Spanish Journal of Agricultural Research
21 (1), e0201, 12 pages (2023)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2023211-19392
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

A hydroponic greenhouse fuzzy control system: design, development and optimization using the genetic algorithm

Hamid KHAFAJEH[1], Ahmad BANAKAR[1*], Saeid MINAEI1, and Majid DELAVAR[2]

[1] *Biosystems Engineering Department, Tarbiat Modares University, Tehran, Iran.* [2] *Department of Water Resources Management, Tarbiat Modares University, Tehran, Iran.*

*Correspondence should be addressed to Ahmad Banakar: ah.banakar@modares.ac.ir

Abstract

Aim of study: The design and development of a hydroponic greenhouse fuzzy control system.

Area of study: The evaluation was performed using experimental data obtained from the literature. The construction and evaluation of the fuzzy control hydroponic greenhouse system was carried out in a greenhouse in Tehran, Iran.

Material and methods: The greenhouse environmental conditions, including temperature, humidity, and carbon dioxide, were controlled. The design of a fuzzy controller begun with the selection of linguistic variables, process status, and input and output variables. The fuzzy control system consisted of three modules: 1) fuzzy module, 2) cost function, and 3) genetic algorithm for the adjustment of the greenhouse environmental conditions.The next step was to select a set of linguistic rules and the type of fuzzy inference process. The rules were set once, and the fuzzy set and output value needed to be specified after the inference, along with the development of a non-fuzzy strategy.

Main results: The mean temperatures provided by the fuzzy control system during the day and night were 34.25°C and 23.22°C, respectively, which were improved to 31.17°C and 21.96°C after optimization. The mean humidity was 39.4% and 56.5% during the day and the night, respectively, which turned 60.22% and 74.59% after optimization. The control system also achieved desirable conditions in terms of CO_2 amount.

Research highlights: The results showed that the measured values of temperature and relative humidity of the greenhouse were improved after optimization with genetic algorithm.

Additional key words: greenhouse climate control; crop yield; greenhouse temperature; relative humidity; CO_2.

Abbreviation used: FLC (fuzzy logic controller); GA (genetic algorithm); MF (membership functions); PI (proportiona integral); PID (proportional integral derivative).

Citation: Khafajeh, H; Banakar, A; Minaei, S; Delavar, M (2023). A hydroponic greenhouse fuzzy control system: design, development and optimization using the genetic algorithm. Spanish Journal of Agricultural Research, Volume 21, Issue 1, e0201. https://doi.org/10.5424/sjar/2023211-19392

Supplementary material (Table S1 and Figs. S1, S2, S3, S4, S5) accompanies the paper on SJAR's website.

Received: 14 Mar 2022. **Accepted:** 23 Feb 2023.

Funding agencies/institutions	Project / Grant
Iranian Fuel Conservation Company	96011475
Tarbiat Modares University	IG/39705 grant for renewable energies of Modares research group.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Statistics show that the current world population will reach 8.5 billion by 2030 and 11.2 billion in 2100. Then, demand for food and water requirement will also grow (Khudoyberdiev et al., 2020). International organizations, societies, institutions, researchers, and individuals should work collaboratively to find practical solutions to develop alternative scenarios to overcome water and food problems. Hydroponic greenhouse is one of the highlighted solutions for the mentioned issue (Tripathi et al., 2015). The greenhouse industry is a developing part of the agricultural sector, and the energy consumption in this industry is expected to increase (Rogge et al., 2008; Pilkington et al., 2010).

According to the US-Energy Information Administration (EIA), global energy demand is expected to increase a 28% by 2040 (Sieminski, 2014). Due to the high costs of energy, several methods have been investigated to reduce the energy consumption in the greenhouses. The optimal control of greenhouse environment is complicated and a costly process because of unstable conditions and continuos changes of the inside and outside variables (Moreton & Rowley, 2012). The main goal when designing the greenhouse control system is to achieve the desired temperature and relative humidity values (Khafajeh et al., 2020). Aaslyng et al. (2003) developed a new greenhouse climate control system to decrease the energy consumption maintaining or even increasing the plant production. In addition, due to existing controllable environmental factors such as temperature and humidity, the potential effectiveness of CO_2 fertilization in the greenhouse requires accurate and reliable detection and then intelligent control of CO_2 concentration. In areas where natural gas is used for the heating system, the exhaust gas from the heating system is added to the greenhouse air. In other cases, strategies have been proposed to maintain CO_2 concentration inside the greenhouse at the same level as outside (Kläring et al., 2007).

In order to achieve the best and most efficient growing environment, it is essential to control the conditions in the greenhouse environment carefully. Considering the experiences and possibilities of managing climatic conditions in modern greenhouses, where the mathematical version of the process is not well known, fuzzy controllers outperform conventional techniques and provide linguistic knowledge on how to control a nonlinear process, such as greenhouses. He & Xue (2012) introduced a control method for the greenhouse environment by combining fuzzy logic and neural networks. Experiments have demonstrated that this control method not only provides fuzzy and uncertain conditions in the greenhouse environment, but also exhibits good stability. Sriraman & Mayorga (2007) used a Mamdani intelligent fuzzy controller to control greenhouse climate factors. The use and design of this smart controller is very easy and flexible. Trabelsi et al. (2007) presented a Takagi-Sugeno (T-S) fuzzy model to solve the dynamic nonlinearity of the greenhouse environmental conditions. They also analyzed the stability of fuzzy control. Márquez-Vera et al. (2016) presented a fuzzy model for indoor temperature using measurements of weather variables in a greenhouse. Ali et al. (2018) designed a fuzzy logic controller (FLC) for greenhouse indoor environment. The simulation results showed the effectiveness of the proposed dynamic model for checking air temperature and relative humidity. Wang & Zhang (2018) used an adaptive fuzzy control method to open the air vents to control the temperature of a tomato greenhouse. The results showed that the fuzzy methods can adequately control the shutters.

Genetic algorithm (GA) is one of the search methods and optimization techniques that aim for the optimal value of a complex objective function based on natural biological evolution such as crossover and mutation. GA is a powerful and universally applicable optimization technique compared to traditional optimization paradigms. It can be used not only for general optimization problems but also in various optimizations and non-conventional optimizations (Banakar & Karimi, 2012). Bruant et al. (2001) and Alscher et al. (2001) presented a fuzzy controller to control the indoor air quality of the greenhouse and easy temperature management. They optimized the number of fuzzy rules using energy consumption function and GA, and reduced energy consumption by 10%. Blasco et al. (2007) optimized water and energy consumption in the greenhouse through a control system and GA. The proposed controller sought to reduce water and energy costs while maintaining a certain range of temperature and humidity. Mohamed & Hameed (2018) introduced an adaptive neuro-fuzzy inference system (ANFIS) to control the greenhouse climate conditions. They used GA to improve the system performance by adapting control parameters such as the number and shape of membership functions (MF) and scale factors.

