

## Research Article

# Fuzzy System of Irrigation Applied to the Growth of Habanero Pepper (*Capsicum chinense* Jacq.) under Protected Conditions in Yucatan, Mexico

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Agriculture is the largest user of water worldwide by using about 70 percent of total consumption. The world food production depends on the availability of water, considering factors such as demographic and climate change, so the use of efficient irrigation is necessary to apply the correct amount of water to crops. The traditional irrigation systems generally program their scheme based on measurements made at Class A evaporimeter pan. In this paper an irrigation scheme defined by an algorithm that automates the amount of water supplied is presented, it considers the consumption of habanero pepper crop, and a fuzzy system evaluates the necessary duration of irrigation. The climatic variables considered are temperature, relative humidity, and soil moisture. The algorithm was programmed in a microcontroller Atmel 328p included in Arduino platform, with the addition of a ZigBee wireless system that allows for monitoring through a PC. The climatic variables were inserted into the fuzzy system by sets of trapezoidal and triangular form and a Mamdani type inference mechanism in which the knowledge of an expert is registered through the fuzzy rules. The system was applied to a habanero pepper crop at Conkal Institute of Technology in Yucatan, Mexico.

## 1. Introduction

Mexico ranks second in volume production of chili peppers and third in area harvested with 2379736 tons and 136132 ha, respectively, engaged with the 7.1% area and 7.6% ton of world production [1]. The fruits of this plant are of great economic importance because there is a wide variety of applications; there is an excellent source of natural dyes, minerals, and vitamins A, C, and E; the mainly substance that is extracted from this crop is capsaicin whose concentration is very high in the variety known as habanero. There are several regions in Mexico who grow habanero pepper [2]; however, more than

50% of production for domestic and export markets comes from the Yucatan Peninsula, which has provided support for obtaining distinctive “appellation of origin” published in the Official Gazette of the Mexican Federation on June 4, 2010. For production even outside station protected cultivation techniques are used, and the most commonly used structures in protected agriculture are greenhouses, shade mesh, high, and low tunnels. The shadow mesh structure mentioned above is a simple and inexpensive alternative, although very low technology [3].

Environmental variables have, by nature, a complex and nonlinear dynamic. Therefore the information processing

solutions are required, based on advanced techniques and technologies, to provide a better result in the production of food [4]. In this context, the use of soft computing techniques (such as neural networks, genetic algorithms, and fuzzy logic) has been considered as real solutions to problems related to the effective management of agricultural resources [5]. One such resource is hydric, characterized by irrigation systems and affecting plant growth and hence production. Due to the above, there are proposals that enable automation and control to carry out this process in the best way [6, 7]. These methods adjust the amount of water supplied according to crop water requirements, the amount of water available in the channel and system components. In systems that use drip irrigation such information has not been considered, because the amount of water is controlled in a certain manner [8]. However, the frequency of irrigation drip systems still depends on climatic factors, soil type, and crop type, so that the control and close monitoring remains necessary in these systems [9–11]. The application of soft computing techniques has been observed in work processes involving environmental control [4, 5], weed control, pest and biological processes [12], and greenhouse climate control [9, 13].

The work presented in [14] is a simulator that aims to provide a model of irrigation scheduling considering different times and different distributions of water in sensitive plant species lack thereof. Project development provides the biophysical modeling, technical and decision subsystems. Time schedule irrigation is carried out considering the water shortage, the amount of available soil water for lawn and plant composition. The limitation of this study is that it is a simulated process and not done in a real environment.

The work in [15] shows an irrigation system used for ornamental plants of different types calculating irrigation from soil type. This work uses: crop coefficient information, the type of soil cultivation, wind speed, solar radiation, temperature, relative humidity, and rainfall level, obtained from a weather station and other measuring devices purchased for that purpose. An important limitation is the use of expensive measuring instruments, applied to field crops, to which most farmers do not have an access.

The work in [16] integrates fuzzy logic and neural networks in a network of sensors in precision irrigation scheme. This is a work in software, which simulates the behavior of irrigation scheduling and is expected to have favorable results in manual application. One drawback is that it proposes the use of precision irrigation equipment (little affordable in most of the time for a producer) to obtain information in a real environment. Blurring the crop is also observed, although some environmental variables needed for irrigation control, such as humidity and temperature which are integrated variables and factors inherent at the crop, are ignored.

In this study, the development of a smart irrigation system based on microclimate variables such as temperature and relative humidity in a shadow mesh structure is proposed. This system is designed to improve irrigation scheme for habanero pepper (*Capsicum chinense* Jacq.) using the fewest number of variables and taking advantage of expert knowledge. A relevant aspect of this proposal is the possibility

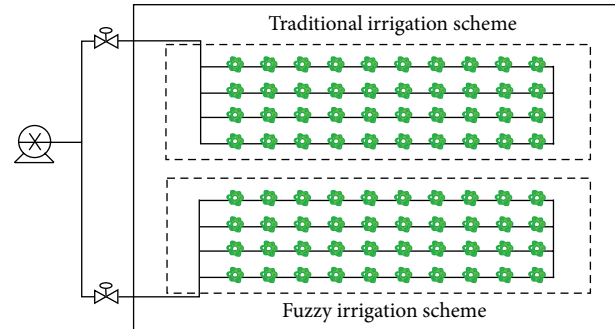


FIGURE 1: Irrigation schemes.

of implementation in crops where farmers do not have sufficient financial resources and therefore less access to the technification.

