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An intelligent monitoring of greenhouse using wireless sensor networks

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Abstract. Over recent years, the interest for vegetables and fruits in all seasons and places has much increased, from where diverse countries have directed to the commercial production in greenhouse. In this article, we propose an algorithm based on wireless sensor network technologies that monitor the microclimate inside a greenhouse and linear equations model for optimization plant production and material cost. Moreover, we also suggest a novel design of an intelligent greenhouse. We validate our algorithms with simulations on a benchmark based on experimental data made at lNRA of Montfavet in France. Finally, we calculate the statistical estimators RMSE, TSSE, MAPE, EF and R^2. The results obtained are promising, which shows the efficiency of our proposed system.

Keywords: algorithms; linear equations mode; wireless sensor networks; actuators; intelligent; greenhouse

1. Introduction

According to later economic guesses, the world population is expected to attain 9.8 billion people by 2050 (Kochhar and Kumar 2019). The population growth imposes high demands on fruits and vegetables (Kochhar and Kumar 2019). In addition, there is a problem with delivering fresh fruits and vegetables, particularly in remote regions. From where several countries have directed to agriculture under the greenhouses. A greenhouse is an environment manufactured from transparent material in which plants can be developed rapidly and with good health anyplace and before the developing season. Plant growth under greenhouses in controlled artificial conditions is becoming a preferred research and engineering areas aimed to fulfill the increasing demand for food in the future (Somov *et al*. 2018, Ataei *et al*. 2016). But, the critical question to be posed is how to monitor the internal microclimate of greenhouses?

Tomato is one of the most demanded vegetables in the world (Ota *et al*. 2019). It positioned second after potato with 124.75 million tones production (Ali *et al*. 2017). Tomato is an essential in the human eating routine because it can be used in various forms. It is a rich source of fiber and vitamins A and C. Moreover, consumption of tomato has been related to decreased risk of some cancers, cardiovascular disease, osteoporosis, etc. (Wan *et al*. 2018). The farmer needs to know information about the ideal microclimate (such as optimal temperature, optimal humidity, etc.) in the greenhouse for good tomato production.

Today, greenhouses became interesting research tools on crops to achieve the optimal plant growth process compared to the field tests. Several researchers have recently drawn attention to the non-uniform distribution of temperature, relative humidity, CO_2 concentration and irradiation caused by the microclimate. It is useful to avoid problems that introduce effects on the growth, the yield and the quality of crops (Ma *et al*. 2019a, b, Singh *et al*. 2018).

Currently, the world has become intelligent where everything is often controlled and monitored automatically (Dondapati and Rajulu 2012, da Silva *et al*. 2018). Nevertheless, some sectors that have not yet used automation and intelligence due to the cost of labor (Dondapati and Rajulu 2012).

1.1 Motivation

Technological advancement has let the improvement of greenhouses to become intelligent. The intelligent greenhouse is a greenhouse that uses sensors (temperature, humidity, CO_2 concentration, etc.) to get continuous information. In addition, they can include actuators (the fan, heating, shading, etc..) to alter the internal microclimate of the greenhouse and controllers that operate based on a set of predefined rules (van Beveren *et al*. 2019). The intelligent greenhouse automation management system cannot only lessen work costs, but also improves agriculture product

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(Xu *et al*. 2019, Liu and Bi 2017, Yan-fang *et al*. 2015, Asadollahfardi *et al*. 2018).

In the literature research, we have found a lot of research papers that trait the problem of monitoring the microclimate of the greenhouse automatically. Besides, most of them propose a partial solution.

1.2 Contribution

In this paper, we propose a novel design of a greenhouse to monitor the environmental parameters automatically. In addition, the proposed system contains algorithms that take in charge the control of the microclimatic parameters of the greenhouse and linear equations model for optimization plant production and material cost. When specific parameters like (temperature, humidity, etc.) exceed a fixed value (threshold) an adequate action is launched by the system to regulate the microclimatic of the greenhouse. The objective of this research is to develop, deploy and test the system for producing the healthy food utilizing sensors, actuators and controllers. We will detail the material used for the smart greenhouse and the algorithms used to adjust the microclimate. Also, we will test the algorithms in simulation based experimental data.

The rest of this article is organized as follows. The related works for automation of greenhouses is displayed in the second section. Following, in the third section we suggest a novel design of greenhouse that monitors the internal microclimate automatically. We explain in this section the network architecture of our greenhouse, giving the details, the material used in the design. We also suggest linear equations and the algorithm that monitors the microclimate of the greenhouse. The experimental site where we examined our algorithm, the results of our algorithm and the discussion are presented in the fourth section. The last section is dedicated to the conclusion of our work with some perspectives that we wish to realize in the future.

2. Related works

Divers works and research have been realized in the domain of automatic and intelligent monitoring of the internal climatic parameters of greenhouses. Even so, the majority of these works do not use the words: smart, intelligent and automatic correctly. They monitor the microclimatic parameters manually employing a personnel computer, phone, or internet, etc. In this section, we discuss and compare the related works.

2.1 Works on monitoring the internal microclimate of a greenhouse with using threshold (or set points)

Many existing works are available aimed to monitor automatically/intelligently the internal climatic parameters in greenhouses using threshold (set point). Some of the researches monitor the internal climatic parameters in greenhouses using Internet of Thinks (IoT) and another monitor them without using IoT. In this section, we will divide these works into two sections. The first section for works that use IoT and threshold to monitor the internal climatic parameters. And the second section for works that don't use IoT but they use threshold to monitor the internal climatic parameters.

2.1.1 With using IoT

Several works are done to monitor the internal microclimate of the greenhouse using IoT and threshold. We will mention some of them.

In Park *et al*. (2011), the authors have proposed a system that collects temperature of leaves, humidity on leaves of the crop, indoor air temperature and humidity of indoor air of the greenhouse. The collected data is stored in a database on a server installed in a greenhouse or on a remote server. They made two possibilities to receive information and control the greenhouse either on the site or from a remote site via a web browser using internet. system components are temperature and humidity sensor (SHT71), leaf temperature sensor, leaf humidity sensor, Zigbee based wireless sensor node, relay nodes for automatic control, and data server to store greenhouse information. The system is implemented using low power wireless components and easy to install.

The authors of Sri Jahnavi and Ahamed (2015) presented a design of a wireless sensor network for real-time monitoring of climatic parameters such as temperature, humidity, and soil moisture of a greenhouse. The sensor node treats the captured data. This last starts the actuators according to the algorithm. The algorithm contains instructions that compare the captured data with the given threshold and is programmed into the microcontroller. The gateway gets the sensor information and control data via ZigBee and transmits it to the web application for remote monitoring using Internet.

The author of Ramadhan (2016) designed three prototypes of greenhouses to remote monitor/automatic control the temperature, humidity and soil moisture of greenhouses in real-time. He used sensors (RHT03 and EC-5) to monitor climatic conditions; and the control system that defines the required parameters by activating /deactivating the fan, air exchanger and irrigation devices if these parameters are changed. He also used GSM and Internet technologies to monitor the greenhouse remotely. The system has been tested in different states and the measured data has been found accurate.

The authors of Vatari *et al*. (2016) have designed a system that contains sensors to collect the current situation of the greenhouse, actuators to control changes of parameters. They also proposed an algorithm which determines the current environmental conditions. In this algorithm, they have fixed a threshold according to the requirement of crops. If environmental conditions such as temperature, soil conditions and humidity become below or above the threshold value, then the data will be transmitted to farmers via IoT. This farmer will make the control decision and send the decision to the system. The system will activate the corresponding actuator and control the parameters.

In Woli Ullah *et al*. (2018), the authors have proposed an automatic system that contains a simple algorithm to control a greenhouse, to store each climate data in a database for future analysis and to ensure remote monitoring to those data. The system controls temperature, humidity, light and soil moisture level. They have defined a fixed threshold range for some climatic parameters such as for the temperature the threshold range is between 14 and 27°C, for humidity the threshold range is between 90 and 96%. For remote monitoring and analysis of data, they have used IoT. And to display this data in real time, they are developed an android application. The data is displayed on an LCD screen using Bluetooth technology. The sensors detect the data of the climatic parameters. To control the system, an ATmega328 microcontroller is used. And the heaters/coolers, sprayers, light bulbs and water pumps are used to manage the greenhouse climate as needed. They also used the LDR sensor to determine the state of the day or night. And at the end, all the data is sent to the user by sending an SMS via GSM, to the mobile application by HC05 and to the server using GPRS.

2.1.2 Without using IoT

Many existing works are available aimed to monitor intelligently the internal climatic parameters in greenhouses using threshold (set point) and without using IoT. Some of the researchers that monitor more than three parameters and use less than four different materials (Kolokotsa *et al*. 2010). Another monitor three parameters and use more than four different materials (Enokela and Othoigbe 2015). And another monitor only two parameters and use more than three different materials (Fezari *et al*. 2011, Canadas *et al*. 2017, Ali *et al*. 2018).

Kolokotsa *et al*. (2010) have developed an intelligent system of environmental and energy management for greenhouses with two fuzzy logic controllers integrant the expert knowledge of farmers and experts in the indoor environment and using set points. They have monitored four climatic parameters (such as interior illumination, temperature, relative humidity and CO_2 concentration) of the greenhouse. Also, they have used actuators in their system: heating, motor windows, shade curtains, artificial lighting, CO_2 enrichment bottles and water misting valves. These controllers are prototyped in a MATLAB environment and simulated utilizing a greenhouse model that is realized as a module in the TRNSYS software. Based on the simulation results, fine-tuning of the controllers is performed with trial-and-error. The system is examined in a greenhouse situated at MAICh (Mediterranean Agronomic Institute of Chania).

In Fezari *et al*. (2011) the authors have presented a hardware design and software simulation to control and monitoring greenhouse parameters such as: air temperature and humidity. They have designed and tested a set of intelligent wireless sensors to control and monitoring system. The heart of the smart sensor is a microcontroller that receives data on greenhouse environment conditions from the sensors. The sensor transfers the data to and from a PC. The sensor changes the state of the greenhouse to reach the desired condition. They have developed a graphical interface to monitor the greenhouse remotely. The program implements the control algorithms comparing the received data with set points, sending control signals to the smart sensors in order to reach the desired conditions. The performance of the designed system was tested by installing it in the model greenhouse with a set of smart sensors.

