A Fuzzy Logic-Based Greenhouse Smart System for Sustainable Tomato Production in Algeria

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ABSTRACT

This paper presents a fuzzy logic-based farming system to help farmers cultivate tomatoes (Solanum lycopersicum) in a greenhouse in Algeria. To achieve high quality and a large crop, various climatic parameters in the greenhouse must be carefully maintained. These parameters are mainly the soil and environmental humidity, the amount of light, and the air temperature. The amount of irrigation water is also an important factor. In the proposed system, these parameters are intelligently controlled using fuzzy logic. The inputs to the developed fuzzy logic controller are the humidity and temperature of the air, the light intensity in the greenhouse, and the humidity of the soil, in addition to the level of water in the irrigation reservoir. The effect of these factors on the growth of the plant was modeled using a fuzzy logic controller developed using MATLAB. Sensors were used to read the values of these parameters and feed them to the inference engine of the system, which was an Arduino UNO card with an Atmega328 processor. The outputs of the system were the speed of the ventilation fan, light intensity, and water flow from the irrigation pump. The membership intervals for these variables were defined, and the system was tested with varying inputs. The simulation results showed that the proposed system intelligently automates the process of irrigation, ventilation, and lighting of the greenhouse.

Keywords-Arduino; greenhouse; irrigation; membership function; smart sensor

I. INTRODUCTION

In addition to fossil fuels, the Algerian economy also depends greatly on agricultural crops, which represent a large share of the domestic market. Due to the country's large geographical area and variable climate, the south has a climate different from that of the north. These climate changes offer great opportunities to grow a wide variety of crops [1]. Water is a critical resource, and its conservation should be a priority in agricultural planning, especially in southern Algeria [2-4]. Greenhouses mitigate the impact of external factors, such as rain, wind, and cold, by creating a controlled environment [5, 6]. Unlike hot greenhouses that do not require temperature and humidity control for plant production [7, 8], greenhouses in cold and dry regions require temperature and humidity control to support plant growth. In these cases, electrical systems must control air and ground temperatures, water and nutrients, CO_2 levels, and humidity. Greenhouses are also useful for providing crops outside of the growing season. To achieve this goal, all factors that affect tree growth must be carefully controlled. There are various methods to regulate weather conditions and combat diseases and pests. This technology enabled the development of advanced systems around the world. However, many of these systems mainly focus on monitoring a single factor, such as temperature, humidity, water, or lighting [9]. Many studies have explored the implementation of automatic irrigation [10-12]. However, few integrated systems [13-15] have been developed to monitor multiple greenhouse climatic parameters simultaneously. In recent years, crop quality detection using artificial intelligence has gained significant attention among researchers [16-18]. Detailed discussions of such intelligent agriculture systems have been reported in [19]. Comprehensive reviews of artificial intelligence-based smart farming systems can also be found in [20-22]. This study aims to develop an automated greenhouse system using fuzzy logic to control different climatic parameters. This system was designed specifically for the cultivation of Solanum lycopersicum (tomato) in Algeria. Initially, an in-depth analysis was performed to identify the ideal climatic conditions [23] to ensure the optimal yield of the crop. The key factors considered included light levels, temperature, and soil moisture. For the germination of tomato seeds, the ideal temperature range is between 25-30°C, with slower growth at 18°C and no germination occurring below 11°C. Increased humidity and temperature lead to the spread of fungal diseases, while dry conditions and excessive heat result in flower drop [24]. Maintaining moderate humidity, around 75% of Relative Humidity (RH), is vital to achieve healthy fruit sizes and prevent defects such as chapping or poor coloring. However, high humidity and temperature can encourage excessive vegetative growth and extend internodes, while also promoting fungal spread and reducing nutrient uptake. Although Solanum lycopersicum is neutral in terms of photoperiod, it requires significant light energy, as insufficient light intensity can hinder flower induction. Low light also negatively affects pollen germination [25]. A detailed assessment led to the selection of suitable sensor technologies, followed by the proposal of a system architecture modeled in the ISIS Proteus simulation environment. A fuzzy logic controller was created and integrated into an Arduino circuit.