## 2. Materials and Methods

This work was carried out in a metal covered roof infrastructure with milky white plastic with 50% and side walls, front and back with mesh antiaphids, in an area of 482.4 m<sup>2</sup> (13.4 m × 36 m) in Technological Institute of Conkal, Yucatan, located at Km 16.3 of the Merida-Motul road. Geographical coordinates are 21° 36' north latitude, 19° 32' south; 87° 32' east, 90° 25' west longitude, at an altitude of 9 meters, according to INEGI Geostatistical Framework (2010). The climate at the experimental site, according to the classification of Köppen modified by Garcia [17], is the Awo ( $x'$ )  $g$  type. In the shade house, when the seedlings had about 10 cm tall, they were transplanted in containers with compost.

For the growing crop, two irrigation schemes were employed, a traditional scheme and a fuzzy scheme (Figure 1).

Traditional irrigation scheme was performed using the following criteria:

- (1) obtaining data through an Class A evaporation pan,
- (2) applying data crop coefficient ( $K_c$ ) for habanero pepper (Tables 1(a) and 1(b)),
- (3) calculating crop evapotranspiration (ET),
- (4) calculating irrigation depth,
- (5) calculating the volume of water to be applied to replace the water lost by evapotranspiration,
- (6) calculating irrigation time.

ETo calculation (reference evapotranspiration) can be estimated from the Class A evaporation pan. The crop coefficient ( $K_c$ ) was determined by relating the measured crop evapotranspiration (ETc) with ETo calculated. ET is evapotranspiration (combined loss of water to plant transpiration and soil evaporation). The irrigation depth is calculated to determine the amount of water that must be applied to the soil to satisfy the needs of the crop. The calculation of the volume of water is obtained for estimating evapotranspiration losses and irrigation time is determined by considering the method of irrigation and type of crop.

```

Initial Value for soilMoisture
REPEAT
  WHILE soilMoisture > 70%
    READ Analog Port Soil Moisture Sensor Value
    CALCULATE soilMoisture based on VH400 eq
    WAIT 10 minutes
  endWHILE
  CALL Fuzzy Irrigation Time for Habanero pepper (INPUT: RelativeHumidity, Temperature; OUTPUT: IrrigationTime)
  WHILE IrrigationTime > 0
    WRITE Digital Value for pump activation
    CALCULATE IrrigationTime countdown
  endWHILE
  WRITE Digital Value for pump deactivate
UNTIL (true)

```

ALGORITHM 1: Fuzzy irrigation process pseudocode.

TABLE 1: (a) Crop coefficient for habanero pepper (60%). (b) Crop coefficient for habanero pepper (100%).

(a)		
Crop growth (%)	Days after transplanting	$K_c$
25	30–36	0.80
30	37–42	0.90
35	43–48	0.93
40	49–54	0.95
45	55–60	1.03
50	61–66	1.05
55	67–72	1.05
60	73–78	1.05
(b)		
Crop growth (%)	Days after transplanting	$K_c$
65	79–84	1.03
70	85–90	1.00
75	91–96	0.97
80	97–102	0.90
85	103–108	0.85
90	109–114	0.80
95	115–120	0.70
100	121	0.60

On the other hand, fuzzy irrigation schema is proposed. The proposed system consists of four sections, first, measuring and estimating the volume of water lost, subsequently, measuring level categorization through measuring the relative humidity and temperature, further, the integration of the communication system, and finally, a fuzzy mechanism for the estimation of irrigation.

**2.1. Measuring and Estimating the Volume of Water.** The soil used was characterized to obtain the parameters of Table 2, to identify the moisture levels percentage. With these properties field capacity is obtained, which is the volume of water that

TABLE 2: Soil properties.

Physical properties	Unit
Apparent density	0.93 g·cm <sup>-3</sup>
Wilting point	17.3%
Field capacity	55.8%
Chemical properties	Unit
Ph	5.88
C.E.	3.85 dSm <sup>-1</sup>

is capable of retaining the soil of 1.4 MLCM<sup>-2</sup>. Once known field capacity, using traditional irrigation scheme, a volume between 70% and 80% range is chosen to make growing Habanero pepper develop properly.

The proposed system can be integrated into an algorithm (Figure 2 and Algorithm 1).

To measure the volume the VH400-2M sensor is used. This element provides a signal from 0 to 3 V in accordance with soil moisture. It can be seen that the useful limits of the sensor are 50% (Figure 3).

The interpolation of the measured data results in

$$V = 4.2 \times 10^{-5} HS^3 - 0.0038 HS^2 + 0.1265 HS + 0.0888. \quad (1)$$

Equation (1) can be simplified for the range of interest, in order to reduce processing time, as indicated in the sensor data sheet, resulting in the linear relation (2). This equation is used to convert the voltage in a soil moisture value:

$$HS\% = 26.32V - 7.89. \quad (2)$$

In this way, with this sensor, the estimated lost soil moisture is obtained.

**2.2. Measurement of Relative Humidity and Temperature.** The measurement of relative humidity and temperature is performed by a sensor DHT11. This sensor is characterized by the calibrated digital signal. It consists of two resistive sensors

TABLE 3: Rules of the fuzzy system in the growth stage of the crop.