They have proposed an automated greenhouse control system in Enokela and Othoigbe (2015) consisting of two stations: the remote monitoring station and the actuator/sensor station. These two stations consist of light (light resistance), temperature (LM35), humidity (HIH4030) and soil moisture (VH400) sensors; ventilator, fogger, drippers and artificial light; Arduino microcontroller board; and a Personal Computer (PC). The sensor/actuator station is responsible for regulating the environment of the greenhouse. The sensors acquire environmental data, and the Arduino board calculates the current values of the controlled variables and compares them to the defined thresholds. The user sets the limits. If one of the controlled variables is outside the specified threshold, the corresponding actuator is activated to restore the optimal conditions. The Arduino board also reads the states of the actuators and transmits the information as well as the current values of the controlled variables to the remote monitoring station. The Arduino controller is used to ensure that the microclimatic parameters remain within the predefined thresholds. The system was built and tested.

Canadas *et al*. (2017) described a real-time Decision Support System (DSS) for greenhouse tomatoes that supports decisions in three steps: the supervision step identifies the faults of the climate sensors, the control step maintains climate variables at set points and the strategic step identifies diseases affecting the crop and modifies climate variables to minimize damage. The DSS was implemented by integrating a real-time tool based on rules into the control system. The data used in this research were acquired in the greenhouses of the experimental station of the Cajamar Foundation in El Ejido, in the province of Almería, Spain. The climatic parameters inside the greenhouse are permanently monitored. During the experiments, indoor climate variables were recorded; especially air temperature and relative humidity with a ventilated psychrometer, solar radiation with a pyranometer and Photosynthetic Active Radiation (PAR) with a silicon sensor. The integral proportional adaptive controller (PI regulator) manages the temperature and humidity of the air in the morning. The potentiometers indicate the position of the window at any time of control. The temperature and humidity of the night air are controlled by the windows and the heating system. They determined the ventilation and heating set points. Climatic data minute by minute was recorded on a personal computer. Experimental results show that the system increases the effectiveness of climate control, and helps prevent diseases that are difficult to eradicate.

In Ali *et al*. (2018), the authors developed a FLC fuzzy logic controller to promote an appropriate microclimate by activating the suitable actuators installed inside the greenhouse at a proper rate. The dynamic modeling of the studied greenhouse is presented and simulated under the MATLAB/Simulink environment to be validated experimentally in the Center of research and energy

Table 1 Comparison of different used material

	Sensors	Actuators	Microcontroller/ controller	Personal computer/ phone	Other
Kolokotsa *et al.* (2010), Ali *et al.* (2018)	✓	✓	✓	-	-
Park *et al.* (2011), Vatari *et al.* (2016)	✓	✓	-	✓	✓
Fezari *et al.* (2011), Enokeland and Othoigbe (2015), Canadas *et al.* (2017)	✓	✓	✓	✓	-
Sri Jahnavi and Ahamed (2015), Ali (2016), Mohammad *et al.* (2018)	✓	✓	✓	✓	✓

Table 2 Comparison of different monitored microclimatic parameters

	Temperature	Relative humidity	CO_2 concentration	Illumination/ light intensity	Soil moisture	Temperature of leaves	Humidity on leaves
Kolokotsa *et al.* (2010)	✓	✓	✓	✓	-	-	-
Park *et al.* (2011)	✓	✓	-	-	-	✓	✓
Fezari *et al.* (2011), Canadas *et al.* (2017), Ali *et al.* (2018)	✓	✓	-	-	-	-	-
Sri Jahnavi and Ahamed (2015), Enokeland and Othoigbe (2015), Ali (2016), Vatari *et al.* (2016)	✓	✓	-	-	✓	-	-
Mohammad *et al.* (2018)	✓	✓	-	✓	✓	-	-

technology of BorjCedria (CRTEn) in Tunisia in a small greenhouse chapel. The experimental greenhouse is used to plant a tomato crop. They used several K-type thermocouples to measure the temperature of the cover and the sandwich panel inside and outside the greenhouse. The HMP155A sensor is installed to measure the ambient parameters. The second HMP155A sensor is installed to measure internal parameters such as temperature and relative humidity. A Kipp and Zonen pyranometer are used to measure solar irradiation, while an anemometer measures the wind speed above ground. Three PT-107 sensors are used to measure soil temperature. The awning temperature is measured using an IR120 infrared temperature sensor. They also studied the physical characteristics of the greenhouse in three-level: cover, canopy and soil. They used the actuators (heater, fan, humidifier and dehumidifier) to adjust the microclimate of the greenhouse. The results of the simulation illustrate the effectiveness of the proposed dynamic model for studying indoor air temperature and relative humidity with a small percentage of error.

2.2 Synthesis of related works

In this section, we introduce Tables 1 and 2. In these tables, we compare the used material and monitored microclimatic parameters of the discussed works.

In the table below (Table 3), we have done a comparison between works that use the IoT and the threshold and works that don't use the IoT and they use the threshold. This comparison is done on different criteria that they helped us to realize the present work. This table summarizes the advantages of works that don't use IoT compared to the works that use IoT.

Table 3 Comparison between works use IoT and threshold and works don't use IoT and use threshold

	Works use IoT and threshold	*Works don't use IoT and use threshold*
Number of researches and works	High	Low
Used material	Lot	Less
Intervention of farmer	Yes	No
Intelligent /automatic	Automatic	Intelligent

In the literature research, we have found a lot of compared to the researches and works that trait the problem of monitoring the microclimate of the greenhouse without using IoT. Also, compared to the works that don't use IoT, the works that use IoT utilize lots of material like personnel computer, phone, etc.
researchers papers and works that trait the problem of monitoring the microclimate of the greenhouse using IoT

In our work, we will focus on works that don't use IoT technology but they use a defined threshold to monitor the internal microclimate of a greenhouse. Some advantages of our proposed system include:

- Our system will be monitored five microclimate parameters such as temperature, humidity, CO_2 concentration, solar radiation and pH of soil.
- Our system will be purely intelligent: The monitoring of the internal climate parameters of our greenhouse will be without the intervention of farmers.

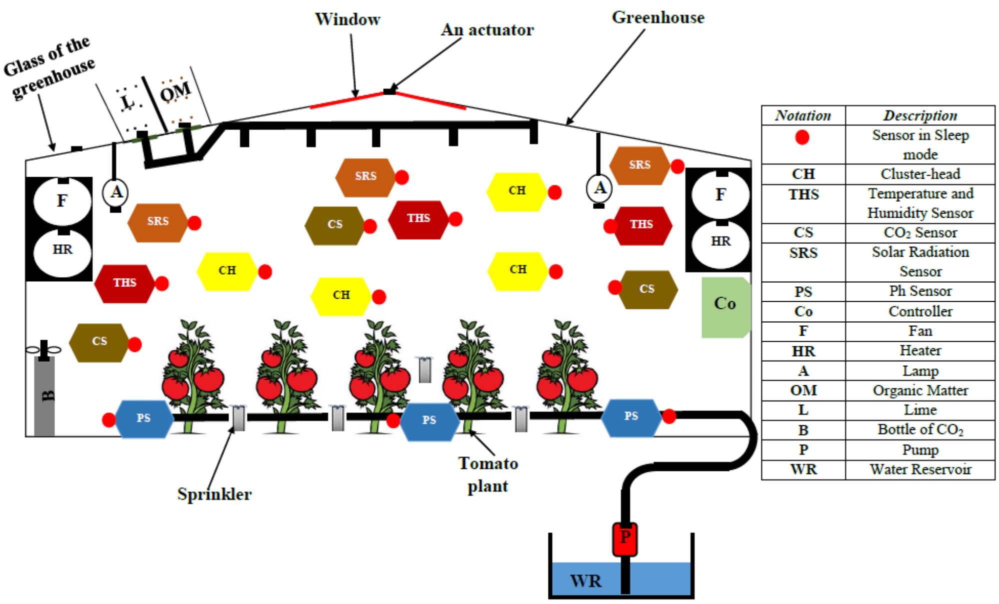


Fig. 1 Proposed design for automatic monitoring of greenhouse

- We will use in our system only:
  - The sensors that capture the data.
  - The actuators that change the climate of the greenhouse.
  - And the microcontroller that sends the orders to the actuators to turn on or off according to the need.
- The communication between the sensors, the actuators and the microcontroller in our system is not done by Internet or by GSM: once the system is installed and configured, the communication is done automatically without any human intervention.

3. Proposed approach

In this section, we expose a proposed design for the intelligent monitoring of the greenhouse. The used material in our model, our proposed algorithms, and the advantages of the proposed algorithm and design will be detailed in the next sections.

3.1 Description of the proposed design

In this subsection, we will detail the proposed design for the automatic monitoring of greenhouses. After a thorough study in the literature that treats the problem of it, we have proposed the design that is visible in Fig. 1.

First of all, our greenhouse is in smart translucent glass. It changes its color from translucent to dark because of an actuator. Moreover, our design includes:

- Twelve sensors (three temperature and humidity sensors, three solar radiation sensors, three CO_2 concentration sensors and three pH sensors) and twelve sensors in sleep mode (in case if the sensor stops working) for each of them.
- Four cluster-head sensors (one for temperature and humidity sensors, one for solar radiation sensors, one for CO_2 concentration sensors and one for pH sensors)
- A microcontroller.
- And twelve actuators at: the window, the fan, the heater, the CO_2 bottle, the tank window of the lime and organic matter, the lamp, the glass of the greenhouse and the water pump that is at the water tank to irrigate the tomato plant by the sprinklers.

Then, we chose to monitor five environmental parameters in our greenhouse. The monitored parameters are the internal air temperature, the relative humidity of the internal air, the internal solar radiation, the concentration of CO_2 in the internal air and the pH of the internal soil of the greenhouse.