Most researchers, due to the high cost of greenhouse construction and its long cultivation time, have worked on greenhouse simulation and modeling. Furthermore, the controllers did not address all environmental conditions simultaneously and were limited to temperature or humidity. In fuzzy logic controllers, only temperature and humidity were considered as inputs, and set points were equal for day and night. The purpose of this research was to design and build an intelligent fuzzy control system for a research greenhouse with the ability to measure, control and monitor the environmental conditions of the greenhouse. The control variables inside the greenhouse, including air temperature, relative humidity and the amount of CO_2 in the air, were accurately measured, displayed, and controlled by the operators (heating system, cooling system, irrigation system, CO_2 regulation, ventilation, and humidity regulation). In addition, the rules of day and night were different depending on the needs of the plant during the night, and the number of linguistic variables in the fuzzy model was extracted from cucumber growth models.

Material and methods

Construction and installation of the greenhouse equipment

Greenhouse structure

The research greenhouse used was built in the Faculty of Agriculture of Tarbiat Modares University, Tehran, Iran.

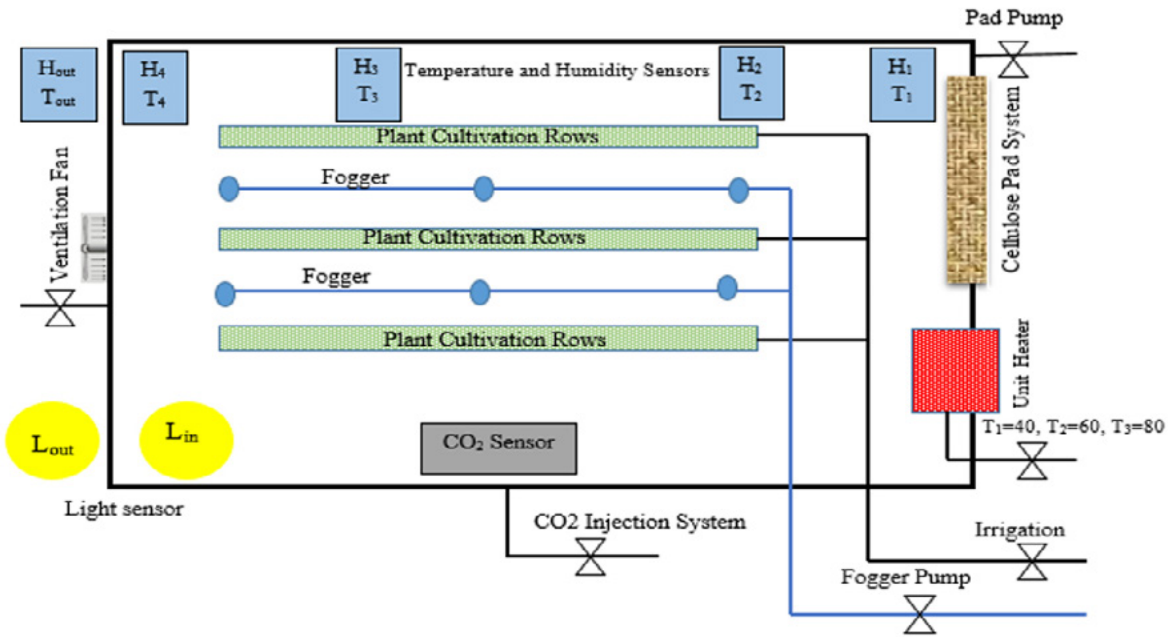

Figure 1. Greenhouse toolbar.

The geographic coordinates of the greenhouse are 51°10' E and 35°44' N at an elevation of 1369 m. The region has a minimum temperature of -12°C, a maximum temperature of 43°C, and the maximum wind velocity is 90 km/h. The specifications and components of the greenhouse are shown in Table S1 [suppl] and Fig. S1 [suppl].

Heating and cooling systems

Fig. 1 shows the toolbars used in the greenhouse. The required equipment was installed according to the calculations made regarding the thermal load calculation, cooling and ventilation. For the research greenhouse, with an area of 40 m^2 (a space with a volume of 100 m^3), the cooling and thermal loads of cucumber were considered. The capacity of the heating system to meet the heating needs of the greenhouse on the coldest night of the year was calculated to be 11.62 kW. The system used to supply the required heat includes a wall gas boiler with an input heating capacity of 26 kW, a thermal efficiency of 91%, a maximum heating circuit water temperature of 80°C, and a hot water unit heater, with a heating capacity of 18.46 to 24.03 kW. The unit heater involved three modes: off, slow (HS), and fast (HF). Gas boiler temperature, which was automatically controlled by a stepper motor, varied between 40°C and 80°C. The input temperature values of the unit heater were T_1=40, T_2=60, and T_3=80.

The cooling system in the research greenhouse under investigation was a cooling pad system. The parameters calculated in the design of the system included: exchanged air volume, that is, air flow intensity in m^3 min^{-1} for each unit of the greenhouse area, available and desirable greenhouse temperature, the locations of the air handlers, and the distances between them and the pads.

Greenhouse ventilation

Ventilation is the process of replacing indoor air with outdoor air and is done for the three main purposes: 1) temperature control, 2) humidity control (reduction), and 3) stabilization and adjustment of the CO_2 required by the plant. Maximum ventilation is required in summer when ventilation should generally be done every minute. In the winter season, the above amount reduces to a maximum of 20-30% of greenhouse air volume per minute. A fan with an *on* and *off* mode was used for the research greenhouse ventilation system.

Humidity supply system

In this research, the purpose of using the greenhouse misting system is cooling and increasing the humidity of the greenhouse. The system consists of two rows of foggers, installed between the cultivated rows. Each row involves three nozzles at 2-m intervals. A PR44 electro pump with a power of 0.5 hp, a pumping speed of 2800 rpm, and a flow rate of 35 L min^{-1}, and a PC-19A automatic water flow pump switch were used to start the pump for water consumption (Arbel et al., 2003).

Carbon dioxide injection system

The amount of available CO_2 in the air is 0.03%, that is about 300 ppm, which is enough for photosynthesis. This value reaches its minimum in winter when the greenhouse is blocked from the outside environment. The optimal range for the amount of carbon dioxide is 500 to 800 ppm. If necessary, the boiler exhaust system directs the heating gas to the greenhouse using a servo motor.

Sensors

The sensors used in the construction of the system include temperature and humidity, a sensor to measure the light inside and outside the greenhouse, and another sensor to measure carbon dioxide (Fig. 1). According to Fig. 1, sensors T_1 to T_4 measure the temperature inside the greenhouse, T_5 outside, H_1 to H_4 measure the humidity inside the greenhouse, and H_5 measures outside. DHT22 sensors were used for temperature and humidity. The DHT22 sensor, also known as the AM2302, is one of the most popular temperature and humidity sensors. Humidity measurement was from 0% to 100%, humidity resolution from 2% to 5%, and humidity response time is 2 sec. Temperature measurement was from -40°C to 125°C, with a resolution of ±0.5°C and a response time of 2 sec.