	Very few	Few	Temperature Medium	High	Very high
Humidity					
Very few	Medium	Medium	Long	Long	Very long
Few	Medium	Medium	Medium	Medium	Long
Medium	Short	Short	Short	Short	Medium
High	Very short	Very short	Very short	Very short	Very short
Very high	Very short	Very short	Very short	Very short	Very short

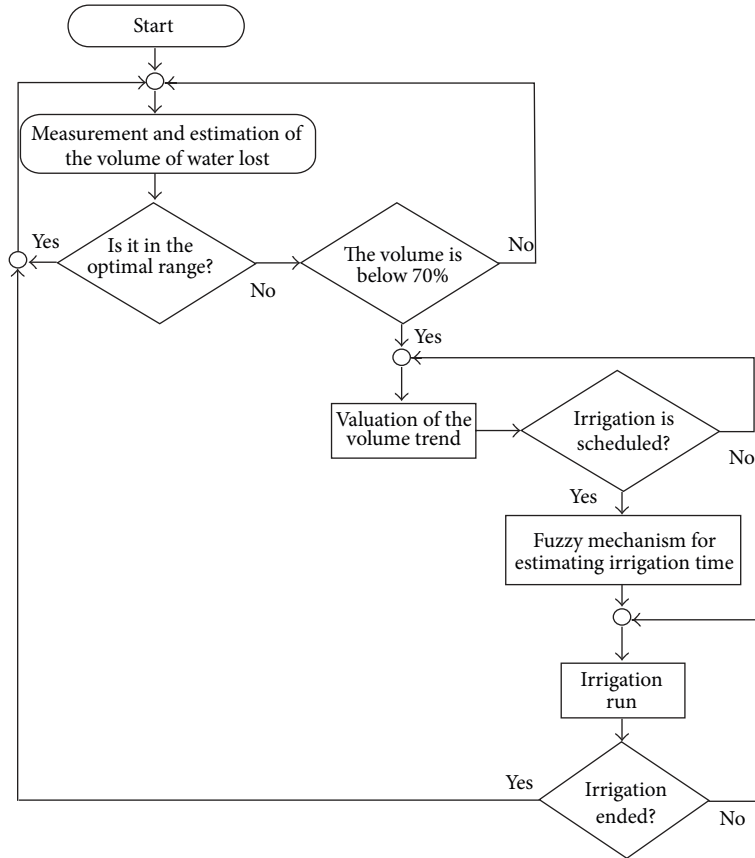


FIGURE 2: Algorithm that incorporated the fuzzy irrigation process.

(NTC and humidity) and a small 8-bit microcontroller. It can measure the humidity in the range 20%, approximately 95% and the temperature range between 0°C and 50°C. Protocol uses 1-wire communication, and the size is small and has low power consumption and the ability to transmit the signal up to 20 meters away.

### 2.3. Fuzzy System

**2.3.1. Fuzzy Rules.** A model for the climate behavior is too complex and the uncertainty is always present so the use of the fuzzy system in order to program an irrigation scheme is proposed. The fuzzy system uses the expert knowledge in form of rules to control the aperture time of the valve and therefor the water supplied. The knowledge base from the

expert provides the information necessary to perform the design of the irrigation program sequence, as well as the generation of the rules that are part of the fuzzy inference mechanism (see Table 3).

The proposed model employs Mamdani fuzzy mechanism described with MISO type fuzzy rules shown on the system equation

$$\begin{aligned}
 R^1 &: \text{If } u_1 \text{ is } A_1^j, u_2 \text{ is } A_2^k, \dots, u_n \text{ is } A_n^l \text{ then } y_1 \text{ is } B_1^r, \\
 R^j &: \text{If } u_1 \text{ is } A_1^j, u_2 \text{ is } A_2^k, \dots, u_n \text{ is } A_n^l \text{ then } y_j \text{ is } B_j^r, \quad (3) \\
 R^m &: \text{If } u_1 \text{ is } A_1^j, u_2 \text{ is } A_2^k, \dots, u_n \text{ is } A_n^l \text{ then } y_m \text{ is } B_m^t,
 \end{aligned}$$

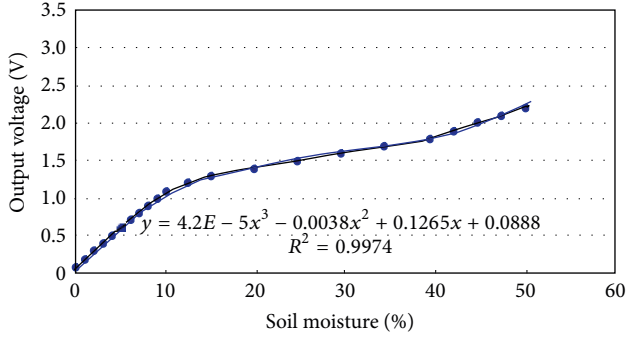


FIGURE 3: Humidity sensor characterization.

where  $A_i^j, A_2^k, \dots, A_n^l$  and  $B_j^s$  for  $R^j$ , represent the corresponding linguistic values [18]. The processing block consists of a hardware Arduino microcontroller which is the Atmel 328p, where the irrigation program established by the fuzzy rules is stored.

**2.3.2. Fuzzy Sets.** The linguistic variables to form the fuzzy sets are as follows.

(i) *Temperature.* Due to the warm air in the shadow house infrastructure is retained, and an important consideration in the cultivation under protected conditions is the temperature factor, because it favors the evaporation of water and has an important impact in the crop. The low technification of this structure only can provide air movement through the roof doors or the antiaphid mesh around of him.

(ii) *Relative Humidity.* The humidity factor has great influence on the crop. Excess moisture in habanero pepper plants affects its development, so it should not be given water to the crop when the humidity is high; however, when the humidity decreases, it is necessary to supply water to the plant.

(iii) *Stages of the Crop.* Growth stages ( $K_c$ ) influence the development of the plant, especially considering that the habanero pepper is a plant that requires large amounts of water, which ultimately affects the quality of the fruit. This is an important factor for the habanero pepper because, to obtain designation of origin, you must have certain characteristics of the fruit at harvest.

(iv) *Irrigation Time.* The output of the fuzzy system is the irrigation time and represents the run time in minutes. The frequency of watering time keeps the amount of water needed to avoid crop water stress.