3.2 The network architecture of our design

The greenhouse is a multi-input and multi-output (MIMO) system. The network architecture of our design is visible in Fig. 2. In this figure, there are sensors (air temperature and humidity sensor DHT11, the HI 99121 pH meter kit to measure soil Ph, the LDR photoresistance for solar radiation, the WRF04 CO_2 sensor to measure the CO_2 of the air) with sensor in sleep mode for each of them, cluster-head sensors, the ATmega328P microcontroller and actuators in: the fan, the heater, the water pump, the window, the reservoir of lime and organic matter, the CO_2 bottle, the artificial lamp, the glass.

Each set of sensors (temperature and humidity sensors, solar radiation sensors, CO_2 sensors and Ph sensors) forms a cluster using the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol. And, each cluster is built and managed by a Cluster-head (CH). The CH is an intelligent sensor which:

- Combines the data collected by the different sensors.
- Compares the data with the different thresholds.
- Sends only the data above or below thresholds to the

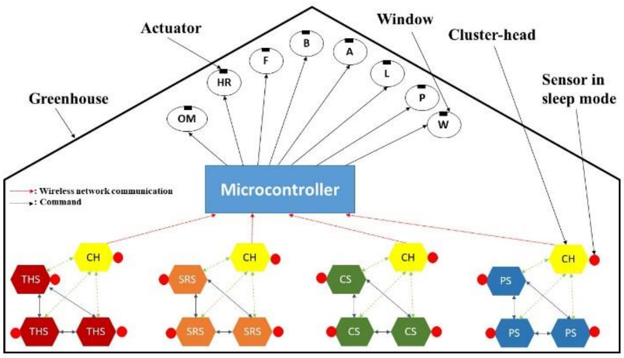


Fig. 2 The network architecture

base station (sink) which is the microcontroller.

The microcontroller obtains the data sent by the different CHs and verifies the status of the various actuators. Thus, we integrated our algorithm into the microcontroller. The objective of our algorithm is to check the parameters measured by the sensors with the different thresholds of these parameters. Then, the microcontroller takes a decision and transmits an order to the actuators depending on the needs. It receives information from cluster-heads and sends commands to actuators.

3.2.1 Protocol description: LEACH

LEACH (Heinzelman *et al*. 2000, 2002) is considered among the best protocols in WSN which are efficient in terms of energy. It is based on adaptive clustering. The most objective of LEACH is to attenuate energy consumption in sensor networks (Maurya and Kaur 2016).

LEACH divides the entire sensor network into clusters. In each cluster, a sensor node must become a cluster-head (CH) and the other nodes are member nodes of this cluster (Mohammad 2018). The communication between the member nodes and the base station is done only via the CH. Therefore, only the CH which might communicate directly with the base station. The CH collects, combines and transmits data from member nodes to the base station. So, the CH consumes more energy compared to the member nodes where it can die quickly. LEACH has solved this problem by dynamically modifying the CH (Mohammad 2018, Salmabadi *et al*. 2015).

The operations of the LEACH protocol contain two phases:

- The setup phase (Mohammad 2018, Salmabadi *et al.* 2015): The clusters are organized and the CH election process is done in each cluster. Each node determines if it will become a CH, during this round, using a stochastic algorithm for every round. If a node becomes a CH for once, it cannot become again a CH for p rounds. If a node is not a CH within the previous 1/p rounds, it produces a number between zero and one. Only nodes whose the generated number is below the threshold T (n) are eligible to become CHs. The rotation of the CH ends up in a balanced energy consumption for all the nodes and so to an extended lifetime of the network.

The formula used to calculate the threshold value is given in Eq. (1).

$$T(n) = \begin{cases} \dfrac{p}{1 - p * \left(r \bmod {}^{1}\!/_{p}\right)} & If\ n \in \mathrm{G} \\ 0 & Otherwise \end{cases} \qquad (1)$$

Where **G:** Group of nodes not selected as CHs in preceding 1/p rounds, **p:** Recommended percentage of CH, **r:** Current round.

- The steady state phase**:** The data is sent to the base station during this phase (Mohammad 2018). Through to the minimization of network overhead, the duration of steady state phase is longer than the duration of setup phase. The data transmission is done through a calendar which is made by the CH (Mohammad 2018, Salmabadi *et al*. 2015).

3.3 Linear equations model

It is necessary to use a dynamic model to have optimal control of the microclimate of a greenhouse. The most goal of optimal control is to have a high yield with a minimal cost of material in the greenhouse. According to the optimal control theory (Kirk 1998) in order to state an optimal control problem it is required to define a dynamic mathematical model of the system, a set of physical constraints, and also a performance measure. In the greenhouse the state variables are air temperature (T_i), humidity (H_i), solar radiation (Rg_i), carbon dioxide concentration (CO_{2i}) and Ph of soil (Ph_i). The crop behavior in inside the greenhouse is influenced by the outside climate and control actions (López-Cruz *et al*. 2014). On one hand, the external inputs are solar radiation (Rg_e), temperature (T_e), wind speed (w), CO_2 concentration (CO_{2e}), and humidity (H_e) outside the greenhouse. On the other hand, the control variables are windows opening (Wo), heating system (Hs), ventilation system (Vs), light system (Ls), organic matter system (Os), CO_2 injection (Ci) or irrigation system (Is). Formalizing the main ideas aforementioned (van Henten 1994, Tap 2000) a dynamic mathematical model (Eq. (2)) of the greenhouse environment as follows.

$$\dot{x} = f(x, u, v, p, t) \qquad (2)$$

Where:

- $x(t) \epsilon R^n$ is the vector of state variables: $x = [T_i \quad H_i \quad Rg_i \quad CO_{2i} \quad Ph_i]^T$
- $u(t) \epsilon R^m$ is the vector of control variables: $u = [Wo \quad Hs \quad Vs \quad Ls \quad Os \quad Ci \quad Is]^T$
- $v(t) \epsilon R^q$ is the vector of external inputs: $v = [T_e \quad H_e \quad Rg_e \quad CO_{2e} \quad w]^T$
- $p \epsilon R^s$ is the vector of model parameters includes physical coefficients associated with the climatic variables and also physiological coefficients that appear in the processes connected to crop growth.

The state variables are the constraints. The constraint for air temperature, air humidity, solar radiation, CO_2 concentration and Ph of soil are detailed in Eqs. (3)-(7) respectively.

$$T_{min}(t) \leq T_i(t) \leq T_{max}(t) \tag{3}$$

$$H_{min}(t) \leq H_i(t) \leq H_{max}(t) \tag{4}$$

$$Rg_{min}(t) \leq Rg_i(t) \leq Rg_{max}(t) \tag{5}$$

$$CO_{2min}(t) \leq CO_{2i}(t) \tag{6}$$

$$Ph_{min}(t) \leq Ph_i(t) \leq Ph_{max}(t) \tag{7}$$

With t = [t_0, …, t_f]

Where t_0 and t_f are the date of planting and the harvest date of crops respectively, T_{min}, H_{min}, Rg_{min}, $CO2_{min}$ and Ph_{min} are the minimum threshold of temperature, humidity, solar radiation CO_2 and Ph of soil respectively and T_{max}, H_{max}, Rg_{max}, $CO2_{max}$ and Ph_{max} are the maximum threshold of temperature, humidity, solar radiation, CO_2 and Ph of soil respectively.

The economic value (Eq. (8)) can be formulated as

$$B(u) = Y\left(x(t_f), t_f\right) - \int_{t_0}^{t_f} C(x, u, v, p, t)dt \tag{8}$$

Where B is the profit realized during the period [t_0, t_f], Y is the gross yield at harvest time (t_f), C is the operating costs of the equipment in the greenhouse.

For a high yield with a minimal cost of material in the greenhouse, we maximize B(u) in Eq. (9).

$$Z_{opt} = \max B(u) \tag{9}$$

According to the Eqs. (3)-(7), we have used the following equations (Eqs. (10)-(18)) to put the actuators in ON state (activate the actuators) or OFF state (deactivate the actuators).

$$F(t) = \begin{Bmatrix} T_i(t) - T_{max}(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{10}$$

$$HR(t) = \begin{Bmatrix} T_{min}(t) - T_i(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{11}$$

$$W(t) = \begin{Bmatrix} H_i(t) - H_{max}(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{12}$$

$$P(t) = \begin{Bmatrix} H_{min}(t) - H_i(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{13}$$

$$G(t) = \begin{Bmatrix} Rg_i(t) - Rg_{max}(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{14}$$

$$A(t) = \begin{Bmatrix} Rg_{min}(t) - Rg_i(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{15}$$

$$B(t) = \begin{Bmatrix} CO_{2min}(t) - CO_{2i}(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{16}$$

$$OM(t) = \begin{Bmatrix} Ph_i(t) - Ph_{max}(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{17}$$

$$L(t) = \begin{Bmatrix} Ph_{min}(t) - Ph_i(t) & ON \\ 0 & OFF \end{Bmatrix} \tag{18}$$

With t = [t_0, …, t_f]

Where F, HR, W, P, G, A, B, OM, and L are the actuators of the fan, the heater, the window, the water pump, the glass, the lamp, the bottle of CO_2, the organic matter and the lime respectively.

Also, the internal and external humidity of the greenhouse is calculated by using Eq. (19).

$$Hi = \frac{Pi}{P(Ti)} \times 100 \tag{19}$$

Where H_i is the internal humidity (%), P_i is the partial pressure of water vapor (hPa), P (T_i) is the water vapor saturation pressure and T_i is the internal temperature (°C).

And the water vapor saturation pressure is calculated by using Eq. (20).

$$P(Ti) = 6.1070((1 + \sqrt{2}\sin(\frac{\pi \times Ti}{540}))^{8.827}) \tag{20}$$

3.4 Description of the proposed algorithm

The proposed algorithms for monitoring the internal climatic parameters intelligently in the greenhouse are presented in this subsection. Our algorithms are based on standard rules with if-then format: If <conditions> then <actions>, where "conditions" represent the comparison between the measured parameter and their threshold, and "actions" represent the associated actions of the correspondent actuator.