II. RESEARCH METHODOLOGY

A. Prototype Block Diagram

The developed fuzzy logic-based greenhouse control system was built on an Arduino UNO board based on an Atmega328 CPU. Arduino provides an Integrated Development Environment (IDE) based on open-source tools. After its conversion into a hex file, the injection of the developed control program into the memory of the microcontroller is performed using a USB connection. Several function libraries are also provided for I/O operations, making the programming process much easier. Figure 1 shows the block diagram of the architecture used for developing the system prototype. The Atmega328 microcontroller features six analog inputs (labeled 0 to 5), each offering 10-bit resolution (ranging from 0 to 1023) input signal using the convenient analogRead() function. These pins read values between 0 V (representing 0) and 5 V (representing 1023), but the measurement range's upper reference can be adjusted through the AREF pin and the *analogReference*() function. Analog signals from input sensors are sent to the processor through these analogue pins. Additionally, the digital pins on the board can be set as either inputs or outputs. In this case, three pins are configured as outputs to regulate the light intensity of the bulb, the speed of the pump motor, and the cooling fan's speed. The obtained data and associated output details are shown on a Liquid Crystal Display (LCD) connected to other output pins.

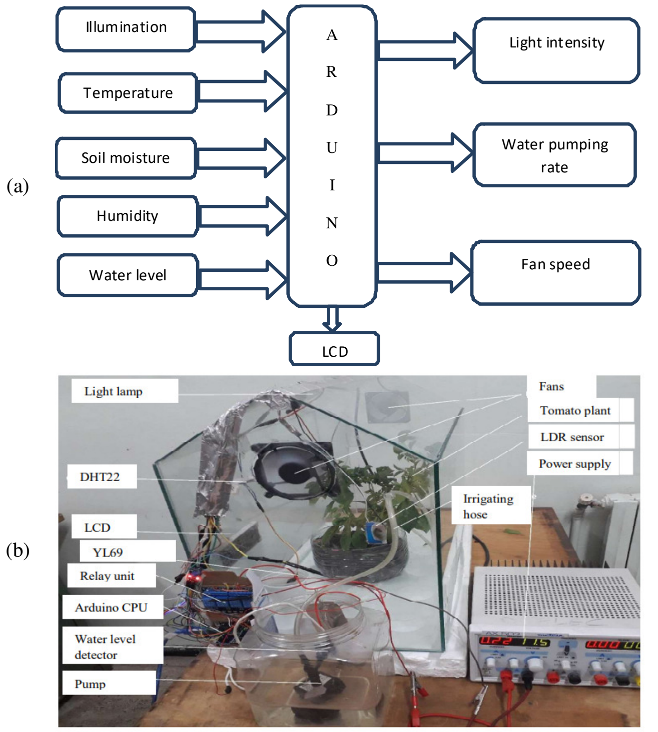

Fig. 1. (a) Block diagram of the developed prototype, (b) The implemented prototype. © IEEE. Reprinted with permission from IEEE proceedings [19], licence number 6026661349036.

B. Fuzzy Logic Controller

Instead of using complex mathematical equations, fuzzy logic uses linguistic descriptions to define the relationship between input information and output action. In engineering, fuzzy logic tools provide a convenient and user-friendly interface for developing control programs that help designers focus on functional goals, not mathematical modeling. A fuzzy logic system has four blocks, as shown in Figure 2.

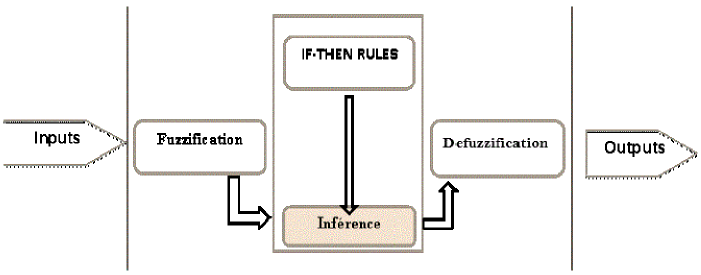

Fig. 2. Block diagram of the fuzzy logic controller.