The K30 sensor (Sense Air, Sweden) was used to measure the amount of CO_2 in the air. The measurement range was from 0 to 10000 ppm, the measurement accuracy was ±30 ppm ±3% of the reading, the operation temperature from 0°C to 50°C, the relative humidity from 5% to 95%, and the analog output was linear from 0 to 5 volts. In the present study, the CO_2 sensor was placed inside a box along with a fan for uniform airflow.

The GY-302 light sensor module was used to measure the light intensity inside and outside the greenhouse. GY-302 light data output, ranged from 0 lx to 65535 lx. The L_{in} and L_{out} sensors were installed inside and outside the greenhouse to measure solar radiation (Fig. S1 [suppl]). The sensor was calibrated and evaluated before use.

Greenhouse climate control center

Inside the greenhouse is a Climate Control Center which contains a control board system, computer (data storage), irrigation timer, voltage stabilizer (to prevent power fluctuations), electrical panel control system, and ups (to store electricity in case of shutdown) (Fig. S2 [suppl]). All sensors data were saved every five seconds in text and Excel files (Fig. S3 [suppl]). A part of the display was dedicated to the light adjustment point to identify day and night. In addition, the coded program had the capability of automatic and manual fuzzy implementation.

The control system board consists of the power supply board, sensor input board, relay board, and main processor board (Fig. S4 [suppl]). First, it was coded in C++ and then simulated and built with Proteus.

Development of the fuzzy control system to control the environmental conditions

Simulation model

To establish a control strategy for each of the control variables, a mathematical model of changes of that variable in relation to other variables should be created (Ursem et al., 2002). So far, many mathematical models for climate greenhouse have been proposed. With the help of these models, it is possible to identify the variables affecting the control factors and simulate or control the greenhouse environment. The general model of greenhouse indoor temperature and humidity equations (1-4), obtained by Lafont & Balmat (2002, 2004), was used for the objective or cost function in the greenhouse.

$$\frac{dT_{ai}}{dt} = (a_1 + a_2 O_v)(T_{ao} - T_{ai}) + a_3 C_h + a_4 R_g - \alpha_5 \quad (1)$$

$$X_{ai} = H_{ai} X_{sat} \quad (2)$$

where T_{ai}: indoor air temperature (ºC); T_{ao}: outdoor air temperature (ºC); T_v: ceiling angle degree (ºC); C_h: thermal power system (kW); R_g: global radiation (kW m^{-2}); X_{ai}: absolute humidity inside the greenhouse (g kg^{-1}); T_{ao}: absolute humidity outside the greenhouse (g kg^{-1}); a_i: model parameters for temperature; b_i: model parameters for temperature; α_5 ,β_5: unmeasured disturbances; ΔX_{ai}: lack of humidity (g kg^{-1}); X_{sat}: saturated humidity (g kg^{-1}); H_{ai}: relative humidity inside the greenhouse (g kg^{-1}); H_{ao}: relative humidity outside the greenhouse (g kg^{-1}).

To validate the model, the control system was placed in the classical control mode and perturbation conditions were considered.

Fuzzy control system

The greenhouse environmental conditions, including temperature, humidity, and CO_2 were controlled. The design of a fuzzy controller starts with the selection of linguistic variables, process state, and input and output variables. The next step is to choose a set of linguistic rules and the type of fuzzy inference process. The rules are set once, and the fuzzy set and output value must be specified after the inference, along with the development of a non-fuzzy strategy (Fig. S5 [suppl]).

Some of the most important topics in fuzzy control are the choice of rules, the fuzzy inference method, membership functions, number of input and output fuzzy sets and their degree of overlapping, implication, connection operations, and defuzzification method (Hellendoorn & Thomas, 1993; Banakar & Azeem, 2011). Fuzzification is the process of transforming a crisp input value into a fuzzy value that uses the information in the knowledge base. Various types of functions such as Gaussian, triangular, and trapezoidal MFs are the most commonly used in the fuzzification process. These types of MFs can easily implemented by embedded controllers. In order to fine-tune the performance of a FLC, these parameters, or the shape of the MFs, can be adapted (Kayacan & Khanesar, 2016). In this study, triangular membership functions were defined for input variables and output variables.

Table 1. Specifications of the genetic algorithm (GA)

Parameter	Value
Population size	100
Crossover rate	0.8
Crossover type	One and multipoint
Number of generations	20
Mutation rate	0.2
Selection	Roulette wheel

In the first step of the fuzzy control design with hydroponic cucumber culture, the information related to temperature, i.e. desired, maximum, and minimum temperatures, was extracted using the plant growth chart (Janoudi et al., 1993). The defuzzification method is the classical center of gravity method with the Mamdani fuzzy inference system.

Cucumber temperature and humidity during the day: The optimal temperature for cucumber growth during the day was 25°C. According to the growth rate curves, the fuzzy ranges of plant temperature during the day were defined as follows: very low (<15°C, temperature very cold, TVCOLD), low (15-20°C, temperature cold, TCOLD), rather low (20-24°C, temperature cool, TCOOL), desirable (24-26°C, temperature good, TGOOD), rather high (26-30°C, temperature slightly hot, TSH), high (30-35°C, temperature hot, TH), and very high (> 35°C, temperature very hot, TVH).

Temperature required by the cucumber during the night: The optimal temperature during the nighy was 20°C. According to the growth rate curves, the fuzzy ranges of plant temperature during the night were defined as follows: very low (< 10°C, TVCOLD), low (10-15°C, TCOLD), rather low (15-19°C, TCOOL), desirable (19-21°C, TGOOD), rather high (21-25°C, TSH), high (25-30°C, TH), and very high (> 30°C, TVH).

Humidity required by the cucumber: The best humidity was 75% and its range included as follow: very low (< 60%, humidity very low, HVL), low (60%-70%, humidity low, HL), desirable (70%-80%, humidity good, HGOOD), high (80%-90%, humidity high, HH), and very high (> 90%, humidity very high, HVH).

Carbon dioxide required by the cucumber: The optimum CO_2 value was between 400 to 1000 ppm and its ranges were defined as: low (< 350 ppm, CL), desirable (350-1000 ppm, CGOOD), high (> 1000 ppm, CH).

A fuzzy rule consists of two parts: the antecedent and the consequence. System inputs are environmental conditions that enter the fuzzy rule base after fuzzification. The *if* part of a rule describes the conditions for which it is defined, and the *then* part describes the response provided by the fuzzy system in those conditions. Considering the number of inputs, the number of membership functions, and the constraints associated with the greenhouse, the fuzzy basis contains 210 rules for day and night. Since the temperatures required by the plant during the day and night were different, the fuzzy control rules were varied. The obtained rules in this research were obtained given in the cucumber growth chart. An example of the fuzzy control rule appears below:

Example: If (Temperature is TVH) and (Humidity is HVH) and (CO_2 is CL) then (FAN is ON) (PAD is ON) (HEATER is OFF) (PACKGE is T3) (FOGSYSTEM is OFF) (CO_2INJECTION is ON).