In order to convert the linguistic variables on fuzzy numbers, this paper proposes the calculation of intermediate values of the linguistic range through the triangular function (4), while outliers are modeled by the Gamma function, left

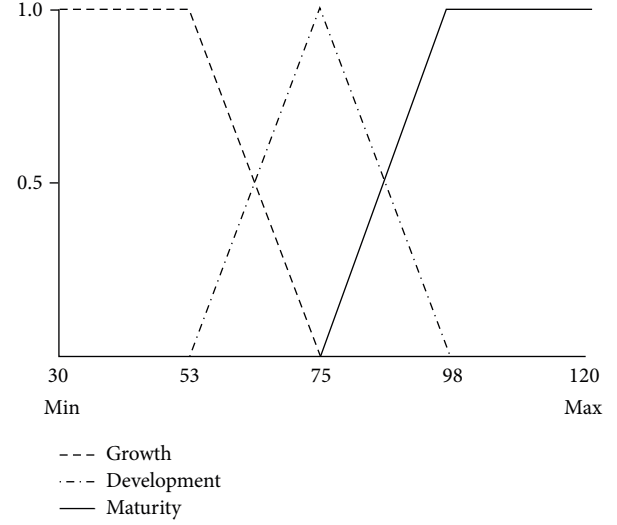


FIGURE 4: Input sets for the variable stage of development.

part of the linguistic rang (5), and  $L$  function, right part of the linguistic range (6):

$$\mu(x; a, m, b) = \max \{ \min \{ (x - a)(m - a) - 1, (b - x)(b - m) - 1 \}, 0 \}, \quad (4)$$

$$\mu(x) = \begin{cases} 0 & x \leq a \\ (x - a)(m - a)^{-1} & x \in (a, m) \\ 1 & x \geq m. \end{cases} \quad (5)$$

The membership function is created with expert knowledge and adopts a graphic form determined according to the type of value associated with the fuzzy set. The  $L$  and Gamma functions correspond to the membership functions, which are used to calculate extreme fuzzy values. Therefore, the  $L$  function is defined by

$$L = 1 - \text{Gamma}. \quad (6)$$

The graphic form of the linguistic variables, defined by the last equations, is shown in Figures 4, 5, 6, and 7.

**2.3.3. Inference Mechanism.** The inference mechanism has two basic tasks, determines the relevance and extent of each rule in relation to the current entries ( $u_i$ ), and generates the corresponding conclusions. The combination of the sets of rules with inputs can be calculated as follows:

$$\begin{aligned} \mu_{\tilde{A}_1^j}(u_1) &= \mu_{A_1^j}(u_1) * \mu_{\tilde{A}_1^{\text{tuz}}}(u_1) \\ \mu_{\tilde{A}_2^k}(u_2) &= \mu_{A_2^k}(u_2) * \mu_{\tilde{A}_2^{\text{tuz}}}(u_2) \\ &\vdots \\ \mu_{\tilde{A}_n^l}(u_n) &= \mu_{A_n^l}(u_n) * \mu_{\tilde{A}_n^{\text{tuz}}}(u_n). \end{aligned} \quad (7)$$

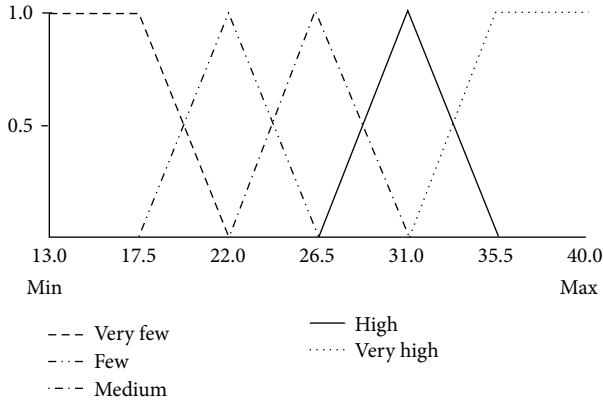


FIGURE 5: Input sets for the variable relative humidity.

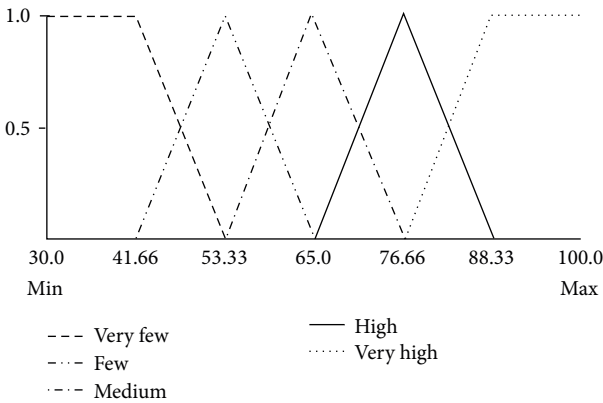


FIGURE 6: Input sets for the variable temperature.

The result is a set with the “fired” rules. To obtain a crisp value that can be applied to the valve, it will be necessary to calculate the center of the graph, and this can be done by

$$y = \frac{\int_y \mu(y) y dy}{\int_y \mu(y) dy}. \quad (8)$$

**2.4. Data Acquisition System.** The proposed communication system includes a basic structure that can be used in agricultural environments, and this proposal aims to organize the sections of a sensor network and facilitates the selection of technologies required to implement the ZigBee network. The communication system uses IEEE802.15.4 protocol (ZigBee), which was implemented on an Arduino board with XBee Pro module of Maxstream, configured with a PAN ID 3332, a rate of 9600 baud, 8 data bits, and no parity (see Figure 8).

