence is averaged, but for most plants, the most significant increase in yield occurs at concentrations of carbon dioxide in the air within the range of 800 ppm to 1400 ppm. Further increase in CO_2 concentration harms plant development, and at a value of 1800 ppm, it becomes toxic to them.

The optimization of microclimate parameters in greenhouse farming has been an actual topic for almost half a century by the global scientific community. An example is in work [7], where greenhouse energy consumption is proposed to be optimized (to reduce energy costs by 27 %) by the proposed control scheme for microclimate parameters. In work [8], the optimization of greenhouse parameters is entrusted to neural networks, and in [9], mathematical models and experimental confirmations of optimization in growing lettuce are presented. Even though microclimate parameters of greenhouses include air temperature and humidity, soil moisture, illumination, CO_2 concentration in the greenhouse air, and oil acidity pH, research has mainly been conducted for temperature and humidity control and optimization. In [10], the feasibility of optimizing water consumption during greenhouse cultivation is demonstrated, and in [11], a mathematical model of optimal temperature and humidity control in the greenhouse depending on environmental weather conditions during rose cultivation is presented. In the study [12], a model in MATLAB environment is developed for controlling the heater's operation and window opening. The use of a Fuzzy controller for performing such functions is studied, and in [13], dynamic models and simulation results in MATLAB of temperature and humidity in the greenhouse depending on the season, solar radiation, wind speed, temperature, and humidity outside the greenhouse are presented.

The MATLAB environment contains a powerful package of programs that allows not only performing mathematical calculations and modeling technical systems but is also used as a computer graphic interface for controlling microclimate parameters [14].

In the study [15], four temperature control techniques in a greenhouse were compared: PI control, fuzzy logic control, artificial neural network control, and adaptive neuro-fuzzy control, and it was concluded that the latter controller is the most effective and fast. Although only thermal processes were modeled in [16], this work considers the type and orientation of the greenhouse, the temperature at different points of the greenhouse, environmental temperature, and the presence and absence of a thermal screen. It provides the results of testing the greenhouse model with experimental data and proposes implementing a temperature control system.

The direction of our research was determined by an experiment described in a project [17]. In this study, identical plants were selected for the experiment and sown in glass jars with the same amount of soil. These jars were placed on a windowsill. One jar was hermetically sealed without the addition of CO_2. The latter's concentration was likely around 350-400 ppm. The second glass jar was sealed, and excess carbon dioxide was added. The drawback of this study is the lack of data on the concentration of this gas. The plants' height was measured every few days for three weeks. The experiment showed that the plants in the glass jar without the additional carbon dioxide content developed better than their excess, and it was concluded that excess CO_2 harms plant development, although initially, opposite results were expected.

The explanation for the experiment's results described above is the unknown carbon dioxide concentration in the second jar. It is possible that the concentration there exceeded 1800 ppm and thus was toxic to plant development. Another factor is that photosynthesis also requires light. Therefore, adding CO_2 without increasing the brightness will not affect photosynthesis processes. Furthermore, carbon dioxide molecules reflect sunlight, which is a hindering factor in photosynthesis.

Therefore, it can be concluded from the research in this study that a positive result in increasing crop yield through an increase in carbon dioxide concentration in a confined space (in this case, a greenhouse) can only be achieved with a proportional increase in the illumination of the surface of the plant leaves and enough water for photosynthesis. Moreover, to ensure resource-efficient management of CO_2 concentration and plant illumination, their optimum levels should be maintained to provide enough light specifically for photosynthesis, without excess, as noted in the study [18], as excessive light irradiation of tomatoes negatively affects photosynthesis processes.

A study [19] is attractive in terms of investigating the effect of carbon dioxide concentration on the rate of photosynthesis. This study proposes the main balance equations of the greenhouse microclimate model and provides the dependencies of the specific rate of crop photosynthesis on the concentration of carbon dioxide, the falling visible radiation and the temperature of the plant leaves. It was found that the maximum specific rate of photosynthesis occurred at a CO_2 concentration of 950 ppm, with sufficient light power for photosynthesis.

Modern control systems for monitoring the microclimate parameters of greenhouses and environmental balance, balancing the supply of nutrients, and lighting systems that use various types of light and renewable energy sources. have achieved high perfection. Despite the popularity of using industrial greenhouse farming, driven by their automation and latest technologies, some systems that significantly affect the yield of greenhouse crops are still in the early stages of development. The only factor limiting maximum plant growth is the amount of carbon dioxide in the greenhouse air, which is necessary for photosynthesis. Therefore, adding CO_2 offers potential opportunities for increasing the yield of crops grown in greenhouses, but it is necessary to consider the advantages and disadvantages of increasing the concentration of carbon dioxide.