Optimization of the fuzzy system using the genetic algorithm

GA maintains a set of candidate solutions called population and iteratively refines them by reproduction, crossover, and mutation operators (Lammari et al., 2020). In each generation, the list of responses are evaluated by the objective function and the best result are reported. Linguistic parameters of input temperature and humidity were generated and entered into the new fuzzy system and determined its output values. The time required to reach the points set by Eqs. (1) to (4) was calculated as an objective or fitness function. The process continued until the desired population size or minimum temperature or humidity error was reached. Finally, the best parameters of the membership function were introduced by the GA, which showed the lowest error of the control parameter regarding the desired values. The GA appears in Table 1.

Active hydroponic culture of the greenhouse cucumber

Cucumber (*Cucumis sativus* L.) is one of the most significant greenhouse crops in Iran. The development of new methods such as soilless culture to increase its quality can play an important role in the productivity of greenhouses involved in its production. The hybrid greenhouse cucumber seed variety Gavrish Karim F1, which was used in this research, is suitable for soil cultivation and hydroponics. Coco peat and perlite were used for hydroponic cultivation of cucumber pots (60:40% of coco peat:perlite, v:v), where 36 pots were placed in three rows. The rows were one me-

Table 2. Comparison of control system performance specifications

	Setting time (min)	Delay time (min)	Rise time (min)
Fuzzy logic controller	72	34	47
GA-fuzzy logic controller	64	26	38

GA: genetic algorithm

ter apart, and the adjacent pots on the same row were half a meter away. Nutrient solution drip systems were used in hydroponics for growing, where the nutrient was held in a separate tank, and applied as pre-programed by the control system.

Results and discussion

In this research, a fuzzy control system was designed and developed to control the environmental conditions in the greenhouse. The system was set up in the greenhouse and evaluated during the cucumber growth period. Data collection for the fuzzy control system started on 31 May 2019. After that, the optimized controller resumed on 22 June 2019. The environmental conditions of the greenhouse were controlled by the fuzzy control system for 125 days, and the required information on temperature, humidity, CO_2, and light was recorded, separately every day. Its performance in the fuzzy control system and optimal graphs of temperature, humidity, and CO_2 on two days (20 June 2019 for the system before optimization and 23 June 2019 for the system after optimization) are presented. The highest light intensity these days was 20,765 and 20,670 lux, respectively.

Evaluation of greenhouse temperature during the growth period

Fig. 2a shows the changes in temperature inside and outside the greenhouse on 20 June 2019 for the system before optimization. The average temperatures inside and outside the greenhouse were 28.2°C and 35.8°C during the day and 22.2°C and 30°C during the night, respectively. According to the chart, large differences can be seen between the day and the night. To evaluate the heating and cooling system, it is necessary to record the temperature inside and outside the greenhouse. The greater the temperature difference, the greater the heat losses, so the greenhouse consumes more energy. Also, to optimize energy, it is necessary to have the temperature inside and outside the greenhouse.

Fig. 2b shows the changes in temperature inside and outside the greenhouse on 23 June 2019 for the system after optimization. The average temperatures inside and outside the greenhouse were obtained as 25.7°C and 34.2°C during the day, and 20.8°C and 28°C during the night, respectively. Comparison of Figs. 2a and 2b showed that the optimized mode includes the minimum difference between the greenhouse temperature and the desired temperature.

Performance analysis of the fuzzy control system

The performance specifications of a control system are often expressed in terms of the transient response to a step input, because the input can be easily generated, and is sufficient for a significant effect. The transient response of the system to a unit step input depends on the initial conditions. To facilitate comparison of the transient responses of different systems, the standard initial conditions are usually used where the system is initially at rest, and the output and all its derivatives are zero. In that case, the specifications of the response can be easily compared. In practice, the transient response of a control system often undergoes vibration damping before reaching a steady state (Ogata & Yang, 2010).

Figs. 2c & 2d show the performance of the conventional and optimized fuzzy control systems in response to step input. Considering that the optimal temperature of the greenhouse during the day (25°C) was different from the temperature at night (20°C), the step input was considered equal to the temperature difference (5°C). The performance characteristics of control systems in terms of transient response to step input are shown in Table 2. The optimized controller tracked the set point faster than the conventional controller.

The temperature increases during the day due to the sunlight, and the plants can reach their optimal conditions only if the control system works properly. The maximum temperature during the day in the greenhouse is of great importance, because as the temperature increases, evaporation and transpiration in the plant increases, and the plant undergoes thermal stress, which affects the plant's performance. As seen in Fig. 3a, the recorded average temperature of the greenhouse in the fuzzy control system was higher in the pre-optimization period than in the post-optimization period. The results showed that the average temperature of the greenhouse during the days of cucumber cultivation was 34.25°C in the conventional fuzzy control system and 31.17°C in the optimized system.