The structure presented is divided into two sections, an internal, for data collection (sensor network), and an external, that can send information to central computers to store and/or process information. The internal section is composed of elements that collect information from the agricultural parameters of interest, such as temperature, relative humidity, and soil moisture (sensors), the data collected will be sent to devices for processing through the ZigBee protocol, which

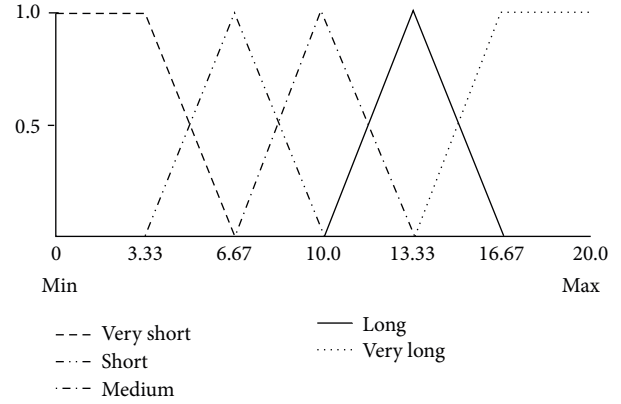


FIGURE 7: Output sets for the variable irrigation time.

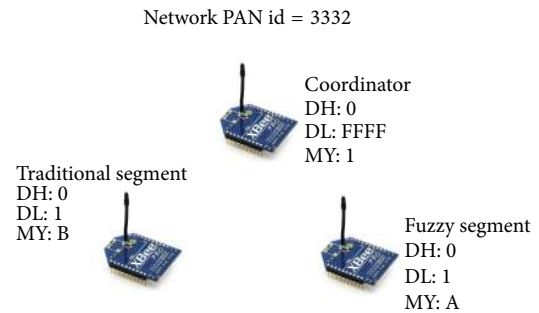


FIGURE 8: Sensor network.

is used for transmission (end devices). The internal section can be implemented through Arduino boards with Xbee modules. In the transmission of information, the router node will receive the information of the end devices and will be transmitted to the coordinator for central processing, in order to be able to connect to a larger network. The external section is composed of central processing devices sending data to remote nodes via Ethernet, WiFi, mobile devices, or other means that can send information to other locations as shown in Figure 9.

The data acquisition is made with a Duemilanova Arduino, and this platform is programed for a sampling rate of 5 minutes. Each value from the corresponding sensor has an header for identification, as shown in Algorithm 2. These data are linked with the Xbee devices for the transmission to the other Xbee configured like a coordinator.

To get data from the serial port that the Xbee Shield (Coordinator) is sending, we program methods as can be seen in Algorithm 3, and the header of each data frame is defined so that it recognizes and takes the indicated action for storage at the database every time that receives data (Algorithm 4).

### 3. Results and Discussion

The behavior of the proposed system was supervised from March to May 2013; this corresponds to all cycle of crop. Tables 4(a), 4(b), and 4(c) show the average values acquired from the system. The results obtained are compared with

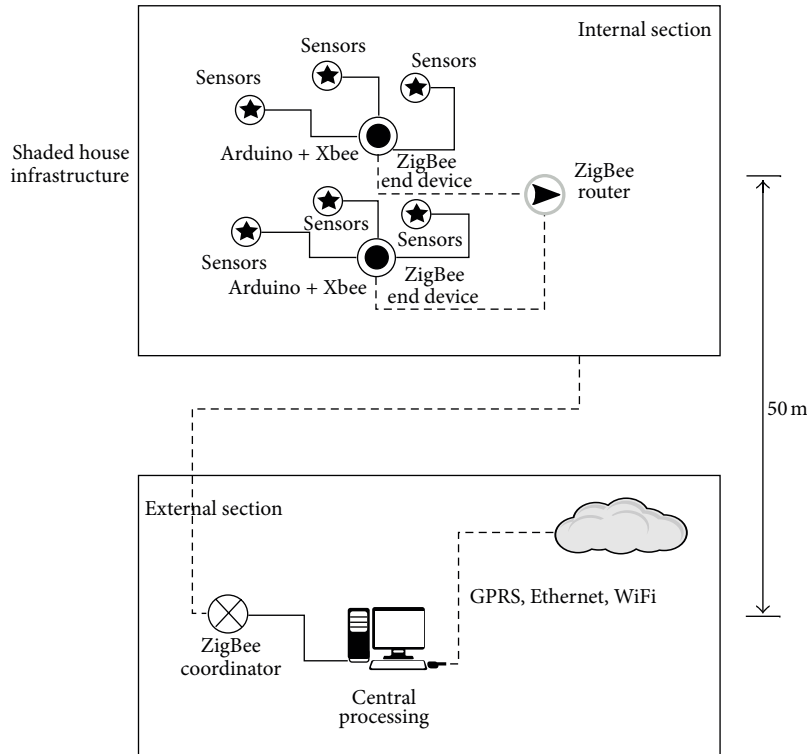


FIGURE 9: Internal and external sections.

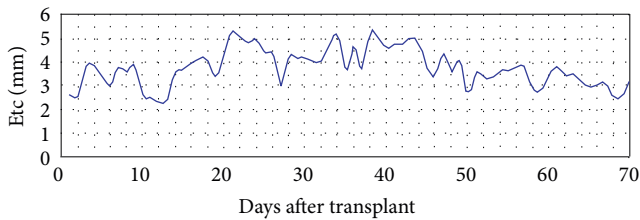


FIGURE 10: Evapotranspiration values for the crop cycle.