3.4.1 The proposed algorithm for monitoring the air temperature in the greenhouse

The algorithm for optimizing the temperature interior of the greenhouse is shown in Algorithm 1. This algorithm

Algorithm 1. The automatic monitoring of the internal air temperature

Input: internal air temperature (T_i), temperature threshold ($T_{threshold}$).
Output: optimal temperature.
01: begin
02: define the value of $T_{threshold}$
03: get T_i capted by the sensor
04: compare T_i with $T_{threshold}$. If ($T_i > T_{threshold}$) then
05: while ($T_i > T_{threshold}$) do
06: send a control message to the actuator of the fan (Fan ← ON) (Eq. (10))
07: end
08: else if ($T_i < T_{threshold}$) then
09: while ($T_i < T_{threshold}$) do
10: send a control message to the actuator of the heater (Heater ← ON) (Eq. (11)
11: end
12: else
13: send a control message to the actuator of the fan and the heater (Fan ← OFF and Heater ← OFF) (Eqs. (10) and (11))
14: end
15: get de new value of T_i
16: go to 04
17: end

Algorithm 2. The automatic monitoring of the internal air humidity

Input: internal air humidity (H_i), humidity threshold ($H_{threshold}$).
Output: optimal humidity
01: begin
02: define the value of $H_{threshold}$.
03: get H_i capted by the sensor
04: compare H_i with $H_{threshold}$. If ($H_i > H_{threshold}$) then
05: while ($H_i > H_{threshold}$) do
06: send a control message to the actuator of the window (Window ← ON) (Eq. (12))
07: end
08: else if ($H_i < H_{threshold}$) then
09: while ($H_i < H_{threshold}$) do
10: send a control message to the actuator of the water pump (Water pump ← ON) (Eq. (13))
11: end
12: else
13: send a control message to the actuator of the window and the water pump (Window ← OFF and Water pump ← OFF) (Eqs. (12) and (13))
14: end
15: get de new value of H_i
16: go to 04
17: end

shows how to adjust the temperature of the greenhouse. First, you have to know the sort of plant developed in a greenhouse to define the most appropriated temperature threshold. Then, the microcontroller checks the current temperature with the temperature threshold. Thus, the microcontroller checks if the greenhouse is too hot or too cold and evaluates the need to activate/deactivate the actuators. If the greenhouse is too hot, the microcontroller sends a command to the actuator of the fan to activate it automatically. On the contrary, if it is too cold, the microcontroller will send a command to the actuator of the heater to activate it automatically. This process is stopped when the temperature in the greenhouse becomes optimal, which means that the current temperature is equal to the threshold temperature. The process starts again when new data from temperature sensors is received and the received temperature values are above or below established thresholds.

3.4.2 The proposed algorithm for monitoring the air temperature in the greenhouse

The procedure for adjusting the humidity of the greenhouse appears in Algorithm 2. Firstly, the microcontroller gets the collected data from the humidity sensor nodes. Depending on the type of plant developed in a greenhouse, a humidity threshold is chosen. Then, the current humidity value is compared with the humidity threshold. So, the microcontroller checks if the greenhouse is too wet or too dry. If the greenhouse is too wet, the microcontroller sends a command to the actuator that opens the window. On the contrary, if it is too dry, the microcontroller sends a command to the actuator of the water pump to spray the plants via the sprinklers. Like the temperature algorithm, this algorithm ends when the humidity values are the desired ones and restarts when new data from humidity sensors are received and that the humidity values received are above or below established thresholds.

3.4.3 The proposed algorithm for monitoring the solar radiation in the greenhouse

The algorithm for monitoring solar radiation in the greenhouse is shown in Algorithm 3. Firstly, the microcontroller received the collected data from the solar radiation sensor. Since in our greenhouse there are tomatoes as a plant, so you have to know the threshold of the internal solar radiation of the greenhouse. Then, the microcontroller checks the value of the current solar radiation with the limit. So, he checks if the greenhouse is very dark or very bright. If the greenhouse is too light, the microcontroller sends a command to the actuator of the glass. As we said before, our greenhouse is in smart transparent glass. So, after sending the microcontroller command to the actuator, the glass becomes black. On the contrary, if the greenhouse is too dark the microcontroller sends an order to the actuator of the artificial lamp to turn it on automatically. As in the previous algorithms, this algorithm ends when the solar radiation values are the desired ones and starts again when new data from solar radiation sensors are received and the received solar radiation values are above or below established thresholds.

3.4.4 The proposed algorithm for monitoring the concentration of CO_2 in the greenhouse

An algorithm to ameliorate the CO_2 concentration in the greenhouse is proposed in Algorithm 4. In this algorithm, we have treated the case where the air of the greenhouse needs CO_2. First of all, you have to know the kind of plant developed in a greenhouse to know the threshold of the concentration of CO_2 in the greenhouse. First, the micro-

Algorithm 3. The automatic monitoring of the internal solar radiation

Input: internal solar radiation (Rg_i), solar radiation threshold ($Rg_{threshold}$)
Output: optimal solar radiation
01: begin
02: define the value of $Rg_{threshold}$
03: get Rg_i capted by the sensor
04: compare Rg_i with $Rg_{threshold}$. If ($Rg_i > Rg_{threshold}$) then
05: while ($Rg_i > Rg_{threshold}$) do
06: send a control message to the actuator of the glass (Glass ← ON) (Eq. (14))
07: end
08: else if ($Rg_i < Rg_{threshold}$) then
09: while ($Rg_i < Rg_{threshold}$) do
10: send a control message to the actuator of the artificial lamp (Lamp ← ON) (Eq. (15))
11: end
12: else
13: send a control message to the actuator of the glass and the artificial lamp (Glass ← OFF and Lamp ← OFF) (Eqs. (14) and (15))
14: end
15: get de new value of Rg_i
16: go to 04
17: end

Algorithm 4. The automatic monitoring of the internal CO_2 concentration

Input: internal CO_2 concentration (CO_{2i}), CO_2 threshold ($CO_{2threshold}$)
Output: optimal CO_2 concentration
01: begin
02: define the value of $CO_{2threshold}$
03: get CO_{2i} capted by the sensor
04: compare CO_{2i} with $CO_{2threshold}$. If ($CO_{2i} < CO_{2threshold}$) then
05: while ($CO_{2i} < CO_{2threshold}$) do
06: send a control message to the actuator of the bottle of CO_2 (Bottle ← ON) (Eq. (16))
07: end
08: end
09: get de new value of CO_{2i}
10: go to 04
11: end

Algorithm 5. The automatic monitoring of the pH of soil

Input: internal pH of soil (pH_i), pH threshold ($pH_{threshold}$)
Output: optimal pH
01: begin
02: define the value of $pH_{threshold}$
03: get pH_i capted by the sensor
04: compare pH_i with $pH_{threshold}$. if ($pH_i > pH_{threshold}$) then
05: while ($pH_i > pH_{threshold}$) do
06: send a control message to the actuator of the thank of organic matter (Organic matter ← ON) (Eq. (17))
07: end.
08: else if ($pH_i < pH_{threshold}$) then
09: while ($pH_i < pH_{threshold}$) do
10: send a control message to the actuator of the tank of lime (Lime ← ON) (Eq. (18))
11: end
12: else
13: send a control message to the actuator of the tank of organic matter and of lime (Organic matter ← OFF and Lime ← OFF) (Eqs. (17) and (18))
14: end
15: get de new value of pH_i
16: go to 04
17: end

controller checks the current CO_2 concentration with the threshold. If the air in the greenhouse needs CO_2, so the current CO_2 concentration is below the threshold, the microcontroller sends a command to the actuator of the bottle of CO_2 to disperse the CO_2 automatically in the greenhouse. As in the previous algorithms, this algorithm ends when the values of the CO_2 concentration are the desired ones and restarts when new data from CO_2 sensors are received and the CO_2 values received are below at established thresholds.

3.4.5 The proposed algorithm for monitoring the pH of the soil in the greenhouse

Finally, Algorithm 5 shows the steps to adjust the soil pH of the greenhouse. Firstly, the data of the pH sensors are collected and transmitted from the sensor nodes to the microcontroller. The microcontroller chooses the threshold value depends on the kind of plant in the greenhouse. Then, the microcontroller checks the current pH with the threshold of pH. Thus, he can decide if the soil is very rich or poor in organic matter. If the soil is very rich, then the value of pH must be decreased. So, the microcontroller sends a command to the actuator responsible for the tank of organic material to open the container. If the opposite situation is detected and the soil is poor, then the value of pH must be increased by opening the limestone tank with the responsible actuator for this tank. The algorithm stops as in the previous cases when the data of pH is between the thresholds and begins when it is not the case.

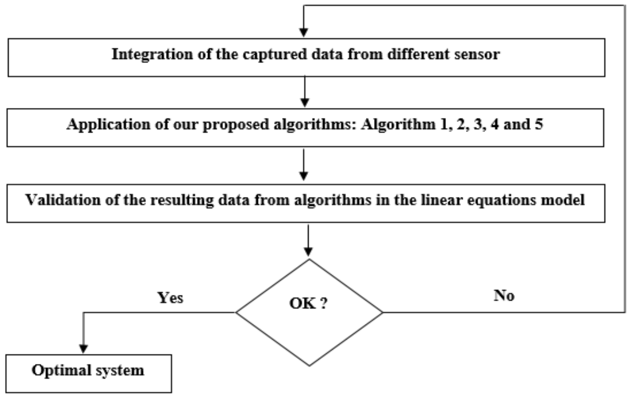


Fig. 3 The relationship between our proposed algorithm and linear equations model

3.5 The relationship between our proposed algorithm and linear equations model

In this section, we present a flowchart in Fig. 3 that summarizes the relationship between our proposed algorithm and the linear equations model.

First of all, we integrate into our system the climatic database captured from different sensors of our greenhouse. Then, we apply, on the database, our proposed algorithms (Algorithms 1-5). So, we get optimal climate parameters. After, we validate and execute the resulting data from algorithms in the linear equations model by the optimization methods. Finally, if the model is validated then our system is optimal. Else, we go to the first step.