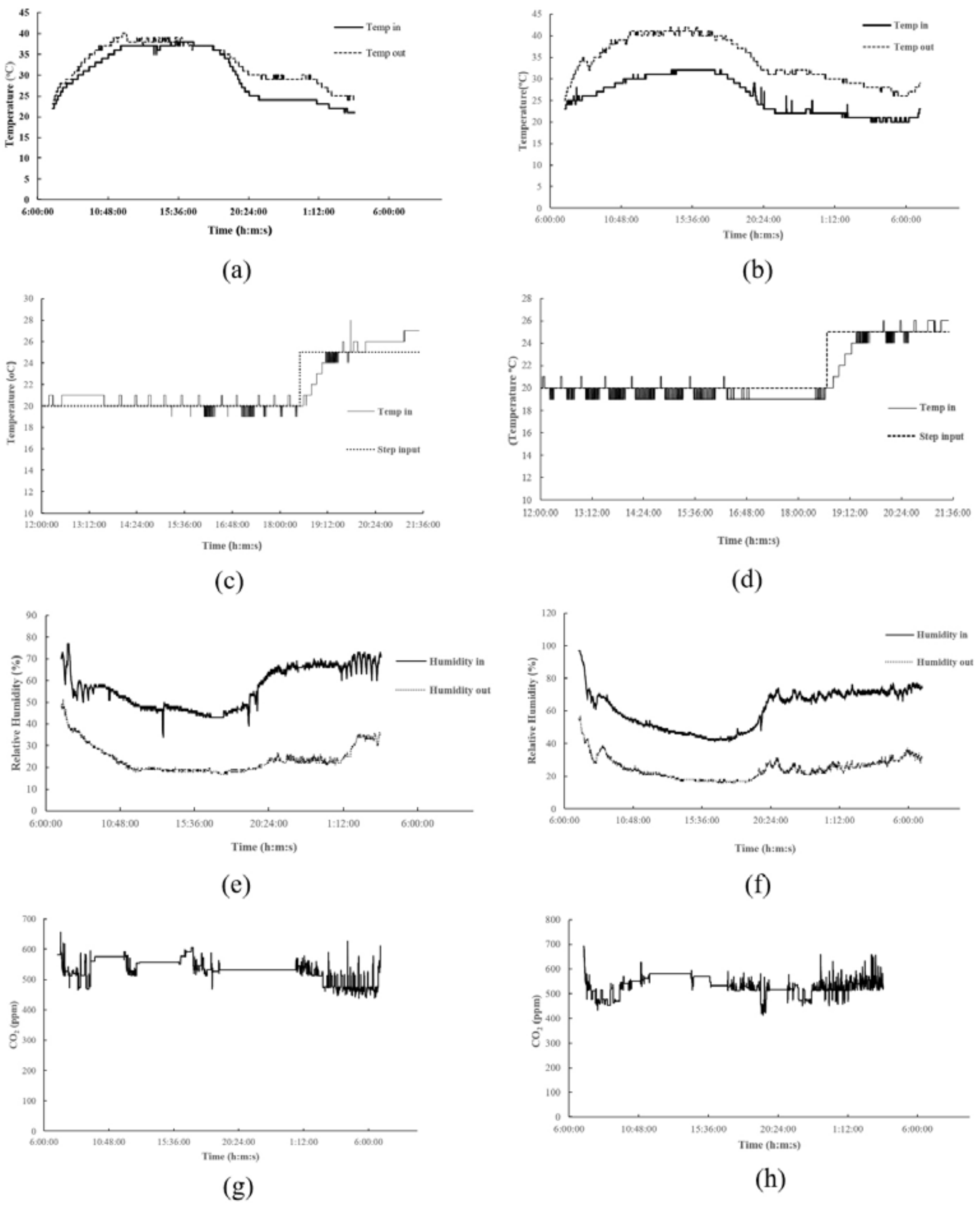

Figure 2. Actual control results of fuzzy logic controller: (a) temperature without optimization, 20 June 2019; (b) temperature with optimization, 23 June 2019 ; (c) response to step input without optimization; (d) response to step input with optimization; (e) relative humidity without optimization, 20 June 2019; (f) relative humidity with optimization, 23 June 2019; (g) CO_2 without optimization, 20 June 2019; (h) CO_2 with optimization, 23 June 2019.

As the air outside the greenhouse cools during the night, the temperature inside greenhouse decreases and only if the heating system works properly, the plants can reach their optimal conditions. The minimum temperature during the night in the greenhouse is very important because the plant undergoes cold stress when the temperature decreases, which is very important during the cold nights of the year. Fig. 3b shows the average recorded temperature inside and outside the greenhouse during the nights of cucumber cultivation. The results showed that the average temperature of the greenhouse during the night was 23.22°C in the conventional fuzzy control system and 21.96°C in the optimized system.

Evaluation of greenhouse humidity during the growth period

Fig. 2e shows the humidity changes inside and outside the greenhouse on 20 June 2019 for the system before optimization. The coefficients of daily and night changes of

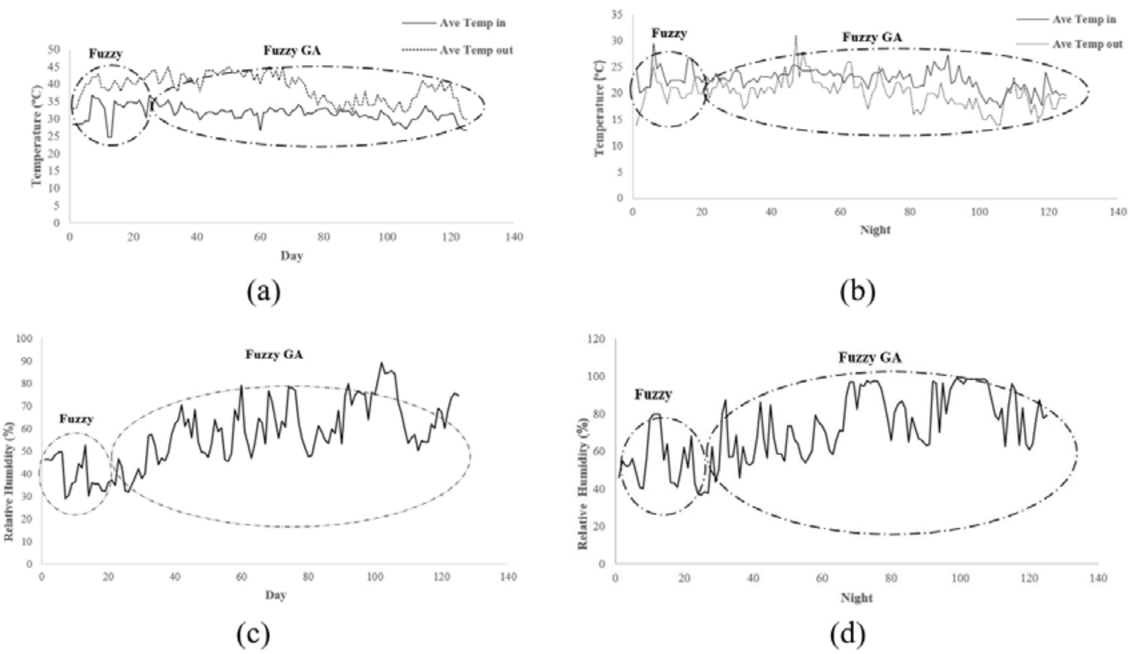

Figure 3. The greenhouse performance during the cultivation period before and after optimization: (a) average temperature inside and outside the greenhouse during day; (b) average temperature inside and outside the greenhouse during night; (c) average relative humidity inside the greenhouse during day; and (d) average temperature inside and outside the greenhouse during night.

humidity variation in that state were obtained as 11.1% and 10.46%, respectively. A big difference in humidity was observed between the inside of the greenhouse and the outside. According to the proposed fuzzy rules, the misting system was turn on when the temperature in the greenhouse was too high, or the humidity was too low. Due to the extremely hot summer weather, the misting system was also turned on to help the fan and pad systems. The average humidity inside the greenhouse during the day and night was 51.35% and 68.57%, respectively, and the average outdoor air humidity was 22.7% during the day and 30.94% at night.

Fig. 2f shows the humidity changes inside and outside the greenhouse on June 23 2019 for the system after optimization. The coefficients of daily and nightly changes of humidity, in that state, were 19.82% and 26.62%, respectively. A big difference in humidity was observed between the inside of the greenhouse and the outside. The average humidity inside the greenhouse during the day and night was 60.18% and 65.7%, respectively, and the average humidity outside was 24.77% during the day and 26.3% at night.