The sensor's net input information is converted to fuzzy values for each input fuzzy set with the fuzzification block. The scope of the input variables determines the number of scales required for the correct operation per unit. The decision-making logic determines the operating mode of the operations of the performed fuzzy logic (sup-min inference), and, together with the knowledge base, determines the results of each If-Then fuzzy rule. These are combined and converted to crisp values by the defuzzification block. To process the input to obtain the output reasoning, six (6) steps are involved in the creation of a fuzzy rule-based system:

1. Identify the entries and their ranges and name them.
2. Identify the outputs and their ranges and name them.
3. Create the fuzzy degree of membership function for each input and output.
4. Build the rule base on which the system will operate.
5. Decide how the action will be performed by assigning strengths to the rules.
6. Combine the rules and defuzzify the output.

Figure 3 illustrates the fuzzy logic control system developed in MATLAB. Input variables are defined as temperature, soil humidity, air humidity, minimum level of water in the reservoir, and illumination. The fuzzy inference system uses the Mamdani inferring method. Finally, the output variables are displayed, namely the lamp (LAMP), the fan (FAN), and the pump (PUMP).

III. RESULTS AND DISCUSSION

A. *Input Variable Membership Functions*

The temperature input variable has three membership functions. They are low (TP), medium (TM), and high (TG). Low has the range of 0-25°, medium has the range of 25-35°, and high has the range of 35-50°. The membership functions for the bottom and top are trapezoidal, while the medium function is triangular.

The air humidity input variable has three membership functions as shown in Figure 4. They are denoted as dry (DH), normal (NH), and wet (WH). Its interval is 0-100%. Dry has a range of 0-50%, normal has a range of 50-80%, and wet has a range of 80-100%. The membership functions for dry and wet are trapezoidal, while the membership function for normal is triangular.

Similarly, the illumination input variable has three membership functions. They are denoted as dark (LP), normal (LM), and brilliant (LG). The range of this variable was chosen between 0 and 500 units. LP has a range of 0-150, LM has a range of 150-250, and LG has a range of 250-500. The membership functions of LP and LM are trapezoidal, while the membership function of LG is triangular.

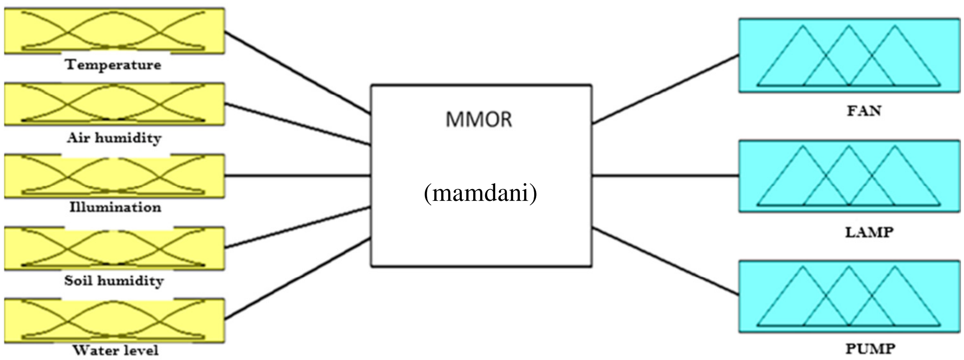

Fig. 3. Fuzzy logic controller of the developed system in MATLAB.

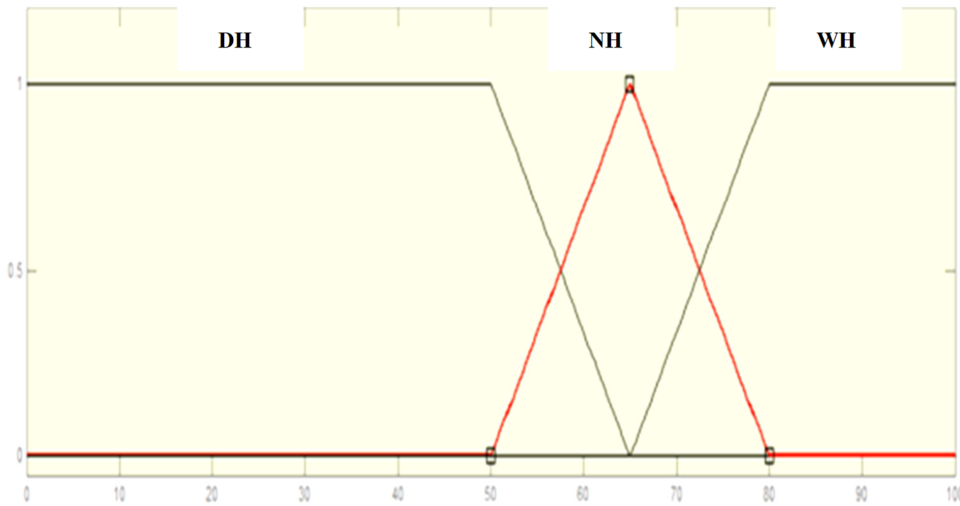

Fig. 4. The air humidity input membership function.