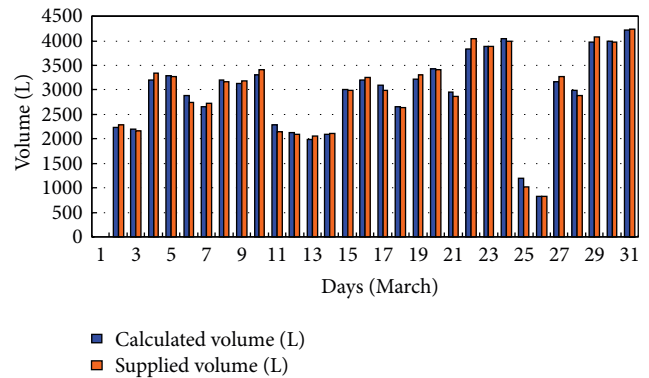


FIGURE 11: Comparison between traditional irrigation and the fuzzy system (March, 2013).

the results of calculations performed for the water loss by evapotranspiration reference (Eto), as shown in the work of Pérez-Gutiérrez et al. [19]. The comparison between fuzzy systems of irrigation and traditional irrigation was performed to validate the data obtained.

The Etc shows values that are in an interval of  $3 \text{ mm} \cdot \text{day}^{-1}$  (Figure 10). This range is stable for all the harvest period, if variations of the Etc were more spacious and then should take into account a greater number of variables therefore; by maintaining a controlled environment with the use of the shadow house, we can use a small number of sensors, and in this proposal the use of three of them is enough to estimate the irrigation.

The system showed a deviation of +0.11% in March, -0.39% in April, and +0.51% in May (Figures 11, 12, and 13). The supplied volume by the fuzzy system is compared with the calculated volume, resulting in a small deviation; therefore, we can establish the reliability of the system.

With the fuzzy system validated, the analysis of the data for each month can be made. As part of the validation sample March 20 is shown. In Figure 14, the frequency of irrigation during the day is graphed.

According to the data obtained with respect to the frequency of irrigation, Figure 14 shows that the frequency of irrigation is higher in the time period between 10:30 and 13:00; in this period, we can observe an increase trend in the temperature (Figure 15) and a low relative humidity (Figure 16), indicating a water accumulation in the soil; therefore, a balance between evapotranspiration and the water applied to the crop is generated.

TABLE 4: (a) Data from the month of March for the cycle of crop. (b) Data from the month of April for the cycle of crop. (c) Data from the month of May for the cycle of crop.

(a)											
March											
Day	Etc (mm·dia <sup>-1</sup> )	Fuzzy IrrigTime (min·dia <sup>-1</sup> )	SuppliedVol Fuzzy (l·dia <sup>-1</sup> )	SuppliedVolTrad (l·dia <sup>-1</sup> )	Day	Etc (mm·dia <sup>-1</sup> )	Fuzzy IrrigTime (min·dia <sup>-1</sup> )	SuppliedVol Fuzzy (l·dia <sup>-1</sup> )	SuppliedVolTrad (l·dia <sup>-1</sup> )	SuppliedVol Fuzzy (l·dia <sup>-1</sup> )	SuppliedVolTrad (l·dia <sup>-1</sup> )
2	2.58425473	13.413409	223.5568182	202.9668918	17	3.57783512	16.811918	280.1986364	281.0025131	280.1986364	281.0025131
3	2.57725364	10.913627	181.8937879	202.4170272	18	3.07273124	14.404782	240.079697	241.3317471	240.079697	241.3317471
4	3.70449566	15.902236	265.0372727	290.9504086	19	3.73218858	17.796109	296.6018182	293.1254056	296.6018182	293.1254056
5	3.84566297	18.2036	303.3933333	302.0376637	20	3.96009363	18.436127	307.2687879	311.0250267	307.2687879	311.0250267
6	3.33154632	14.9705	249.5083333	261.659036	21	3.4154618	15.833791	263.8965152	268.2497426	263.8965152	268.2497426
7	3.07303393	14.569518	247.2201515	241.3555204	22	4.4459937	22.096245	368.2707576	349.1875286	368.2707576	349.1875286
8	3.70648946	17.890227	298.1704545	291.1070015	23	4.50743937	21.169736	352.8289394	354.0134599	352.8289394	354.0134599
9	3.62726428	17.962364	299.3727273	284.8846704	24	4.67591342	21.811636	363.5272727	367.2453809	363.5272727	367.2453809
10	3.83003911	18.524945	317.4921212	300.8105683	25	1.3804632	5.6689909	94.48318182	108.4213265	94.48318182	108.4213265
11	2.65560684	11.413364	190.2227273	208.5708733	26	0.96752606	4.5595818	75.9930303	75.98931903	75.9930303	75.98931903
12	2.47468837	11.749273	199.9775758	194.3615697	27	3.66104898	17.867809	297.7968182	287.5381141	297.7968182	287.5381141
13	2.31084615	11.122518	185.375303	181.4934321	28	3.46753609	15.760455	262.6742424	272.3396476	262.6742424	272.3396476
14	2.42255034	10.806673	180.1112121	190.2666591	29	4.60879854	22.293755	371.5625758	361.9741905	371.5625758	361.9741905
15	3.49001336	16.748164	279.1360606	274.1050084	30	4.62318448	21.561836	359.3639394	363.1040596	359.3639394	363.1040596
16	3.69959684	17.351655	289.1942424	290.5656565	31	4.88327963	22.941936	382.3656061	383.5318856	382.3656061	383.5318856