The temperature increases during the day due to sunlight, and the cooling system (including fan and pad) works for the plant to reach the desired conditions. When the fan is on, the humidity is removed from the greenhouse, which is compensated by the fogger. In addition, the control system becomes complex because the control parameters influence each other, in which case prioritization must be applied between them. In the greenhouse, the priority is to regulate the temperature, the humidity is the second, and the amount of carbon dioxide is the last. Fig. 3c shows the average humidity recorded inside the greenhouse during the days of cucumber cultivation. The results showed that the greenhouse humidity recorded in the conventional fuzzy control system was lower than the humidity obtained in the period after the optimization of the system. The average humidity recorded inside the greenhouse in the conventional fuzzy control system was 39.4%, which reached 60.22% in the optimized system with GA. During the night, due to lack of photosynthesis and reduction of evaporation and transpiration in the plant, the humidity of the greenhouse increases. As can be seen in Fig. 3d, the greenhouse humidity recorded in the fuzzy control system in the period before optimization was lower than the greenhouse humidity obtained after. The average humidity recorded inside the greenhouse was 56.5% in the conventional fuzzy control system and 74.59% in the optimized system with GA.

In the research conducted by Faouzi et al. (2017), the simulation results of a fuzzy control system in a greenhouse in a dry region showed that the highest temperature values in spring and summer were in the range of 20°C to 28°C. Robles et al. (2017) designed and implemented a low-cost system for remote monitoring and control of a greenhouse using fuzzy logic. The method included an Arduino board with a fuzzy algorithm for ambient temperature, soil moisture, relative air humidity, and greenhouse light control. The results of the fuzzy system showed that the temperature was between 28°C and 29°C, and the relative humidi-

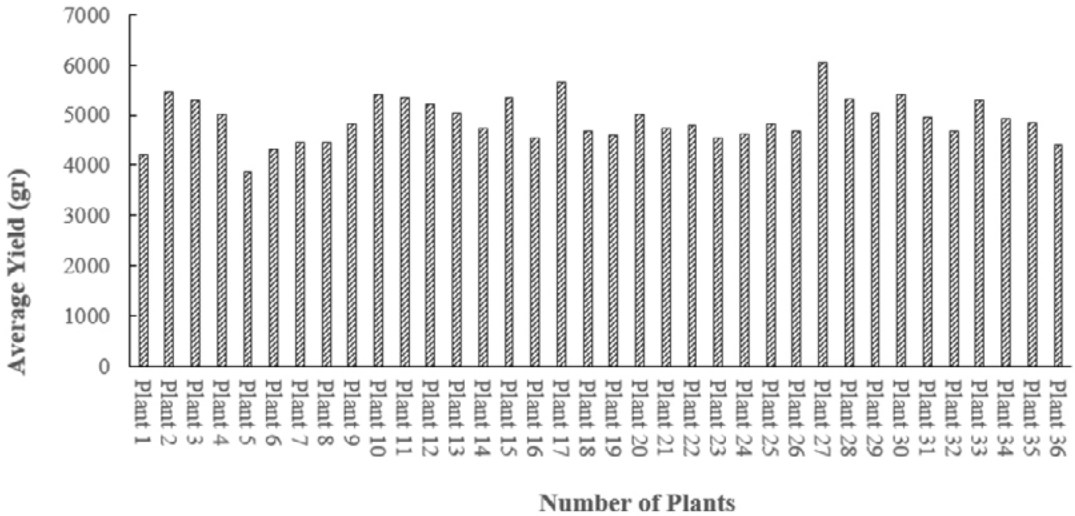

Figure 4. Yield average of cucumber plants in hydroponic cultivation.

ty was 45%. Chen et al. (2011) used the proportional integral derivative (PID) and fuzzy method to control a cherry tomato greenhouse with an optimal temperature of 26.5°C and an optimal humidity of 85%. The average daily temperatures using fuzzy and PID controllers were 27°C and 28.2°C, respectively, and the humidity was 80.2% with the fuzzy controller and 78.5% with the PID controller. Guerbaoui et al. (2013) presented a control system based on fuzzy logic to adjust climate parameters in a greenhouse using LabVIEW software to control temperature and humidity. The control system was evaluated for three days in December. The evaluation results showed that the overall performance of the fuzzy controller was satisfactory for temperature and humidity control within the specified range. The temperature outside the greenhouse varied between 8°C and 18°C. The control system maintained the temperature inside the greenhouse at around 21°C and mean relative humidity between 47% and 55%. Azaza et al. (2014) used a fuzzy control system to control temperature and humidity in a greenhouse in summer using meteorological data. The design was simulated in MATLAB/Simulink. The results of the control system showed that the response time of the system was 40 min while sampling rate was 10 min. The temperature varied between 18°C and 35°C, and humidity between 65% and 75% with fuzzy control. Using fan and pad cooling systems, Ganguly & Ghosh (2007) recorded temperature difference of 6°C between the inside and outside of the greenhouse during peak summer sunlight. Also, they recorded the maximum temperature of 29.5°C inside the greenhouse in summer in an ambient temperature of 35.85°C, a relative humidity of 50%, and a shading level of 75%. Lammari et al. (2020) optimized a proportional integral (PI) controller in greenhouse climate control by GA. They emphasized that the optimized controller had better energy saving parameters. The comparison of the present study with the optimized PI controller, shows that temperature and humidity fluctuations were much lower in the optimized fuzzy system.

Evaluation of carbon dioxide amount inside the greenhouse during the growth period

Fig. 2g shows the CO_2 changes on June 20, 2019 for the system before optimization. The coefficient of variation in the amount of carbon dioxide in that state was equal to 6.2. As can be seen, there were large changes in CO_2 at night, when the carbon dioxide injection system did not work due to the complete absence of photosynthesis. Fig. 2h shows the changes in CO_2 on June 23, 2019 for the system after optimization. The coefficient of variation of CO_2 in that state was equal 2.2. The average amount of carbon dioxide was recorded as 574 ppm. There were lower changes in the amount of CO_2 than in the normal fuzzy control mode.

The optimal amount of CO_2 inside the greenhouse in this research was considered as 500 ppm, which was almost constant by the control system. The value was 510.66 ppm in the conventional fuzzy control system and 514 ppm in the optimized system.

Kläring et al. (2007) investigated the effect of CO_2 on cucumber. The obtained results indicated an increase in CO_2 density to 400 g kg^{-1}, which increased yield. The difference between CO_2 –supply and non-CO_2–supplied greenhouses is in photosynthesis. The efficiency of CO_2 supply was maximum in moderate light and decreased as air temperature outside the greenhouse increased due to the ventilation required in strong light. Chen et al. (2011) investigated greenhouse environmental factors and obtained the average light intensity and CO_2 concentration in the fuzzy controller during the day at 18,900 lux and 617 mg L^{-1}, respectively.