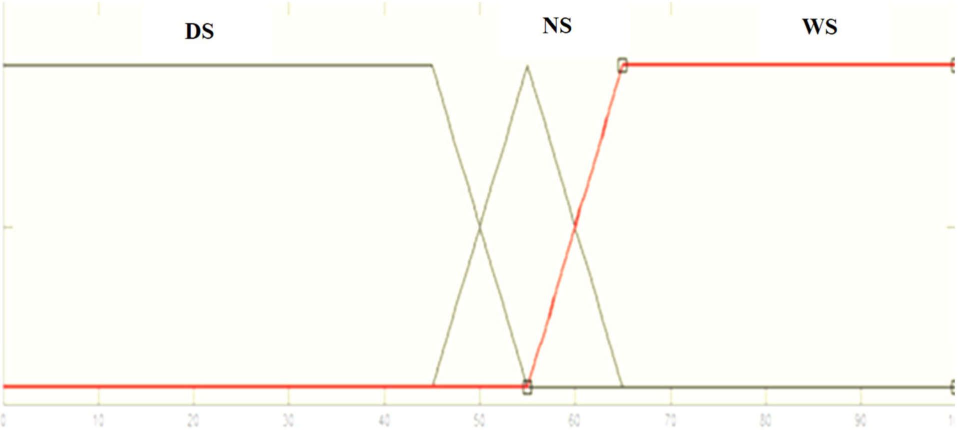

Fig. 5. The soil humidity input membership function.

The soil humidity input variable has three membership functions, shown in Figure 5, denoted dry (DS), normal (NS), and wet (WS). DS has the range of 0-45, NS has the range of 45-65, and WS has the range of 65-100. The water level in the reservoir input variable has two membership functions, low and high, which are trapezoidal.

B. Membership Functions of Output Variables

The output variable LAMP represents the intensity of light needed by the plant and has three membership functions, as shown in Figure 6. They are denoted LOW, MEDIUM, and HIGH. LOW ranges from 0 to 200 lux, MEDIUM ranges between 200 and 300 lux, while HIGH ranges from 300 to 500 lux.

The output variable PUMP represents the amount of irrigating water and has three membership functions, as shown in Figure 7, denoted LOW flow, NORMAL flow, and HIGH flow. LOW is between 0% to 40%, NORMAL has a range of 40-70%, and HIGH has a range of 70-100%. 100% represents full speed of the pump, which corresponds to a duty cycle of the converter equal to 1. The OFF command is used to deactivate the water pump. The output variable FAN models the speed of the ventilating fans and has four membership functions, as shown in Figure 8. They are denoted OFF, SLOW, MEDIUM, and FAST.

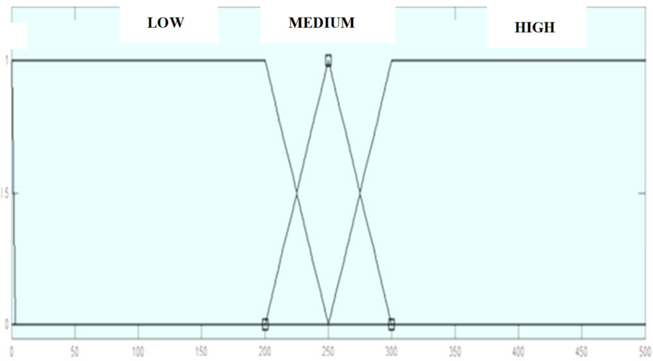

Fig. 6. The membership functions for the output variable LAMP.

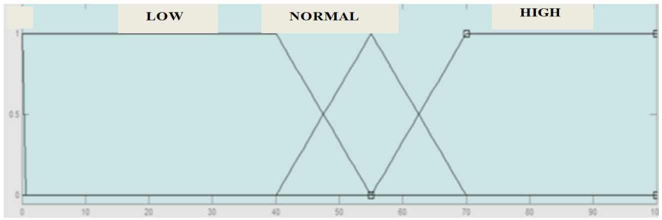

Fig. 7. The membership functions for the output variable PUMP.