If the system is optimal so:

- The internal microclimate of our greenhouse and the production of plants are optimal.
- The cost of equipment is minimal.

3.6 The advantages of the proposed algorithm and design

There are several advantages of the proposed design and algorithm, we will cite below some of them.

- Robust, flexible and reliable design.
- Efficiency, yield and quality of improved crops.
- Prevention of water wastage in the irrigation process and of fertilizer wastage.
- Exact regulation of the microclimate of the greenhouse for optimal growth of the plant.
- Clear and easy system to use it.

4. Results and discussion

In this section, the experimental setting and the results are presented. We show the adjustment of climatic parameters inside the greenhouse when we apply the above algorithms.

4.1 Experimental setting

The experimental tests were realized on the site of INRA (National Institute of Agronomic Research) of Montfavet (near Avignon in the Vaucluse). The volume of the greenhouse (Fig. 4) in which all experimental recordings were realized is 1700 m^3 (32 m long by 13 m wide by 3.20 m high) and a surface of 416 m^2. Their principal axis is parallel to the north-south direction. It comprises a set of equipment and software for the acquisition and digital storage of climate data such as temperature, humidity, and radiation (Draoui 1994).

The cultivated plant was the tomato. Sown in November in a breeding greenhouse, with transplanting in December. The plants were set in the greenhouse in January at a density of 2 plants per m^2 (Draoui 1994).

Fig. 4 Our experimental greenhouse

4.2 Experimental data base

For this simulation, a real benchmark is applied in two different seasons and two different phases of tomato growth: spring (March 19-26) in the flowering stage and summer (July 01-08) in the period of ~~of~~ fruit development.

The benchmark (Draoui 1994) included the evolution of the indoor and outdoor climatic conditions such as: the internal and external air temperature, the internal and external air humidity, the internal and external solar radiation. We tested also our algorithm with data from another benchmark. This benchmark contains: pH of soil.

The benchmark (Draoui 1994) used to test our algorithm contains:

- For spring: 50 data for the internal temperature diurnal, 118 data for the internal temperature nocturnal, 168 data for the internal humidity and 84 data for the internal solar radiation.
- For summer: 80 data for the internal temperature diurnal, 84 data for the internal temperature nocturnal, 161 data for the internal humidity and 103 data for the internal solar radiation.

And:

- For spring: 60 data for pH of soil.
- For summer: 90 data for pH of soil.

An example of a sample of the data used is presented in Table 4 to show you the structure of the algorithm.

With: T_e is the external temperature, H_e is the external humidity, Rg_i is the internal solar radiation and Rg_e is the external solar radiation.

4.3 Results and discussion

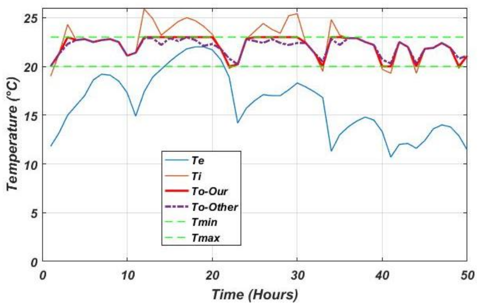
The implementation and simulation of our algorithms

Table 4 A sample of the used data

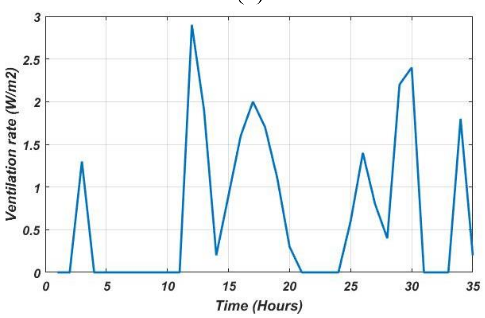
Spring							Summer						
T_i (°C)	T_e (°C)	H_i (%)	H_e (%)	Rg_i (W/m^2)	Rg_e (W/m^2)	pH	T_i(°C)	T_e (°C)	H_i (%)	H_e (%)	Rg_i (W/m^2)	Rg_e (W/m^2)	pH
19.0	11.8	91.6	64.39	80.0	140.0	4.0	25.2	24.9	47.47	34.65	344.0	672.0	9.0
21.3	13.2	88.94	60.05	179.0	319.0	4.3	27.7	26.5	50.67	38.17	455.0	792.0	9.0
24.3	15.0	79.09	54.02	294.0	529.0	4.5	28.6	28.1	49.36	34.23	562.0	887.0	9.0
22.7	16.0	70.77	51.22	265.0	469.0	4.5	28.7	28.0	50.6	38.93	599.0	918.0	8.7
22.8	17.0	62.04	48.58	296.0	502.0	4.9	29.0	27.8	45.98	34.03	567.0	925.0	8.5
22.5	18.6	52.53	47.66	365.0	588.0	5.0	29.0	27.8	44.23	31.88	551.0	832.0	8.0
22.7	19.2	58.43	50.86	292.0	444.0	5.0	28.5	27.4	45.79	32.36	430.0	672.0	8.0
22.8	19.1	58.44	52.08	227.0	333.0	5.2	27.3	27.1	45.24	31.82	294.0	490.0	7.9
22.5	18.5	63.18	53.6	78.0	156.0	5.7	25.6	26.0	49.71	35.14	143.0	306.0	7.8
21.1	17.3	84.83	60.34	9.0	19.0	6.0	24.8	25.8	43.89	40.12	101.0	243.0	7.4
18.8	16.1	91.83	65.12	24.0	48.0	6.0	25.0	26.0	45.04	42.36	42.0	98.0	7.0
17.5	15.4	91.63	66.96	102.0	209.0	6.0	21.8	21.2	60.95	48.92	1.0	3.0	7.0
17.2	14.7	91.34	71.24	182.0	406.0	6.8	26.3	25.4	86.08	62.61	18.0	31.0	6.9
16.8	14.1	92.12	75.3	274.0	562.0	7.0	25.5	23.2	90.08	72.16	79.0	146.0	6.8
16.2	13.1	92.98	81.7	346.0	645.0	7.0	24.9	23.0	90.55	77.02	152.0	298.0	6.7

Table 5 The thresholds of the four climatic parameters for the tomato greenhouse (Technical institute of vegetable and industrial crops)

	Spring		**Summer**	
	Minimum threshold	Maximum threshold	Minimum threshold	Maximum threshold
Diurnal temperature	T_{min} = 20°C	T_{max} = 23°C	T_{min} = 20°C	T_{max} = 25°C
Nocturnal temperature	T_{min} = 15°C	T_{max} = 17°C	T_{min} = 15°C	T_{max} = 17°C
Relative humidity	H_{min} = 60%	H_{max} = 65%	H_{min} = 60%	H_{max} = 65%
Solar radiation	R_{min} = 14.6 W/m^2	R_{max} = 17.6 W/m^2	R_{min} = 73.2 W/m^2	R_{max} = 73.2 W/m^2
pH of soil	Ph_{min} = 4.5	Ph_{max} = 8.2	Ph_{min} = 4.5	Ph_{max} = 8.2



(a)



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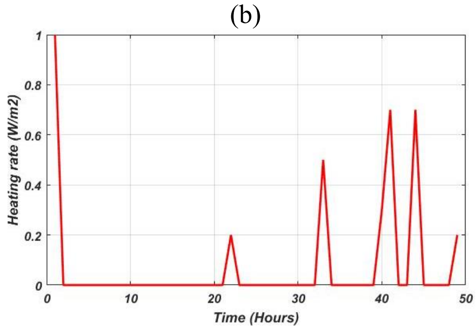
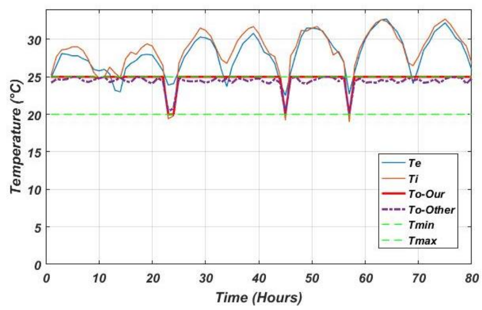
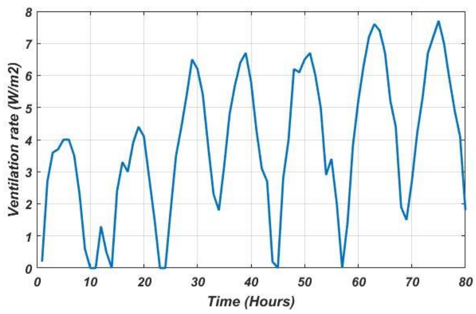


(c)

Fig. 5 (a) Monitoring the diurnal temperature of our greenhouse for spring; (b) The ventilation rate; (c) The heating rate



(a)



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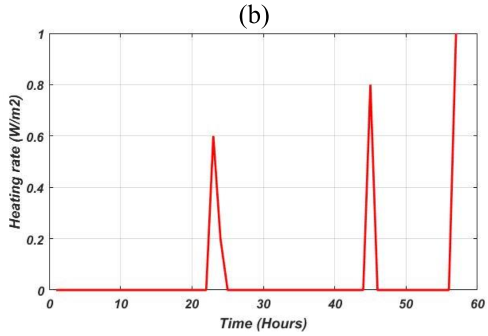


(c)

Fig. 6 (a) Monitoring the diurnal temperature of our greenhouse for summer; (b) The ventilation rate; (c) The heating rate

were done under the MATLAB environment and on four climatic parameters such as internal air temperature, internal air humidity, internal solar radiation and pH of soil. Also, we neglected the coupling effect between these climatic parameters. The objective of this implementation and simulation is to maintain the four climatic parameters in the threshold as shown in Table 5. The choice of the threshold of the climatic parameters rely upon the type of cultivated plant and its phase of growth. The results obtained indicate that the four climatic parameters measured are well regulated.