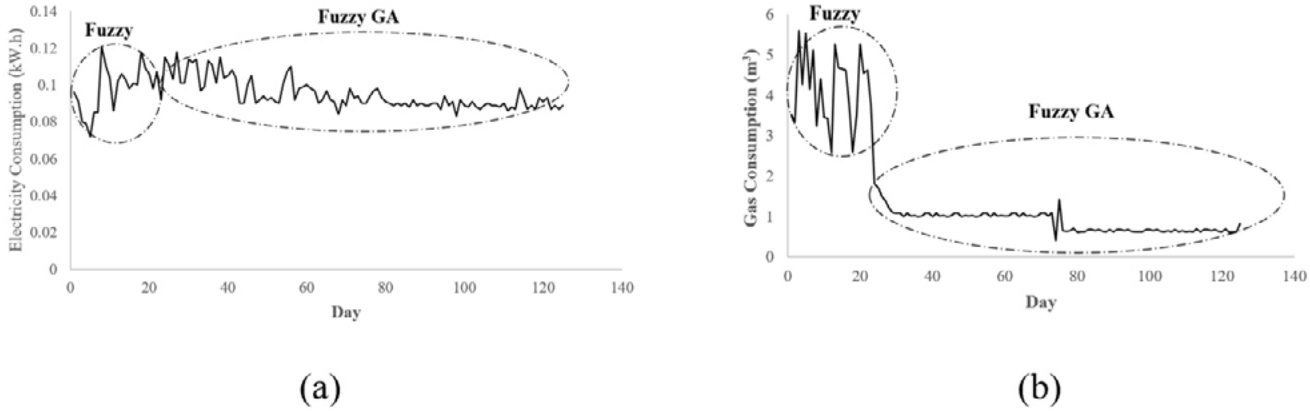

Figure 5. Energy consumption during the period of cucumber hydroponic cultivation: a) electrical energy consumption; b) fuel energy consumption.

Hydroponic cucumber culture yield

One of the most important goals of this research was to obtain the yield of hydroponic cucumber, which was measured weekly during the period. Fig. 4 shows the yield during the harvest period: the mean yield was 5.49 kg pot^{-1} and the yield per unit area was 24.4 kg m^{-2} (i.e. 244,000 kg ha^{-1}). Alomran and & Luki (2012) obtained yields of cucumber in greenhouse of 19.49, 5.18, and 15.07 kg m^{-2} in summer, fall, and winter, respectively. Mao et al. (2003) obtained a maximum yield of 193,999 kg ha^{-1} in greenhouse cucumber.

Energy consumption

Greenhouse producers usually face many problems in the optimal use of energy used in greenhouses, and energy carriers without subsidies have doubled their economic problems. These cases mainly include the use of outdated heating systems with very low efficiency, improper distribution, unbalanced heat production on the greenhouse, and heat energy waste in different ways. In the current research, the amount of energy consumed during the period of hydroponic cucumber cultivation was calculated by daily measurements. Total electrical energy consumption during the period was 11.912 kWh. The average daily energy consumption was 0.098 kWh in the conventional fuzzy control system and 0.094 kWh in the optimized system by GA (Fig. 5a). Mohammadi & Omid (2010) in Iranian greenhouses obtained values of 2438.74 kWh and 1108.63 L ha^{-1} of electricity energy and diesel fuel energy, respectively. In this research, a gas meter was used to measure the gas consumption of the gas boiler used in the heating system. Fuel energy consumption was calculated every day. Since hydroponic cucumber cultivation was done during the hot season of the year, gas consumption was very low. The total fuel energy consumed during the cultivation period was 184.6 m^3 (Fig. 5b).

Conclusion

First step of the current research included the installation of the greenhouse sensor with a fuzzy control system. After setting up the heating and cooling systems, hydroponic cucumber cultivation was done inside the greenhouse. Then the fuzzy control system was evaluated, and the data was used for optimization using genetic algorithm. In addition, the greenhouse was evaluated for a 125-day cultivation period to compare the results obtained by conventional and optimized fuzzy control systems. The results of data analysis showed that the average temperature of the greenhouse during the day using the conventional fuzzy control system was higher compared to the optimized system. Meanwhile, the humidity recorded in the conventional fuzzy control system was lower than the humidity obtained in the period after the optimization of the system. Similarly, changes in carbon dioxide were lower in the conventional fuzzy control mode.

Authors' contributions

Conceptualization: A. Banakar
Data curation: H. Khafajeh
Formal analysis: H. Khafajeh, A. Banakar
Funding acquisition: A. Banakar
Investigation: H. Khafajeh, A. Banakar
Methodology: A. Banakar, H. Khafajeh, S. Minaei, M. Delavar
Project administration: A. Banakar, H. Khafajeh
Resources: A. Banakar
Software: H. Khafajeh, A. Banakar
Supervision: A. Banakar, S. Minaei, M. Delavar
Validation: H. Khafajeh, A. Banakar, M. Delavar
Visualization: H. Khafajeh
Writing – original draft: H. Khafajeh, A. Banakar
Writing – review & editing: H. Khafajeh, A. Banakar, S. Minaei, M. Delavar

References

Aaslyng JM, Lund JB, Ehler N, Rosenqvist E, 2003. IntelliGrow: A greenhouse component-based climate control system. Environ Model Softw 18: 657-666. https://doi.org/10.1016/S1364-8152(03)00052-5

Ali RB, Bouadila S, Mami A, 2018. Development of a Fuzzy Logic Controller applied to an agricultural greenhouse experimentally validated. Appl Therm Eng 141: 798-810. https://doi.org/10.1016/j.applthermaleng.2018.06.014

Alomran AM, Luki II, 2012. Effects of deficit irrigation on yield and water use of grown cucumbers in Saudi Arabia. Trans Ecol Environ 168: 353-358. https://doi.org/10.2495/SI120301

Alscher G, Krug H, Liebig HP, 2001. Optimisation of CO2 and temperature control in greenhouse crops by means of growth models at different abstraction levels III. Simulation and optimisation with the combined model. Gartenbauwissenschaft 66: 213-218.

Arbel A, Barak M, Shklyar A, 2003. Combination of forced ventilation and fogging systems for cooling greenhouses. Biosyst Eng 84: 45-55. https://doi.org/10.1016/S1537-5110(02)00216-7

Azaza M, Echaieb K, Mami A, Iqbal A, 2014. Optimized micro-climate controller of a greenhouse powered by photovoltaic generator. 5th Int Congr on Renewable Energy (IREC). Hammamet, Tunisia. https://doi.org/10.1109/IREC.2014.6826937

Banakar A, Azeem MF, 2011. Parameter identification of TSK neuro-fuzzy models. Fuzzy Sets Syst 179: 62-82. https://doi.org/10.1016/j.fss.2011.05.003

Banakar A, Karimi R, 2012. Genetic algorithm optimizing approach in rosa petals hot air dryer. Int J Agric Food Sci 2: 60-65.