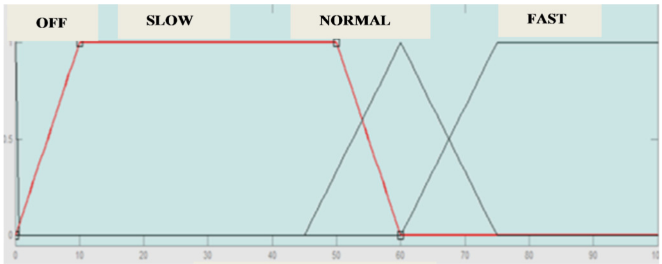

Fig. 8. The membership functions for the output variable FAN.

C. Rule Base

The If-Then rules are defined in the rules part of MATLAB, as shown in Figure 9. Tables I and II show samples of these rules. Before building the prototype, the system circuit was designed using Proteus ISIS software, as shown in Figure 10. Figure 11 illustrates the connection of various subcircuit components. The sensors employed to monitor environmental parameters included the temperature and humidity sensor (DHT22), the light sensor (LDR), and the soil moisture sensor (YL-69).

TABLE I. FAN SPEED AS A FUNCTION OF AIR HUMIDITY AND TEMPERATURE INPUTS

Temperature/ Air Humidity	TP	TN	TG
DH	OFF	OFF	MEDIUM
NH	SLOW	SLOW	FAST
WH	MEDIUM	MEDIUM	FAST

Photosynthesis takes place within wavelengths ranging from 400 to 700 nm, a spectrum referred to as Photosynthetically Active Radiation (PAR). Chlorophyll plays a key role in absorbing this radiation, with peak absorption occurring in two specific ranges: blue light (430-500 nm) and red light (630-680 nm). A Light-Dependent Resistor (LDR) was used as the primary sensor to measure the light intensity. Its resistance fluctuates in response to varying illumination levels, enabling it to measure visible light effectively. To monitor soil moisture, the YL-69 sensor was utilized, relying on the soil's dielectric constant to determine volumetric water content. This device is inserted into the ground to detect water availability. The air circulation within the greenhouse was regulated using a fan, ensuring adequate ventilation. The fan was powered by a PWM DC motor, whose speed was adjusted based on temperature and humidity readings from the DHT22 sensor. Meanwhile, a centrifugal pump controlled irrigation, activated in response to soil moisture data.

In Algeria, greenhouse lighting is generally sufficient, particularly in southern areas where sunshine dominates most of the day and year. However, northern regions experience more overcast conditions during winter, making artificial illumination necessary, especially in the morning when tomato plants engage in photosynthesis [26]. A set of net values was applied to the fuzzy logic controller. For example, the values of [29 66 55 215 198] were applied to the input variables of temperature, soil humidity, air humidity, minimum reservoir level, and lighting as shown in Figure 12. The corresponding net fuzzy logic outputs for the lamp, pump, and fans are shown in Figure 13.