The quantity of carbon dioxide in the greenhouse is most often maintained constant [20], and the greenhouse lighting is turned on depending on the time of day. Such control leads to losses in the energy spent on lighting and excess carbon dioxide consumption. At the same time, climate control inside the greenhouse for growing a particular plant can be considered based on a model of the evolution of the crop over time as a function of the climate created inside the greenhouse. During the development of such models, it is necessary to have a clear understanding of the biological processes that occur in the plant.

Before the 1980s, the development of mathematical modeling of greenhouses was sluggish. However, as the world population grew and science and technology advanced, greenhouses became increasingly used to grow crops in unfavorable conditions. This led to increased commercial and scientific interest in organizing greenhouse farms. The commercial component of greenhouse farms influenced the expansion of greenhouses, the search for new materials, the implementation of new technologies, new equipment, and new scientific research. Consequently, the number of mathematical models overgrew from the 1980s. There was also a continuous improvement of mathematical models of greenhouses, with the discovery of new dependencies, patterns, and modeling methods. Various models describing greenhouses from different aspects, such as goals, precision, complexity, and transparency, emerged. Inadequate transparency of mathematical models led to the creation of new models. In pursuit of accuracy and comprehensiveness, models became increasingly complex, losing an understanding of critical processes. Therefore, among such a variety of models, without systematization, it is not easy to choose a mathematical model that meets specific requirements. Choosing the wrong initial model makes it impossible to obtain adequate results.

Regarding mathematical models of greenhouse farming, they have a typical structure but differ in various components and dependencies. Most models combine previously published elements of mathematical models, with only a small number containing new components.

To identify standard features of mathematical models of plant cultivation in greenhouses, review articles are emerging that analyze the commonalities and differences of models.

In the paper [21], more than 100 scientific publications on dynamic models describing climatic conditions in greenhouses were analyzed. Models were considered in terms of their purpose (theoretical or applied application), the set goal of controlling microclimate parameters (proportional-integral-derivative regulation, optimal, adaptive, robust, and predictive control), methods of parameter estimation, and the possibility of expanding the application of dynamic models of greenhouses to other objects.

3 Research Methodology

The concentration of carbon dioxide (CO_2) in the air of greenhouses is a microclimate parameter that is not always considered. The starting point for investigating the need to control and regulate the concentration of CO_2, which is one of the parameters of the greenhouse microclimate, was associated with the peculiarities of plant cultivation, specifically the process of photosynthesis. It is well known from biology that organic compounds are formed from carbon dioxide and water in plants under the influence of light energy with the participation of chlorophyll. This reaction has a chemical formula [24]:

$$6\,CO_2 + 6\,H_2O = C_6H_{12}O_6 + 6\,O_2$$

Chlorophylls, which are found in plant chloroplasts, are primarily located in leaves. Each leaf cell contains 20-100 chloroplasts, which are structural components of cells that convert CO_2 into glucose C6H12O6.

Based on the above facts, it can be concluded that to increase crop yields, it is necessary to increase the amount of carbon dioxide and water. The amount of light should be sufficient for photosynthesis. Considering the resource-saving orientation of this work, it is essential to find an optimum between the amount of light required for photosynthesis and the concentration of CO_2, considering the presence of chloroplasts, the number of which depends on the area of the plant's leaves.

We will assume that water is sufficient for photosynthesis and plant growth.

We will use a mathematical plant growth model and simulation modeling in MATLAB Simulink to identify the optimal dependence between carbon dioxide concentration and lighting. The initial conditions for choosing a mathematical model were as follows:

The purpose of mathematical modeling is to determine the optimal dependences between microclimate parameters to minimize material and energy costs for the cultivation of a unit of the crop.

The mathematical model should represent a dynamic carbon balance.

The selected microclimate parameters include air temperature in the greenhouse, concentration of carbon dioxide, and light intensity.

The model of the microclimate will consider some environmental climate parameters.

The growth model should consider plants' biological processes and microclimate parameters' effect on their speed.

To minimize biological processes considered in the growth's mathematical model, a plant that does not form flowers and does not require pollination will be selected. The growth modeling work was carried out for lettuce. Only the process of photosynthesis was considered from the biological processes that affect yield.