(b)											
April											
Day	Etc (mm·dia <sup>-1</sup> )	Fuzzy IrrigTime (min·dia <sup>-1</sup> )	SuppliedVol Fuzzy (l·dia <sup>-1</sup> )	SuppliedVolTrad (l·dia <sup>-1</sup> )	Day	Etc (mm·dia <sup>-1</sup> )	Fuzzy IrrigTime (min·dia <sup>-1</sup> )	SuppliedVol Fuzzy (l·dia <sup>-1</sup> )	SuppliedVolTrad (l·dia <sup>-1</sup> )	SuppliedVol Fuzzy (l·dia <sup>-1</sup> )	SuppliedVolTrad (l·dia <sup>-1</sup> )
1	3.961718653	18.771482	312.8580303	311.1526554	16	3.99938767	17.371336	289.5222727	314.111173	289.5222727	314.111173
2	4.169559209	25.227564	420.4593939	327.4764145	17	4.09686903	19.2428	320.7133333	321.7673412	320.7133333	321.7673412
3	4.048530602	18.909436	315.1572727	317.9708499	18	4.71907325	21.807836	363.4639394	370.6351464	363.4639394	370.6351464
4	3.418113126	15.290055	254.8342424	268.4579772	19	5.057651274	22.931773	382.1962121	397.2270022	382.1962121	397.2270022
5	4.344343997	20.729182	345.4863636	341.2039796	20	3.687610895	14.040036	234.0006061	289.6242824	234.0006061	289.6242824
6	5.216459781	24.479782	407.9963636	409.6997931	21	4.583233577	21.846064	364.1010606	359.9663234	364.1010606	359.9663234
7	5.021289634	23.754855	395.9142424	394.3711656	22	3.708343758	17.238536	287.3089394	291.2526377	287.3089394	291.2526377
8	4.818401971	25.410745	423.5124242	378.4364058	23	5.197175777	24.6604	411.0066667	408.185231	411.0066667	408.185231
9	4.929600332	23.378527	389.6421212	387.1699047	24	5.013674745	23.637727	393.9621212	393.7730937	393.9621212	393.7730937
10	4.425304818	20.769664	346.1610606	347.5626276	25	4.604622494	21.392809	356.5468182	361.646205	356.5468182	361.646205
11	4.304687447	20.112073	335.2012121	338.0893615	26	4.715697984	22.946236	382.4372727	370.3700535	382.4372727	370.3700535
12	3.030269642	14.473727	241.2287879	237.9968211	27	4.767017231	22.359845	372.6640909	374.4006578	372.6640909	374.4006578



(b) Continued.

April									
Day	Etc (mm·día <sup>-1</sup> )	Fuzzy IrrigTime (min·día <sup>-1</sup> )	SuppliedVol Fuzzy (l·día <sup>-1</sup> )	SuppliedVolTrad (l·día <sup>-1</sup> )	Day	Etc (mm·día <sup>-1</sup> )	Fuzzy IrrigTime (min·día <sup>-1</sup> )	SuppliedVol Fuzzy (l·día <sup>-1</sup> )	SuppliedVolTrad (l·día <sup>-1</sup> )
13	4.228506725	19.813964	330.2327273	332.1061416	28	4.9999503	23.134864	385.5810606	392.6951783
14	4.199469641	21.049973	350.8328788	329.8255743	29	4.685183652	22.165509	369.4251515	367.9734635
15	4.13400889	18.688127	311.4687879	324.6842989	30	3.708190798	17.870818	297.8469697	291.2406242

(c)

May									
Day	Etc (mm·día <sup>-1</sup> )	Fuzzy IrrigTime (min·día <sup>-1</sup> )	SuppliedVol Fuzzy (l·día <sup>-1</sup> )	SuppliedVolTrad (l·día <sup>-1</sup> )	Day	Etc (mm·día <sup>-1</sup> )	Fuzzy IrrigTime (min·día <sup>-1</sup> )	SuppliedVol Fuzzy (l·día <sup>-1</sup> )	SuppliedVolTrad (l·día <sup>-1</sup> )
1	3.48400241	16.046282	267.43803	273.632909	14	2.81323798	12.056146	200.935758	220.951194
2	4.28945109	19.954027	332.567121	336.892701	15	3.45795001	15.992027	266.533788	271.586759
3	3.64868417	17.514855	291.914242	286.566985	16	3.76349121	17.962409	299.373485	295.583908
4	4.00339841	19.0312	317.186667	314.426176	17	3.41760316	16.101982	268.366364	268.417925
5	2.70640388	12.413646	206.894091	212.560464	18	3.43767282	15.971582	266.19303	269.994192
6	3.51451778	16.295346	271.589091	276.029581	19	3.13612887	15.119536	251.992273	243.822456
7	3.29792176	16.091009	268.183485	259.01817	20	2.93326251	14.367546	239.459091	246.310986
8	3.35111737	15.496273	258.271212	263.196142	21	3.05215788	13.911227	231.853788	230.377899
9	3.58129742	16.387591	273.126515	281.274442	22	3.04887854	14.010273	233.504545	239.715919
10	3.65825019	17.664609	294.410152	287.318298	23	2.52884747	15.035646	250.594091	239.458361
11	3.77619727	17.437236	290.620606	296.58184	24	2.52884747	11.3733	189.555	198.615216
12	3.73897867	17.908982	298.48303	293.658698	25	3.20855932	15.548046	259.134091	251.999659
13	2.83378267	13.126791	218.779848	222.564771					

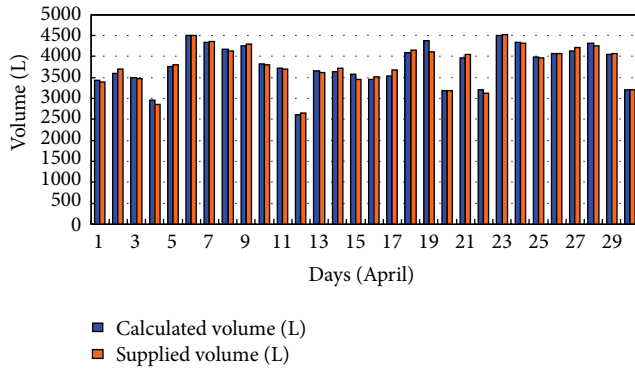


FIGURE 12: Comparison between traditional irrigation and the fuzzy system (April 2013).