Figs. 5(a) and 6(a) present the diurnal temperature setting in a sequence of hours for spring and summer, respectively. In these figures, we presented the outside air temperature (T_e), the inside air temperature (T_i), the diurnal temperature threshold (T_{min} and T_{max}), the internal temperature after the control using our proposed algorithm (To-Our), and the internal temperature after the monitoring using the proposed algorithm in Achouak *et al*. (2018) (To-Other). After applying our algorithm, we remark that the internal temperature of our greenhouse was well adjusted in the given threshold for the two seasons i.e. the measured temperature, in a sequence of hours, has become between T_{min} and T_{max}. But after the application of the proposed algorithm in Achouak *et al*. (2018), we remark, in a few times, the internal temperature of our greenhouse was not well adjusted in the 'given thresholds. Also, the actuators of the heater and the fan (Figs. 5(b), (c) and 6(b), (c)) have been functioned well to regulate the temperature. Thus, in figures, the actuators activate continuously:

- When the temperature of our greenhouse is higher ($T_i > T_{max}$), the fan is running automatically.
- When our greenhouse is cold ($T_i < T_{min}$), the heater is working automatically.

For example:

- In Fig. 5(a), in t = 1, T_i =1, 9° < T_{min} (the greenhouse is cold) so the actuator of the heater is working automatically to heat the greenhouse. And after a few seconds, the actuator of the heater will stop working and T_i will become equal to T_{min} ($T_i = T_{min}$).
- In Fig. 6(a), in t = 1, T_i = 25.2° > T_{max} (the greenhouse is hot) so the actuator of the fan is working automatically to cool the greenhouse. And after a few seconds, the actuator of the fan will stop working and T_i will become equal to T_{max} ($T_i = T_{max}$).

Figs. 7(a) and 8(a) present the nocturnal temperature setting in a sequence of hours for spring and summer. In these figures, we presented the outside air temperature (T_e), the inside air temperature (T_i), the nocturnal temperature threshold (T_{min} and T_{max}), the internal temperature after the monitoring using our proposed algorithm (To-Our), and the internal temperature after the tracking using the proposed algorithm in Achouak *et al*. (2018) (To-Other). After applying our algorithm, we remark that the internal temperature of our greenhouse was well adjusted in the given threshold for the two seasons i.e., the measured temperature, in a sequence of hours, has become between T_{min} and T_{max}. But after the application of the proposed algorithm in Achouak *et al*. (2018), we remark, in a few times, the internal temperature of our greenhouse was not

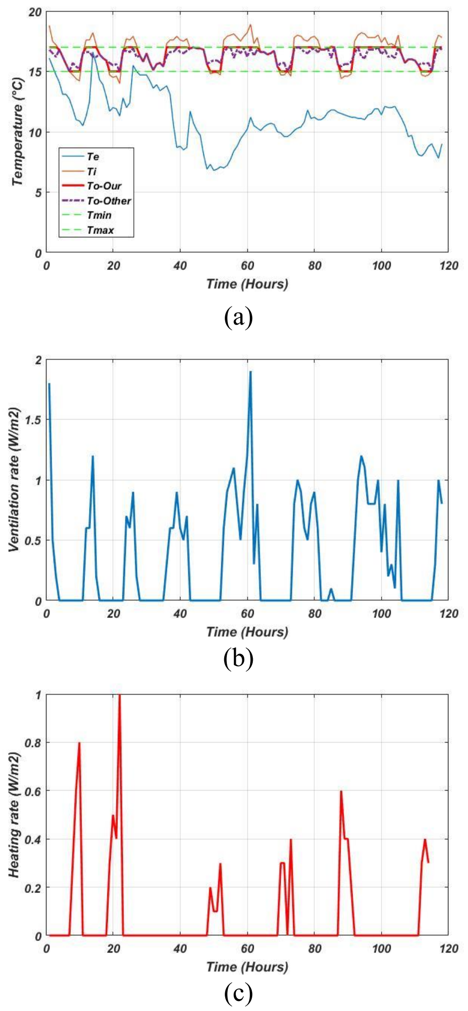


Fig. 7 (a) Monitoring the nocturnal temperature of our greenhouse for spring; (b) The ventilation rate; (c) The heating rate

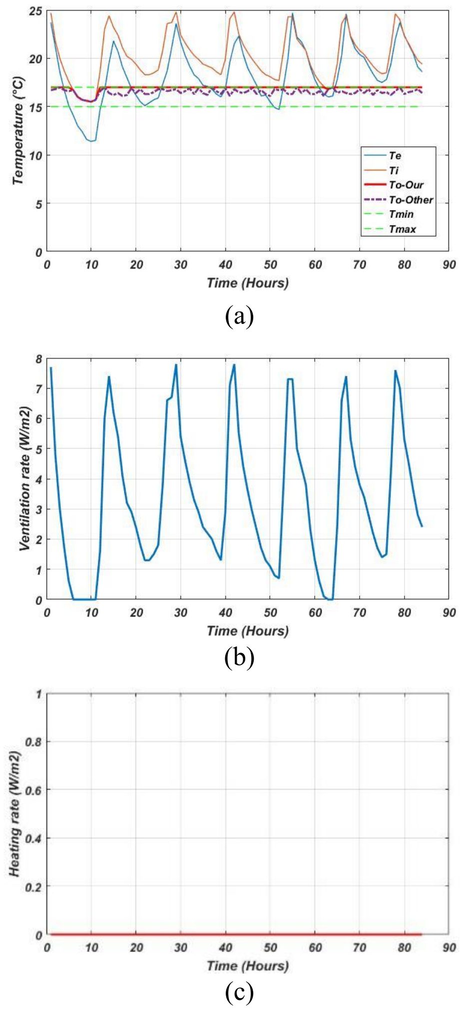
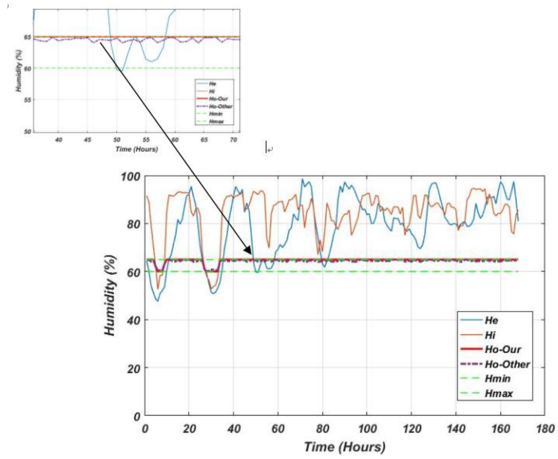
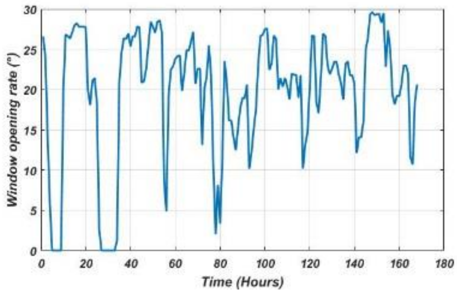


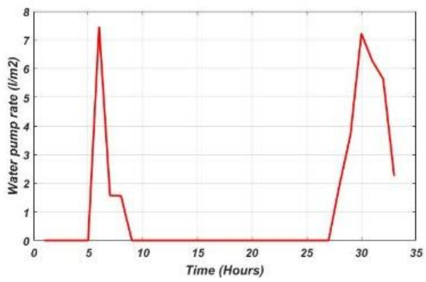
Fig. 8 (a) Monitoring the nocturnal temperature of our greenhouse for summer; (b) The ventilation rate; (c) The heating rate



(a)

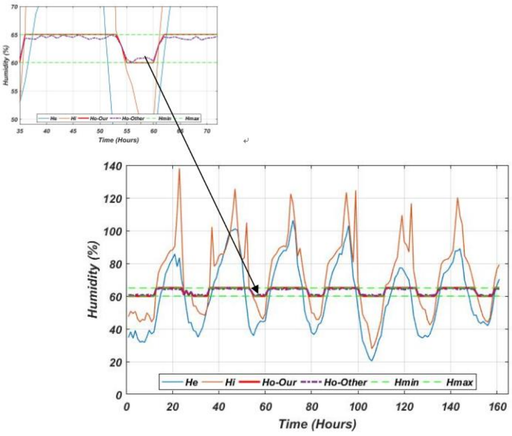


(b)

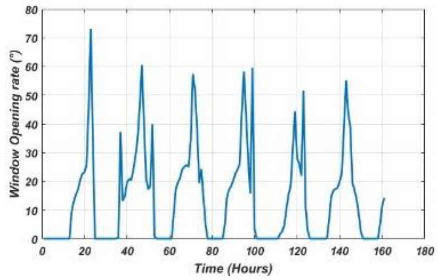


(c)

Fig. 9 (a) Monitoring the humidity of our greenhouse for spring; (b) The window opening rate; (c) The water pump rate



(a)



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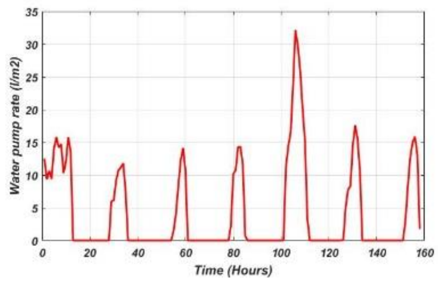


(c)

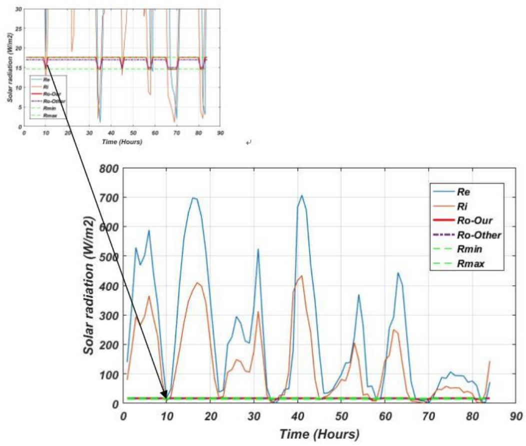
Fig. 10 (a) Monitoring the humidity of our greenhouse for summer; (b) The window opening rate; (c) The water pump rate

well adjusted in the given thresholds. Also, the actuators of the heater and the fan (Figs. 7(b), (c) and 8(b), (c)) have been functioned well to regulate the temperature. Thus, in Figs, the actuators activate continuously:

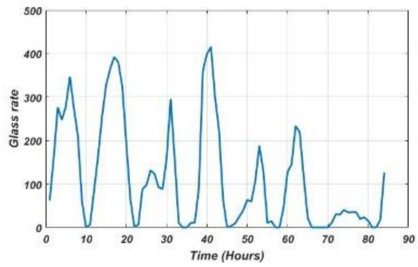
- When the temperature of our greenhouse is higher, the fan is running automatically
- When our greenhouse is cold, the heater is working automatically. But, in Fig. 8(b) and (c), only the actuator of the fan that works because the monitoring in this figure have been done in the summer.