The plant yield will be assessed based on the plant's dry mass and the size of the leaves per unit of soil.

Economic indicators and elements of control systems are not the purposes of the presented mathematical modeling.

Based on critical scientific publications regarding new mathematical models of greenhouses, we will select and simplify a model with experimental verification of its adequacy. As the simplest model that satisfies most requirements, we will take the Van Henten mathematical model [25] in the first approximation.

Experimental studies were conducted to verify the adequacy of the model for the growth of lettuce. The lettuce was chosen as the greenhouse crop. According to Van Henten, the experimental results confirmed the mathematical model for lettuce growth with a high degree of correlation, with deviations not exceeding 5 %. Such claims prompted the study of the Van Henten growth model, its analysis, and the identification of opportunities for improvement or simplification.

The increase in lettuce weight was assessed based on the dry mass of the lettuce, which was divided into two components: the structural component (X_{str}) and the non-structural component (X_{nstr}) of dry mass. The structural component consists of structural components such as cytoplasm and cell walls. The non-structural dry mass contains formations such as starch, glucose, and sucrose produced by the process of photosynthesis.

In the Van Henten model, it is considered that the processes of photosynthesis, respiration, and an increase in the mass of the structural component influence the increase in the non-structural component (X_{nstr}). The increase in the mass of the structural component (Xstr) is proportional to its mass. Therefore, the Van Henten growth equations take the following form [25]:

$$\frac{dX_{nstr}}{dt} = c_\alpha \times f_{photosyn} - v_{grow} \times X_{str} - f_{transp} - \frac{(1 - c_\beta)}{c_\beta} \times v_{grow} \times X_{str};$$

$$\frac{dX_{str}}{dt} = v_{grow} \times X_{str}, \qquad (1)$$

where $f_{photosyn}$ – the rate of plant mass increase due to photosynthesis; f_{transp} – reduction of plant mass in the process of exhaling carbon dioxide; v_{grow} – the specific growth rate of the structural component, [C^{-1}]; c_α, c_β – coefficients; $v_{grow} \times X_{str}$ – reduction of the mass of the non-structural component due to its transformation into a structural one.

The coefficient $(1 - c_\beta) / c_\beta$ considers the increase in mass losses due to synthesis and respiration during plant growth, i.e., its structural component. For lettuce, c_β is equal to 0.8, and $(1 - c_\beta) / c_\beta = 0.25$.

The coefficient c_α is calculated assuming that carbon dioxide is transformed into glucose during photosynthesis, and the ratio of molecular weights of glucose and carbon dioxide is 30 / 44, i.e., $c_\alpha = 0.68$.

At this stage of the research, the Van Henten equation for non-structural components can be simplified to the following form:

$$\frac{dX_{nstr}}{dt} = c_\alpha \times f_{photosyn} - \frac{v_{grow}}{c_\beta} \times X_{str} - f_{transp}. \qquad (2)$$

The drawback of model (2) is the complexity of determining a plant's dry weight in real time. This can be overcome by transitioning from the dry weight of the plant to the area of its leaves. The experimentally obtained formula for lettuce [25] is as follows:

$$S_{leaf} = (1 - c_T) \times k_{leaf} \times X_{str}, \tag{3}$$

where $(1 – C_T)$ is a coefficient expressing the proportion of leaf mass in the total structural mass; k_{leaf} is the leaf area coefficient as the leaf area per dry structural plant component mass.

For lettuce, $(1 – C_T) = 0.85$, and it was experimentally determined that $k_{leaf} = 0.075$ $[m^2 \times g^{-1}]$.

If the number of plants per unit area is n, the mass of one plant can be determined by dividing X_{str} by n, and then the expression (3) takes the following form [25]:

$$S_{leaf} = \frac{(1-c_T) \times k_{leaf} \times X_{str}}{n}. \tag{4}$$

Another drawback of growth model (2) is the complexity of separating structural components from non-structural ones. Such separation is essential for further use of the crop in the processing industry. As for lettuce, which this model is adapted for, it is usually consumed raw and sold by weight, without dividing into components. Therefore, in the model (2), we will move from the mass of structural (X_{str}) and non-structural (X_{nstr}) components to the total mass of the plant ($X_{general}$), considering that:

$$X_{general} = X_{str} + X_{nstr}. \tag{5}$$

Experimental data from lettuce cultivation [25] revealed that the dry weight of one plant's structural component was 2.0 g, while the non-structural component was only 0.7 g. Therefore, the dry weight of the non-structural component represents approximately 25 % (0.7 × 100 / 2.7 = 26 %) of the plant's total weight, and it can be stated that $X_{str} = 0.75 \cdot X_{general}$, and $X_{nstr} = 0.25 \cdot X_{general}$.