TABLE II. PUMP FLOW AS A FUNCTION OF WATER LEVEL IN THE RESERVOIR AND SOIL HUMIDITY INPUTS

Water level/ Soil humidity	LOW	HIGH
DS	OFF	HIGH
NS	OFF	MEDIUM
WS	OFF	SLOW

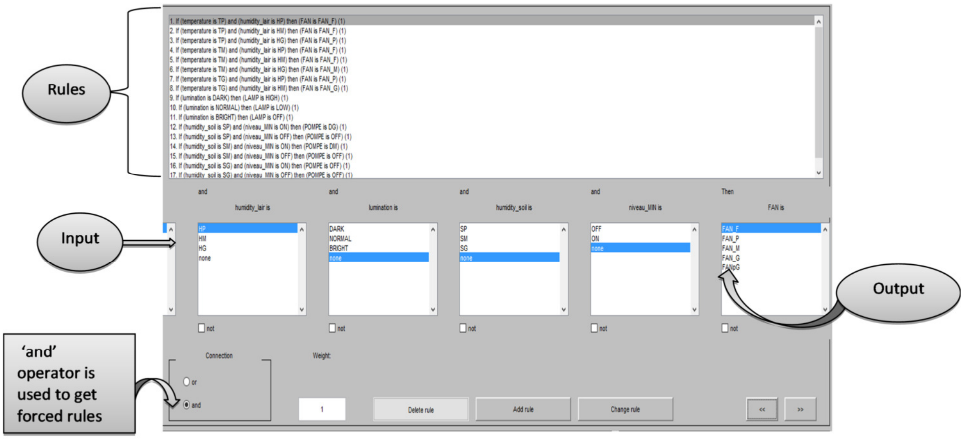

Fig. 9. A sample of the rule base developed under the MATLAB environment.

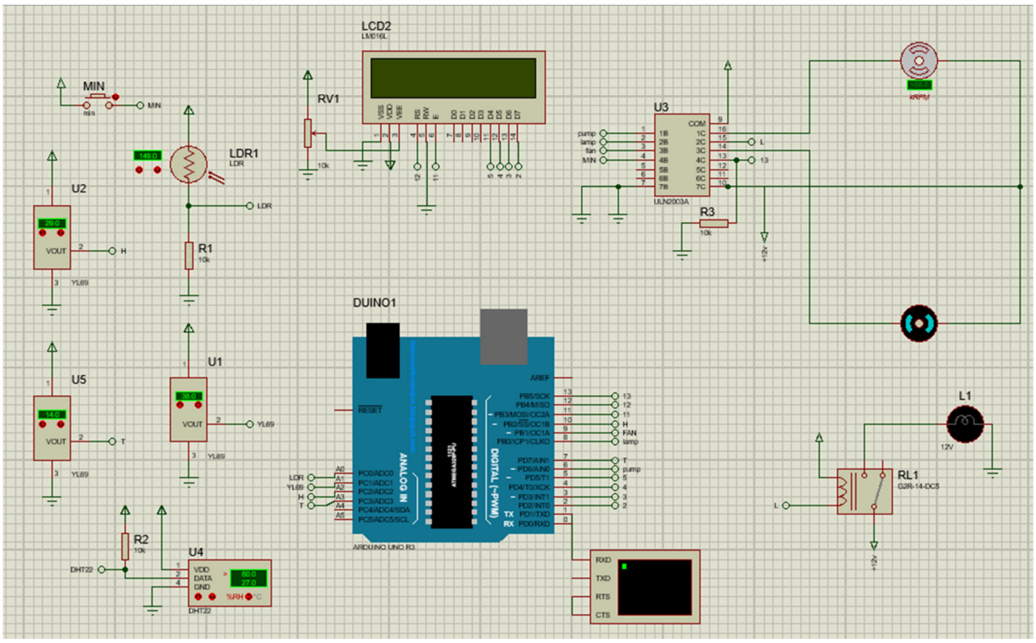

Fig. 10. The designed circuit and prototype under Proteus ISIS.

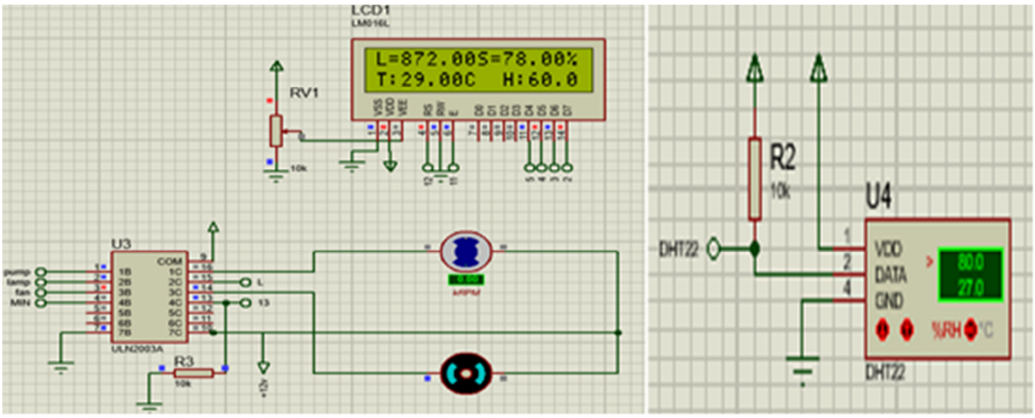

Fig. 11. Samples of subcircuit connections in ISIS: LCD unit, ventilation driver unit, and DHT22 sensor.