Figs. 9(a) and 10(a) show the results obtained after applying our algorithm for the monitoring of the humidity in a sequence of hours for the spring and summer. In Figs. 9(a) and 10(a), we presented the outside air humidity (H_e), the inside air humidity (H_i), the humidity threshold (H_{min} and H_{max}), the internal humidity after the monitoring using our proposed algorithm (Ho-Our), and the internal humidity after the monitoring using the proposed algorithm in Achouak *et al*. (2018) (Ho-Other). After the application of our algorithm, we remark that the internal humidity of our greenhouse has been well adjusted in the given threshold for the two seasons i.e., the measured humidity, in a sequence of hours, has become between H_{min} and H_{max}. But after the application of the proposed algorithm in Achouak *et al*. (2018), we remark, in a few times, the internal humidity of our greenhouse was not well adjusted in the given thresholds. Also, we have remarked that the actuators of the window and the water pump (Figs. 9(b), (c) and 10(b), (c)) function permanently:

- When our greenhouse is wet ($H_i > H_{threshold}$), the window is opening automatically.
- When our greenhouse is dry ($H_i < H_{threshold}$), the water pump irrigates the plants via the sprinklers



(a)



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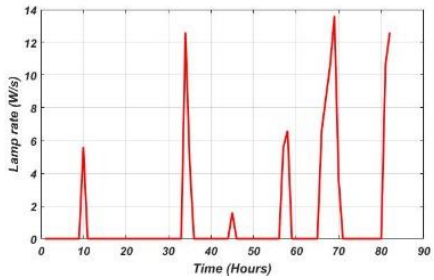
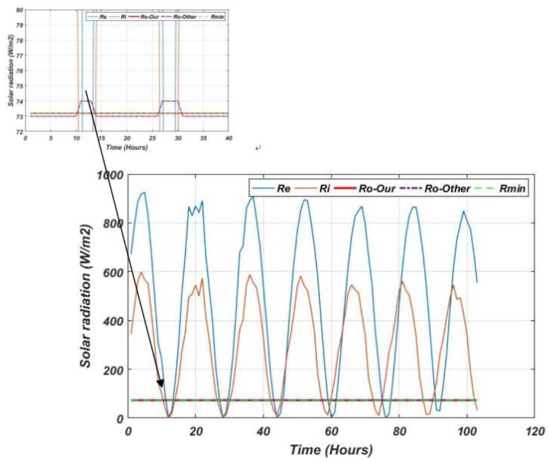
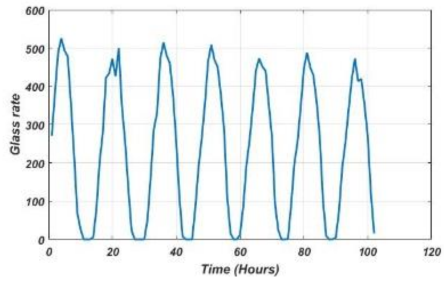


(c)

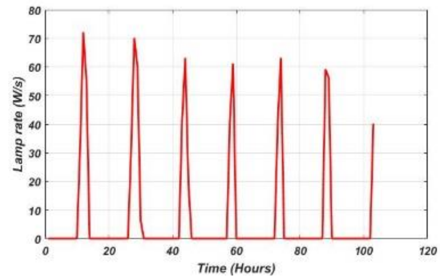
Fig. 11 (a) Monitoring the solar radiation of our greenhouse for spring; (b) The glass rate; (c) The lamp rate



(a)



(b)



(c)

Fig. 12 (a) Monitoring the solar radiation of our greenhouse for summer; (b) The glass rate; (c) The lamp rate

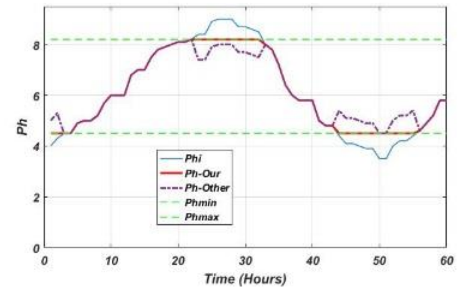
automatically.

For example:

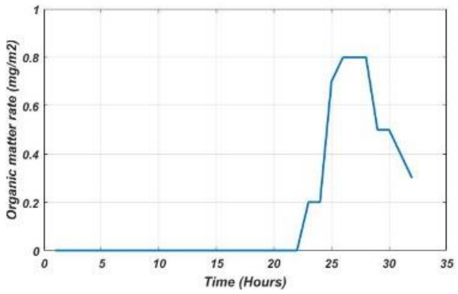
- In Fig. 9(a), in t = 1, H_i = 91.6% > H_{max} (the greenhouse is wet) so the actuator of the window is working automatically to aerate the greenhouse. And after a few seconds, the actuator of the window will stop working and H_i will become equal to H_{max} ($H_i = H_{max}$).
- In Fig. 10(a), in t = 1, H_i = 47.47% < H_{min} (the greenhouse is dry) so the actuator of the water pump is working automatically to moisten the greenhouse. And after a few seconds, the actuator of the water pump will stop working and H_i will become equal to H_{min} ($H_i = H_{min}$).

But, the actuator of the window works much more than the water pump in Fig. 9(b), because our greenhouse is almost always wet ($H_i > H_{max}$).

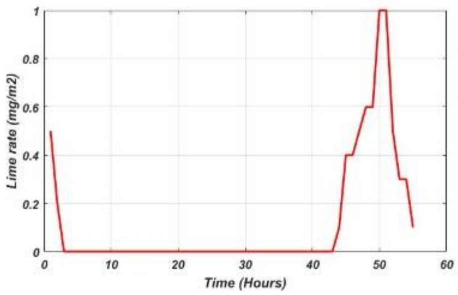
Figs. 11(a) and 12(a) present the results obtained after applying our algorithm for the monitoring of the solar radiation in a sequence of hours for the spring and summer. In Figs. 11(a) and 12(a), we presented the outside solar radiation (R_e), the inside solar radiation (R_i), the solar radiation threshold (R_{min} and R_{max}), the internal solar radiation after the monitoring using our proposed algorithm (Ro-Our), and the internal solar radiation after the monitoring using the proposed algorithm in Achouak *et al.* (2018) (Ro-Other). Also, a zoomed figure that shows clearly the results is presented in the Figs. 11(a) and 12(a). After applying our algorithm, we remark that the solar radiation of our greenhouse has been well adjusted in the given threshold for the two seasons i.e., the measured solar radiation, in a sequence of hours, has become between R_{min} and R_{max}. But after the application of the proposed algorithm in Achouak *et al.* (2018), we remark, in a few times, the internal solar radiation of our greenhouse was not well adjusted in the



(a)

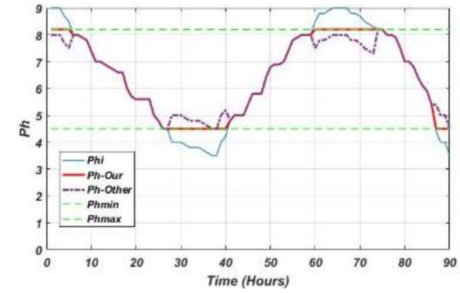


(b)

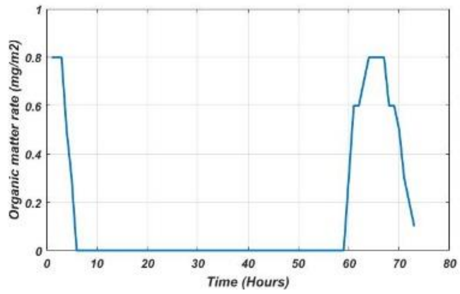


(c)

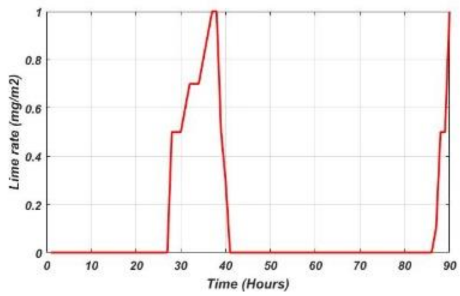
Fig. 13 (a) Monitoring the pH of soil of our greenhouse for spring; (b) The window of the reservoir of organic matter rate; (c) The window of the reservoir of lime rate



(a)



(b)



(c)

Fig. 14 (a) Monitoring the pH of soil of our greenhouse for summer; (b) The window of the reservoir of organic matter rate; (c) The window of the reservoir of lime rate

given thresholds. And in Fig. 12(a), in a few times, the internal solar radiation after applying the proposed algorithm in Achouak *et al*. (2018) exceeds the given threshold. Also, the actuators of the glass and the lamp (Figs. 11(b), (c) and 12(b), (c)) have been worked well to adjust the solar radiation. Thus, in Figs, the actuators activate continuously:

- If the greenhouse is dark ($R_i < R_{min}$), the lamp that functions automatically.
- If the opposite ($R_i > R_{max}$), the glass that works automatically.