Estimation calculations of growth model (2) were made based on the results of the mathematical model and lettuce cultivation experiment [27], indicating that plant mass increase occurs exclusively due to photosynthesis. The loss of plant mass due to respiration can be neglected. In this case, the growth model's error for greenhouse conditions will not exceed 1%, and the model will take the following form:

$$\frac{dX_{general}}{dt} = c_\alpha \times f_{photosyn}. \tag{6}$$

It can be inferred from this model that the increase in plant mass occurs through photosynthesis, and the influence of other processes is insignificant, which is supported by biological research. The increase in weight of the non-structural component of the plant due to the process of photosynthesis can be described by the following empirical expression [25]:

$$f_{photosyn} = \{1 - exp(-c_K \times k_{leaf} \times (1 - c_T) \times X_{str})\} \times f_{photosyn.max}, \tag{7}$$

where coefficient C_K is used to consider the orientation of the leaf. In the case of a plant with horizontally oriented leaves called pianophiles, the coefficient C_K equals 0.9.

In the case of a plant with vertically oriented leaves called electrophiles, the coefficient $C_K = 0.3$. As lettuce is a more pianophile crop, we will choose $C_K = 0.9$ because its leaves are situated in a horizontal plane.

The parameter $f_{photosyn.max}$ represents the rate at which the plant mass increases due to photosynthesis in the case of complete coverage of the ground surface with leaves and is measured in $[g \times m^{-2} \times s^{-1}]$.

The coefficient $(1 – C_T)$ expresses the proportion of the total structural mass that is made up of leaves. For lettuce, $(1 – C_T) = 0.85$. The $k_{leaf} \times (1 – C_T) \times X_{str}$ multiplier is the leaf area index.

The expression in curly brackets in (7) demonstrates how many times the rate of plant biomass increase due to photosynthesis is lower than the maximum possible rate when leaves fully cover the soil. It considers the fact that leaves do not entirely cover the ground. When leaves fully cover the soil, this expression equals one.

As the rate of photosynthesis depends on the concentration of carbon dioxide, the intensity of light radiation, temperature, and leaf area, Van Henten proposed the following dependence [25]:

$$f_{photosyn.max} = \frac{c_{rad,phot} \times I_{light} \times g_{CO2} \times \rho_{CO2} \times (CO_2 - R)}{c_{rad,phot} \times I_{light} + g_{CO2} \times \rho_{CO2} \times (CO_2 - R)} \tag{8}$$

where $C_{rad,phot}$ – light use efficiency, which is the fraction of radiation that is used in the process of photosynthesis $[g \times J^{-1}]$; I_{light} – the power of photosynthetically active radiation per unit area of greenhouse surface, measured in watts per square meter $[W \times m^{-2}]$; g_{CO2} – the conductance of leaves to the diffusion of carbon dioxide through their surface, measured in meters per second [m/s]; ρ_{CO2} – the density of carbon dioxide gas, with a value of $1.83 \cdot 10^{-3}$ $[g \times m^{-3}]$; CO_2 – the concentration of carbon dioxide gas in the air, measured in parts per million [ppm]; r – the compensation point for carbon dioxide, corresponds to photorespiration at high light intensities, [ppm].

The compensation point depends on temperature as follows [25]:

$$r = c_R \times c_{comp}{}^{0,1T-2}, \tag{9}$$

where C_R – the compensation point of carbon dioxide at a temperature of 20 °C and is equal to 40 ppm; C_{comp} – coefficient, which considers the effect of temperature on the compensation points and has a value of 2.

The light use efficiency $C_{rad \cdot phot}$ can be calculated using the following formula, as described in [25]:

$$c_{rad,phot} = c_{eff} \times \frac{CO_2 - R}{CO_2 + 2R}, \tag{10}$$

where C_{eff} – the effective use of light during high carbon dioxide concentration and is equal to $1.7 \cdot 10^{-5}$ $[g \times J]$.

The conductivity of leaves for the diffusion of carbon dioxide through their surface, g_{CO2}, consists of two physical conductivities and one chemical conductivity. The physical conductivities include the conductivity of the surface layer, g_{bound}, and the stomatal conductivity, g_{stom}, while the chemical conductivity is the conductivity of carboxylation, g_{carb}.