D. Discussion

Most greenhouse systems discussed in the literature are designed using a generalized approach, without focusing on the specific microclimatic requirements of individual plants or crops. This limitation hinders their commercial implementation. Additionally, some systems incorporate IoT technology for communication between components and users. Although this method is highly promising on a global scale, its application in many developing countries is hindered by inadequate internet infrastructure. In addition, security and reliability remain major concerns that require further research to address them effectively. A key observation is that most of the reviewed studies utilize the Arduino board as the primary control unit. Its widespread availability, ease of use, and adaptability to various development scenarios contribute to its popularity. Some systems have also reported using the Raspberry Pi microcontroller, which offers greater processing power and additional features, particularly for wireless and Internet-based communication. However, it is significantly more expensive and complex compared to Arduino.

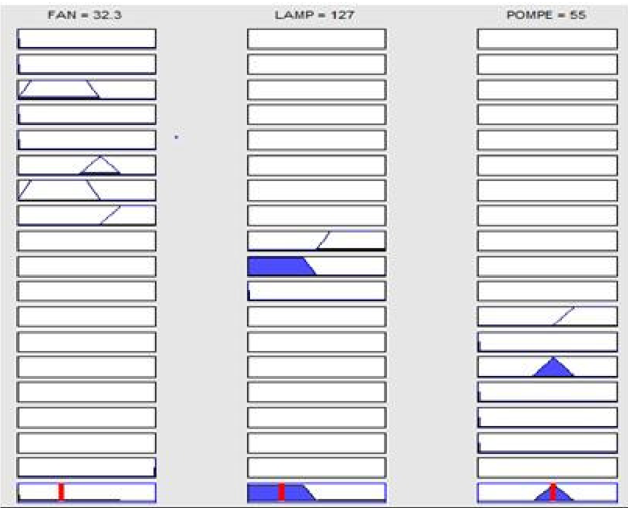

Fig. 12. Outputs of the applied inputs.

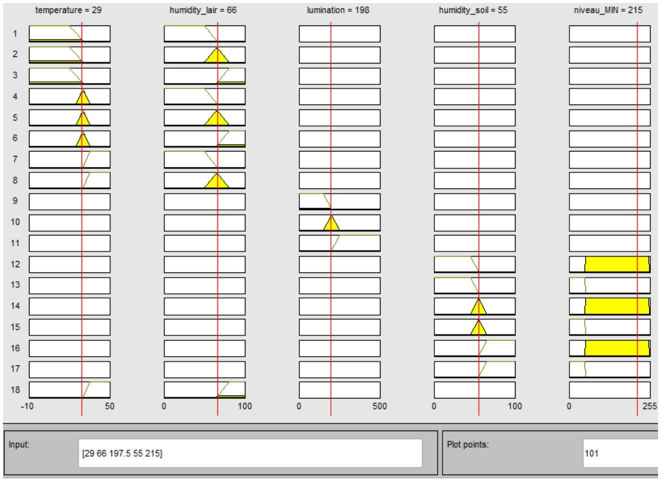

Fig. 13. Example of net values applied to the inputs.

IV. CONCLUSION

A smart greenhouse system was designed, modeled, and simulated. The system was designed to enhance tomato crop production in Algeria by regulating four key microclimatic factors, making cultivation more manageable for farmers. The project began with an analysis of optimal greenhouse conditions for tomato growth. Although numerous factors influence the plant's development, the initial focus was on four key factors: soil moisture, air temperature, humidity, and light intensity. Suitable sensors for each parameter were chosen, and their combined impact on plant growth was modeled using a fuzzy logic controller developed in MATLAB.

The system hardware was designed around the Arduino ATmega328 microcontroller and simulated in ISIS Proteus. Subcircuits were developed to interface the sensors with the microcontroller's inputs and the actuators with its output. Although the fuzzy logic controller showed promising results, further enhancements are proposed, including adding CO_2 concentration measurement and pH monitoring to improve environmental control and integrating a camera to assess leaf and fruit conditions for better decision-making. An IoT-based communication module is also suggested to enable seamless data exchange between users and stakeholders.

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