Blasco X, Martínez M, Herrero JM, Ramos C, Sanchis J, 2007. Model-based predictive control of greenhouse climate for reducing energy and water consumption. Comput Electron Agric 55: 49-70. https://doi.org/10.1016/j.compag.2006.12.001

Bruant M, Guarracino G, Michel P, 2001. Design and tuning of a fuzzy controller for indoor air quality and thermal comfort management. Int J Sol Energ 21: 81-109. https://doi.org/10.1080/01425910108914366

Chen F, Tang YN, Shen MY, 2011. Coordination control of greenhouse environmental factors. Int J Autom Comput 8: 147-153. https://doi.org/10.1007/s11633-011-0567-3

Faouzi D, Bibi-Triki N, Draoui B, Abène A, 2017. Greenhouse environmental control using optimized, modeled and simulated fuzzy logic controller technique in MATLAB SIMULINK. I.J. Math Sci Comput 3: 12-27. https://doi.org/10.5815/ijmsc.2017.03.02

Ganguly A, Ghosh S, 2007. Modeling and analysis of a fanpad ventilated floricultural greenhouse. Energ Build 39: 1092-1097. https://doi.org/10.1016/j.enbuild.2006.12.003

Guerbaoui M, Ed-Dahhak A, ElAfou Y, Lachhab A, Belkoura A, Bouchikhi B, 2013. Implementation of direct fuzzy controller in greenhouse based on labview. Int J Electr Electron Eng Stud 1(1): 1-13.

He H, Xue H, 2012. The design of greenhouse environment control system based on variable universe fuzzy control algorithm. In: Computer and Computing Technologies in Agriculture V. CCTA 2011; Li D, Chen Y (eds). IFIP Advances in Information and Communication Technology, vol 368. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-27281-3_10

Hellendoorn H, Thomas C, 1993. Defuzzification in fuzzy controllers. J Intell Fuzzy Syst 1: 109-123. https://doi.org/10.3233/IFS-1993-1202

Janoudi AK, Widders IE, Flore JA, 1993. Water deficits and environmental factors affect photosynthesis in leaves of cucumber (*Cucumis sativus*). J Am Soc Hortic Sci 118: 366-370. https://doi.org/10.21273/JASHS.118.3.366

Kayacan E, Khanesar MA, 2016. Chapter 2: Fundamentals of type-1 fuzzy logic theory. fuzzy neural netw. Real Time Control. Amsterdam: Elsevier, 13-24. https://doi.org/10.1016/B978-0-12-802687-8.00002-5

Khafajeh H, Banakar A, Minaei S, Delavar M, 2020. Evaluation of AquaCrop model of cucumber under greenhouse cultivation. J Agric Sci 158: 845-854. https://doi.org/10.1017/S0021859621000472

Khudoyberdiev A, Ahmad S, Ullah I, Kim D, 2020. An optimization scheme based on fuzzy logic control for efficient energy consumption in hydroponics environment. Energies 13(2): 1-27. https://doi.org/10.3390/en13020289

Kläring HP, Hauschild C, Heißner A, Bar-Yosef B, 2007. Model-based control of CO2 concentration in greenhouses at ambient levels increases cucumber yield. Agric For Meteorol 143: 208-216. https://doi.org/10.1016/j.agrformet.2006.12.002

Lafont F, Balmat JF, 2002. Optimized fuzzy control of a greenhouse. Fuzzy Sets Syst 128: 47-59. https://doi.org/10.1016/S0165-0114(01)00182-8

Lafont F, Balmat JF, 2004. Fuzzy logic to the identification and the command of the multidimensional systems. Int J Comput Cogn 2: 21-47.

Lammari K, Bounaama F, Ouradj B, Draoui B, 2020. Constrained Ga Pi sliding mode control of indoor climate coupled Mimo Greenhouse model. J Therm Eng 6: 313-326. https://doi.org/10.18186/thermal.711554

Mao X, Liu M, Wang X, Liu C, Hou Z, Shi J, 2003. Effects of deficit irrigation on yield and water use of greenhouse grown cucumber in the North China Plain. Agric Water Manag 61: 219-228. https://doi.org/10.1016/S0378-3774(03)00022-2

Márquez-Vera MA, Ramos-Fernández JC, Cerecero-Natale LF, Lafont F, Balmat JF, Esparza-Villanueva JI, 2016. Temperature control in a MISO greenhouse by inverting its fuzzy model. Comput Electron Agric 124: 168-174. https://doi.org/10.1016/j.compag.2016.04.005

Mohamed S, Hameed IA, 2018. A GA-based adaptive neuro-fuzzy controller for greenhouse climate control system. Alexandria Eng J 57: 773-779. https://doi.org/10.1016/j.aej.2014.04.009

Mohammadi A, Omid M, 2010. Economical analysis and relation between energy inputs and yield of greenhouse cucumber production in Iran. Appl Energ 87: 191-196. https://doi.org/10.1016/j.apenergy.2009.07.021

Moreton OR, Rowley PN, 2012. The feasibility of biomass CHP as an energy and CO2 source for commercial glasshouses. Appl Energ 96: 339-346. https://doi.org/10.1016/j.apenergy.2012.02.023

Ogata K, Yang Y, 2010. Modern control engineering. Pearson Upper Saddle River, NJ, USA.

Pilkington LJ, Messelink G, van Lenteren JC, Le Mottee K, 2010. Protected biological control-Biological pest management in the greenhouse industry. Biol Control 52: 216-220. https://doi.org/10.1016/j.biocontrol.2009.05.022

Robles C, Callejas J, Polo Llanos A, 2017. Low-cost fuzzy logic control for greenhouse environments with web monitoring. Electronics 6(4): 71. https://doi.org/10.3390/electronics6040071

Rogge E, Nevens F, Gulinck H, 2008. Reducing the visual impact of ‘greenhouse parks’ in rural landscapes. Landsc Urban Plan 87(1): 76-83. https://doi.org/10.1016/j.landurbplan.2008.04.008

Sieminski A, 2014. International energy outlook. Energy Inf Adm 18.

Sriraman A, Mayorga RV, 2007. Climate control inside a greenhouse: An intelligence system approach using fuzzy logic programming. J Env Inf 10: 68-74. https://doi.org/10.3808/jei.200700101

Trabelsi A, Lafont F, Kamoun M, Enea, G, 2007. Fuzzy identification of a greenhouse. Appl Soft Comput 7: 1092-1101. https://doi.org/10.1016/j.asoc.2006.06.009

Tripathi P, Rabara RC, Shulaev V, Shen QJ, Rushton PJ, 2015. Understanding water-stress responses in soybean using hydroponics system-A systems biology perspective. Front Plant Sci 6: 1145. https://doi.org/10.3389/fpls.2015.01145

Ursem RK, Krink T, Jensen MT, Michalewicz Z, 2002. Analysis and modeling of control tasks in dynamic systems. IEEE Trans Evol Comput 6: 378-389. https://doi.org/10.1109/TEVC.2002.802871

Wang L, Zhang H, 2018. An adaptive fuzzy hierarchical control for maintaining solar greenhouse temperature. Comput Electron Agric 155: 251-256. https://doi.org/10.1016/j.compag.2018.10.023