The dependence between the mentioned conductivities can be expressed as follows [25]:

$$\frac{1}{g_{CO2}} = \frac{1}{g_{bound}} + \frac{1}{g_{stom}} + \frac{1}{g_{carb}}. \tag{11}$$

The conductivity of the leaf surface layer g_{bound} is determined by the wind speed and the temperature difference between the leaf and the greenhouse air. It has been experimentally determined that for lettuce, at a temperature difference of 5°C and a wind speed of 0.1 m/s, typical for a greenhouse, $g_{bound} = 0.007$ [$m \times s^{-1}$] [25].

The stomatal conductance g_{stom} depends on the plant’s condition and the presence of stress factors. Without stress, the stomatal conductance of lettuce for carbon dioxide was experimentally determined to be 0.005 [$m \times s^{-1}$].

The conductivity of carboxylation g_{carb} depends on temperature. For lettuce, it reaches its maximum value $g_{carb.max} = 0.004$ at a temperature of 17.5 °C and approaches zero at temperatures of 5 and 40 °C. For the temperature range of 5 °C to 40 °C, the conductivity of carboxylation can be described by the following expression [25]:

$$g_{arb} = c_{carb,1} \times T^2 + c_{carb,2} \times T + c_{carb,3}; \tag{12}$$

$c_{carb,\,1} = –1{,}32 \times 10^{-5}$ [$m \times s^{-1} \times °C^{-2}$];

$c_{carb,\,2} = 5{,}94 \times 10^{-4}$ [$m \times s^{-1} \times °C^{-1}$];

$c_{carb,\,3} = –2{,}64 \times 10^{-3}$ [$m \times s^{-1}$].

4 Results

The resource efficiency of management is based on the regulation of greenhouse lighting depending on the concentration of carbon dioxide gas to obtain the maximum yield due to the maximum photosynthetic rate of the plant. It is assumed that plant illumination should be sufficient for photosynthesis, but solar radiation should also be considered. The control of lamp irradiance can be described using Equation (8), which represents a balance between the concentration of carbon dioxide gas (CO_2) and the light intensity (I_{light}) necessary for maximum photosynthesis. The relationship between them can be found by dividing the numerator and denominator by the factor $C_{rad,\,phot} \times I_{light}$:

$$f_{photosyn.max} = \frac{g_{CO2} \times \rho_{CO2} \times (CO_2 - R)}{1 + \frac{g_{CO2} \times \rho_{CO2} \times (CO_2 - R)}{c_{rad,phot} \times I_{light}}}. \tag{13}$$

A relationship between the concentration of carbon dioxide (CO^2) and the light intensity (I_{light}) involved in photosynthesis can be obtained from this expression. The lack of data on the maximum rate of photosynthesis poses a problem for detecting such a relationship. We will implement expression (13) and perform modeling in Simulink (Fig. 1) to address this.

The subsystems used in this model are presented in Figures 2-5.

During the simulation, the relationship between the rate of photosynthesis and the power of light radiation was determined at different concentrations of carbon dioxide, which varied from 400 ppm to 1200 ppm with a step of 200 ppm (Fig. 6).

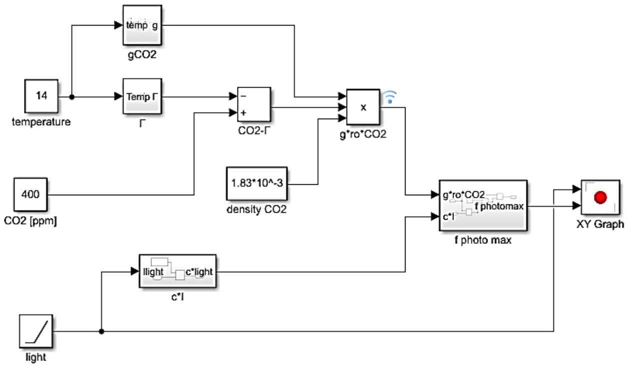

Figure 1 –MATLAB Simulink model for expression (13)

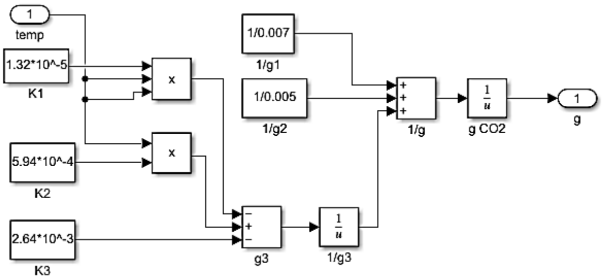

Figure 2 – Simulink subsystem for expressions (11) and (12)