For example:

- In Fig. 11(a), in t = 1, R_i = 80 W/m^2 > R_{max} (the greenhouse is too light) so the actuator of the glass is working automatically. And after a few seconds, the actuator of the glass will stop working and Ri will become equal to R_{max} ($R_i = R_{max}$).
- In Fig. 12(a), in t = 12, R_i = 1 W/m^2 < R_{min} (the greenhouse is dark) so the actuator of the lamp is working automatically. And after a few seconds, the actuator of the lamp will stop working and R_i will become equal to R_{min} ($R_i = R_{min}$).

Figs. 13(a) and 14(a) present the monitoring of the pH of soil in a sequence of hours for the spring and summer. In these Figs, we have presented the measured pH of soil (pHi), the threshold of pH (Ph_{min} and Ph_{max}), the pH after the monitoring using our proposed algorithm (Ph-Our), and the Ph after the monitoring using the proposed algorithm in Achouak *et al*. (2018) (Ph-Other). After the application of our algorithm, we remark that the pH of the soil of our greenhouse was well adjusted in the given threshold for the two seasons i.e. the measured pH of soil, in a sequence of hours, has become between Ph_{min} and Ph_{max}. But after the application of the proposed algorithm in (Achouak *et al*. 2018), we remark, in a few times, the pH of the soil of our greenhouse was not well adjusted in the given thresholds. Thus, the actuators of the reservoir of organic matter and lime (Figs. 13(b), (c) and 14(b), (c)) have worked well to adjust the pH. Also, in figures, the actuators function permanently:

- When the soil of our greenhouse is poor of organic matter (Ph_i < Ph_{min}), so the lime will distribute automatically on the soil.
- If the opposite situation (Ph_i > Ph_{max}), the organic matter that will distribute automatically on the soil.

For example:

- In Fig. 13(a), in t = 1, Ph_i = 4 < Ph_{min} (the soil of our greenhouse is poor of organic matter), so the actuator of the lime is working automatically to enrich the soil of the greenhouse. And after a few seconds, the actuator of the lime will stop working and Phi will become equal to Ph_{min} (Ph_i = Ph_{min}).
- In Fig. 14(a), in t = 1, Ph_i = 9 > Ph_{max} (the soil of our greenhouse is rich of organic matter), so the actuator of the organic matter is working automatically. And after a few seconds, the actuator of the organic matter will stop working and Ph_i will become equal to Ph_{max} (Ph_i = Ph_{max}).

4.4 Statistical analysis

Five criteria can be used to evaluate the performance of the proposed algorithm and design: The Root Mean Squared Error (RMSE), the Total Sum of Squared Error (TSSE), the Mean Absolute Percentage Error (MAPE), the Model Efficiency (EF) and the coefficient of determination (R^2). They are calculated based on acquired data series to compare the optimal to the measured parameters by using, respectively, Eqs. (21)-(25) (Ali *et al*. 2018, Zarifneshat *et al*. 2012, Taki *et al*. 2016).

$$RMSE = \sqrt{\frac{\sum_{w=1}^{n}(e_w)^2}{n}} \quad (21)$$

$$TSSE = \sum_{w=1}^{n}(e_w)^2 \quad (22)$$

$$MAPE = \frac{1}{n}\sum_{w=1}^{n}\left|\frac{e_w}{Pm(w)}\right| \times 100 \quad (23)$$

$$EF = \frac{\sum_{w=1}^{n}(Pm(w)-\overline{Pm})^2 - \sum_{w=1}^{n}(Po(w)-Pm(w))^2}{\sum_{w=1}^{n}(Pm(w)-\overline{Pm})^2} \quad (24)$$

$$R^2 = \left(\frac{\sum_{w=1}^{n}(Pm(w)-\overline{Pm})(Po(w)-\overline{Po})}{\sum_{w=1}^{n}(Pm(w)-\overline{Pm}) \times \sum_{w=1}^{n}(Po(w)-\overline{Po})}\right)^2 \quad (25)$$

Where Pm and Po are, respectively, the measured parameter and the optimized parameter, $\overline{Pm}$ and $\overline{Po}$ are, respectively, the average of the whole measured and optimized parameters, e_w is the error between Pm and Po and n is the variable number. A model with the smallest RMSE, MAPE and TSSE and with the largest EF and R^2 is considered to be the best.

Statistical estimators RMSE, TSSE, MAPE, EF and R^2 are determined to study the performance of our proposed algorithm. They are calculated under MATLAB using Eqs. (21)-(25) respectively. The results are summarized in Figs. 15-19. These figures represent the comparison results between the proposed algorithm in Achouak *et al*. (2018) and our proposed algorithm in the spring and summer season on four environmental parameters (temperature, humidity, solar radiation and pH of soil).

In these Figs, we remark the results of TSSE, RMSE and MAPE of our proposed algorithm are small than the results of the proposed algorithm in Achouak *et al*. (2018). Also, the results of EF and R^2 of our proposed algorithm are significant results compared to the results of the proposed algorithm in Achouak *et al*. (2018).

The results of the statistical analysis in Figs. 15-19 prove the effectiveness of our proposed algorithms that permits to monitor the climate parameters intelligently

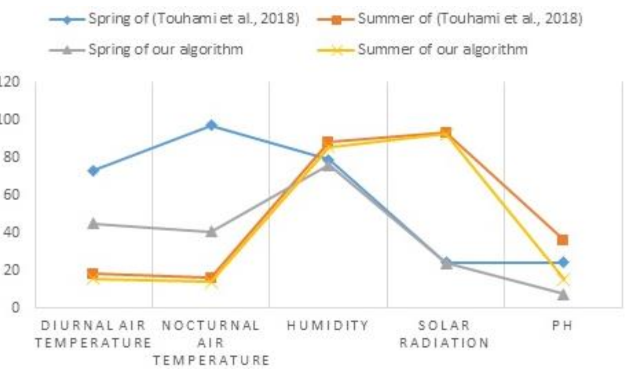


Fig. 15 TSSE results

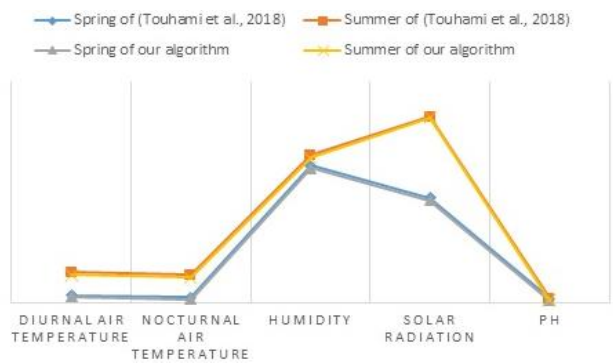


Fig. 16 RMSE results

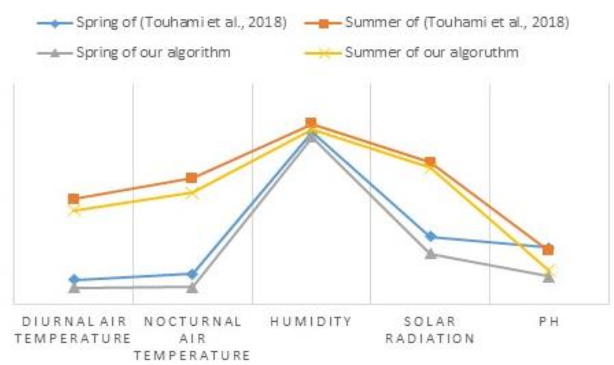


Fig. 17 MAPE results

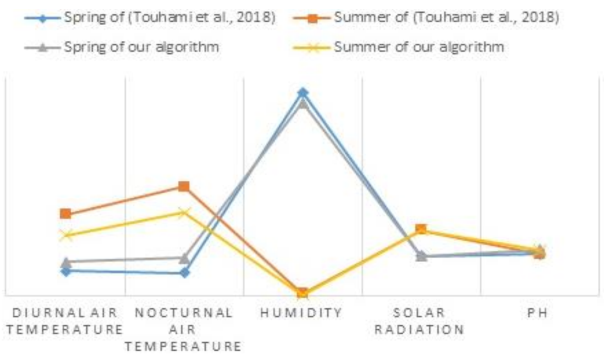


Fig. 18 EF results

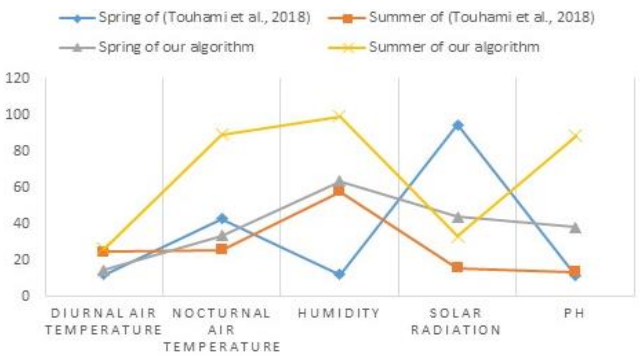


Fig. 19 R^2 results

inside the greenhouse with a small RMSE, MAPE and a significant EF and R^2.

5. Conclusions

In a greenhouse, several parameters must be monitored in the process of plant growth. However, there are periods during which these parameters such as temperature, humidity, solar radiation, pH of soil, etc., inside the greenhouse, become unfavorable for the plant.

In this article, we have proposed a novel design and a polynomial algorithm for monitoring the microclimate of greenhouses automatically and linear equations model for optimization plant production and material cost. The proposed algorithm depends on the comparison of the data collected by the sensors in real-time with given thresholds. We have examined five environmental parameters (temperature, humidity, solar radiation, CO_2 concentration and soil pH). We have tested in simulation our algorithm on four environmental parameters (temperature, humidity, solar radiation and pH of soil), where we obtained satisfactory results in an execution time of 2.09 seconds. Also, we have calculated the statistical estimators RMSE, TSSE, MAPE, EF and R^2. The obtained results prove the importance and effectiveness of our proposed algorithm.

In terms of perspective, in our future work, we hope to validate our algorithms in real-time and realize this project in arid areas where the climate is challenging. We also plan to include other parameters. Finally, we also want to add new technologies in the system such as the Internet of Things, cloud computing, etc., and other materials such as a computer, mobile phone.

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