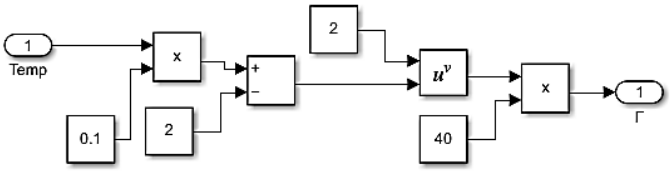

Figure 3 – Simulink subsystem. that implements expression (9)

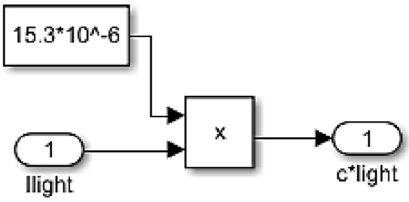

Figure 4 – Simulink subsystem that implements the product of the efficiency of light use and the power of light radiation

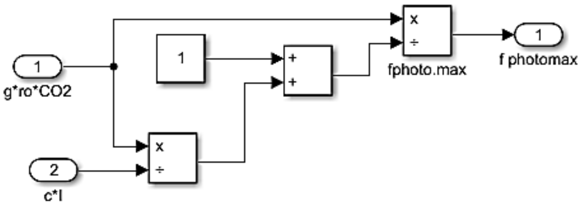

Figure 5 – Simulink subsystem that implements expression (13)

For each case, the value of light intensity at saturation was determined, indicating the impracticality of increasing the intensity as it had little effect on the rate of photosynthesis. The results of the study are presented in Table 1.

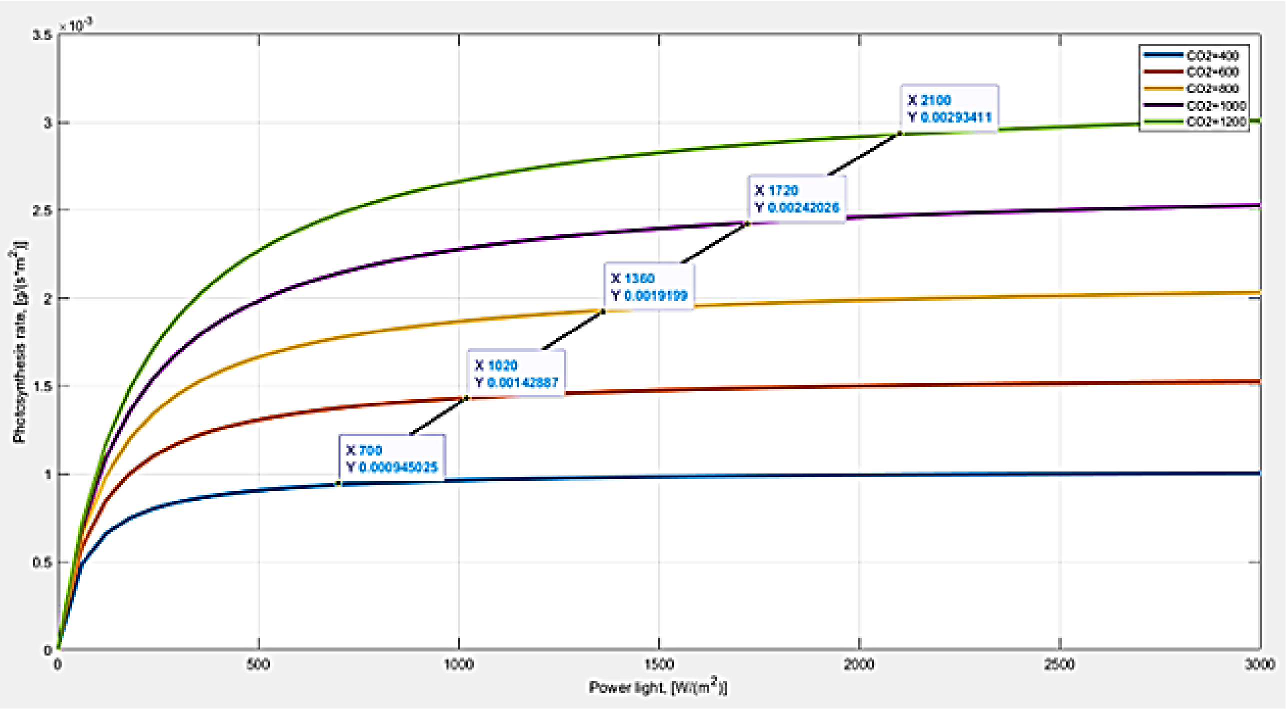

Figure 6 – Graphs of the dependence of the rate of photosynthesis on illumination
at a CO_2 concentration of 400, 600, 800, 1000, and 1200 ppm

Table 1 – Results of modeling in MATLAB Simulink

CO_2 concentration, [ppm]	400	600	800	1000	1200
Light intensity, [W / m^2]	700	1000	1400	1700	2100
Ratio, [ppm × × W^{-1} × m^2]	0.57	0.6	0.57	0.59	0.57
Average light intensity, [W / m^2]	700	1020	1360	1720	2100
Relative error of the average, %	0.0	2.0	2.9	1.2	0.0

From Table 1, the ratio of carbon dioxide concentration to the light intensity that participates in photosynthesis ranges from 0.57 to 0.6 [ppm × W^{-1} × m^2]. An averaging line was plotted on the graphs of Fig. 6, corresponding to the plant photosynthesis rate’s saturation.

From Fig. 6, it was determined that increasing the illumination intensity above the saturation point can change the photosynthesis rate by no more than 5 %. Therefore, the light intensity per unit area of the greenhouse can be regulated according to the concentration of CO_2, considering a coefficient of 0.57.

5 Conclusions

The simplified mathematical model and simulation in the MATLAB Simulink environment made it possible to establish the relationship between the concentration of carbon dioxide [ppm] and the lighting intensity in the greenhouse plant [W / m^2], at which photosynthesis occurs at a maximum specific rate. A coefficient of 0.57 was determined for lettuce. The optimal specific photosynthesis rate for lettuce corresponds to a CO_2 concentration of 950 ppm at a specific lighting intensity of 542 [W × m^{-2}]. The obtained relationship can be adjusted for other greenhouse crops and yield requirements, considering lighting costs. For lettuce, it can be increased to save energy. The proposed methodology can be used to investigate other relationships between microclimate parameters in the greenhouse, based on the energy balance equation or water vapor balance. The results will be used to develop and investigate a resource-saving microclimate control system in the greenhouse by controlling the supply of carbon dioxide depending on the leaf area of the plant and maintaining the optimum between lighting and CO_2 concentration parameters.

References

1. Kläring, H. P., Becker, C., Wünsche, J. N., Lenz, R., & Dietrich, P. (2007). Model-based control of CO2 concentration in greenhouses at ambient levels increases cucumber yield. Agricultural and Forest Meteorology, 143(3-4), 208-216. doi: 10.1016/j.agrformet.2006.12.002
2. Singh, H., Poudel, M. R., Dunn, B., Fontanier, C., & Kakani, G. (2020). Greenhouse carbon dioxide supplementation with irrigation and fertilization management of geranium and fountain grass. HortScience, 55(11), 1772-1780. doi: 10.21273/HORTSCI15327-20
3. Idso, S. B., & Idso, K. E. (2001). Effects of atmospheric CO2 enrichment on plant constituents related to animal and human health. Environmental and Experimental Botany, 45(2), 179-199. doi: 10.1016/S0098-8472(00)00091-5
4. Streck, N. A. (2005). Climate change and agroecosystems: The effect of elevated atmospheric CO2 and temperature on crop growth, development, and yield. Ciência Rural, 35(3), 730-740. doi: 10.1590/S0103-84782005000300041
5. Taub, D. R. (2010). Effects of rising atmospheric concentrations of carbon dioxide on plants. Nature Education Knowledge, 3(10), 21.
6. Kumari, M., Verma, S. K., Bhardwaj, S., Thakur, A., Gupta, R., & Sharma, R. (2016). Effect of elevated CO2 and temperature on growth parameters of pea (Pisum sativum L.) crop. Journal of Applied and Natural Science, 8(4), 1941-1946. doi: 10.31018/jans.v8i4.1067
7. Ullah, I., Fayaz, M., Aman, M., Qadir, J., Ali, S., & Ahmad, S. (2022). An optimization scheme for IoT-based smart greenhouse climate control with efficient energy consumption. Computing, 104(1), 433-457. doi: 10.1007/s00607-021-00963-5
8. Su, Y., Xu, L., & Goodman, E. D. (2017). Nearly dynamic programming NN-approximation-based optimal control for greenhouse climate: A simulation study. Optimal Control Applications and Methods, 39(2), 638–662. doi: 10.1002/oca.2370
9. Van Henten, E. J. (2003). Sensitivity analysis of an optimal control problem in greenhouse climate management. Biosystems Engineering, 85(3), 355-364. doi: 10.1016/S1537-5110(03)00068-0
10. Stanghellini, C. (2014). Horticultural production in greenhouses: Efficient use of water. Acta Horticulturae, 1034, 25-32. doi: 10.17660/ActaHortic.2014.1034.1
11. Van Beveren, P. J. M., Bontsema, J., Van Straten, G., & Van Henten, E. J. (2015). Minimal heating and cooling in a modern rose greenhouse. Applied Energy, 137, 97–109. https://doi.org/10.1016/j.apenergy.2014.09.083
12. Caponetto, R., Fortuna, L., Nunnari, G., Occhipinti, L., & Xibilia, M. G. (2001). Soft computing for greenhouse climate control. IEEE Transactions on Fuzzy Systems, 9(4), 713-720. https://doi.org/10.1109/91.890333
13. Ben Ali, R., Aridhi, E., & Mami, A. (2015). Dynamic model of an agricultural greenhouse using Matlab-Simulink environment. In 2015 12th International Multi-Conference on Systems, Signals & Devices (SSD) (pp. 346-350). https://doi.org/10.1109/STA.2015.7505185
14. Katırcıoğlu, F. (2019). Control and monitoring of greenhouse system with Matlab GUI. International Journal of Scientific and Technological Research, 5(3), 95-100.
15. Atia, D., & Tolba, H. (2017). Analysis and design of greenhouse temperature control using adaptive neuro-fuzzy inference system. International Journal of Advanced Research in Computer Science and Software Engineering, 7(4), 34-48.
16. Taki, M., Ajabshirchi, Y., Ranjbar, F., Rohani, A., & Matloobi, M. (2016). Modeling and experimental validation of heat transfer and energy consumption in an innovative greenhouse structure. Information Processing in Agriculture, 3(1), 20-32. https://doi.org/10.1016/j.inpa.2016.06.002
17. USC. (n.d.). How do increased carbon dioxide levels affect plant growth? https://csef.usc.edu/history/projects/J2321/
18. O’Carrigan, A., Hinde, E., Lu, N., Xu, X.-Q., Duan, H., Huang, G., Mak, M., Bellotti, W., & Chen, Z.-H. (2014). Effects of light irradiance on stomatal regulation and growth of tomato. Environmental and Experimental Botany, 98, 65-73. https://doi.org/10.1016/j.envexpbot.2013.10.007
19. Effat, M. B., Shafey, H. M., & Nassib, A. M. (2015). Solar greenhouses can be promising candidate for CO2 capture and utilization: Mathematical modeling. International Journal of Energy and Environmental Engineering, 6(3), 295-308. https://doi.org/10.1007/s40095-015-0175-z
20. Van Henten, E. J. (1994). Validation of a dynamic lettuce growth model for greenhouse climate control. Agricultural Systems, 45(1), 55–72. https://doi.org/10.1016/S0308-521X(94)90280-1
21. López-Cruz, I., Fitz-Rodríguez, E., Raquel, S., Rojano-Aguilar, A., & Kacira, M. (2018). Development and analysis of dynamical mathematical models of greenhouse climate: A review. European Journal of Horticultural Science, 83, 269-279. https://doi.org/10.17660/eJHS.2018/83.5.1
22. Katzin, D., van Henten, E. J., et al. (2022). Process-based greenhouse climate models: Genealogy, current status, and future directions. Agricultural Systems, 198, 104124. https://doi.org/10.1016/j.agsy.2022.104124
23. Rezvani, S. M.-E.-D., Jafari, A., Ghoosheh, E. Z., et al. (2021). Greenhouse crop simulation models and microclimate control systems, a review. In Next-Generation Greenhouses for Food Security. IntechOpen. https://doi.org/10.5772/intechopen.97361
24. Blank, D. (2015). Global warming and global change: Facts and myths. International Journal of Earth Science and Geophysics, 1(4), 1-4. https://doi.org/10.15436/2381-0697.15.004
25. Van Henten, E. J. (1994). Greenhouse climate management: An optimal control approach. Wageningen University and Research.