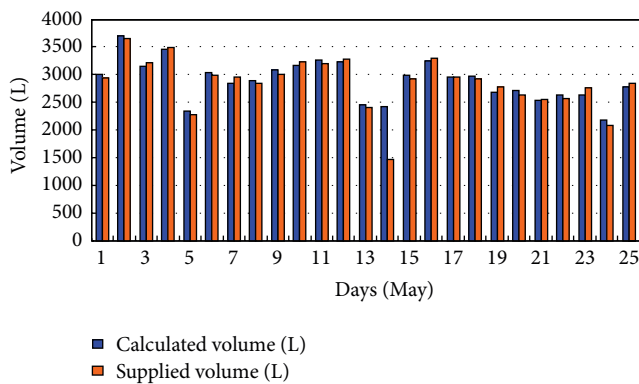


FIGURE 13: Comparison between traditional irrigation and the fuzzy system (May 2013).

These results establish the reliability of the proposed system to provide adequate water and maintain optimum moisture level with low relative humidity, to obtain the desirable quality of habanero pepper production.

In the work of Ortiz et al. [20], the percentage of optimum soil moisture for growing good quality fruits is 60%; the fuzzy system employs the percentage of 70% indicated by the expert so that it is possible to also set the reliability in the final quality of the fruit. The work presented by Pérez-Gutiérrez et al. [19] mentioned that the volume of water applied to 80% of potential evapotranspiration generates the amount of water in the soil to favor a constant process of transpiration, fruit yield, and improvement of water use; this requires a water volume  $2223 \text{ m}^3 \text{ ha}^{-1}$ ; however, the fuzzy system only requires  $449.95 \text{ m}^3 \text{ ha}^{-1}$ , which represents a saving of 79.8% water.

The proposed system is a better form to schedule irrigation; unlike Yao et al. [16], the objective is to give to the poor communities a form to harvest a high demand product like habanero pepper (with designation of origin) with enough technologic structure. The work of Yao et al. [16] is using a neural network to refine the sprinkle time based on a pattern that is not described in the paper; in a real environment especially in Yucatan, Mexico, the humidity and temperature variables have to be considered, to obtain a quality product

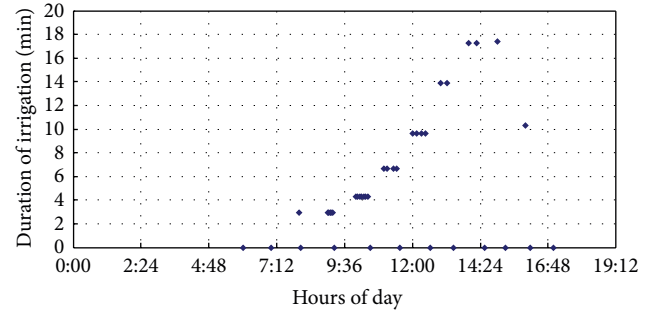


FIGURE 14: Irrigation frequency using the fuzzy system (sample of 20 March 2013).

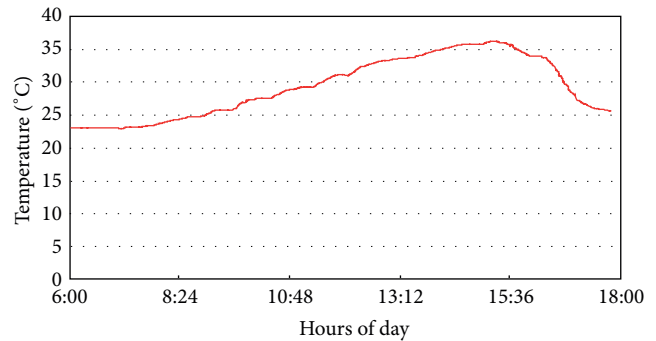


FIGURE 15: Temperature measurement (sample of 20 March 2013).

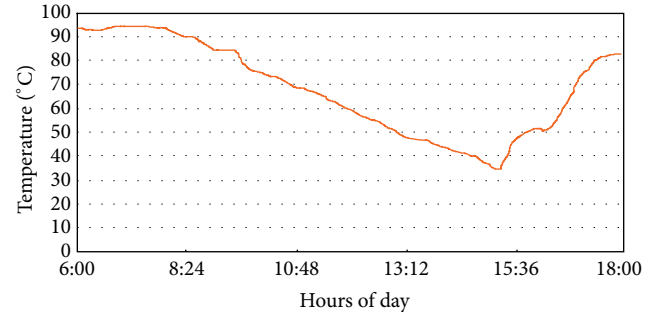


FIGURE 16: Measurement of relative humidity (sample of 20 March 2013).

and, unlike the work of Yao et al. [16], in this work are taken into account in the fuzzy model and in the expert knowledge. The use of a neural network is not a significant contribution for managing the time of irrigation on a shadow house because there are no other important variables included, and in the Yao et al. [16] proposal only the soil moisture and the error are considered to set the irrigation time.

#### 4. Conclusions

This paper has presented a fuzzy system that manages a wireless irrigation scheme through an algorithm that takes into account the conditions of microclimate of a shadow house used for growing habanero pepper with designation of origin in the state of Yucatan. The water volume consumed,

```

float h = dht.readHumidity( );
float t = dht.readTemperature( );
    // revisa si retorna un valor valido, de lo    //contrario hay un error
if (isnan (t) || isnan (h)) (
    Serial.println ("Failed to read from DHT");
) else (
    String hume = "Humedad: ";
    Serial.println (hume + h + "% de Humedad");
    String tempe = "Temperatura: ";
    Serial.println (tempe + t +" Grados Centrigrados ");
)

```

ALGORITHM 2: Section of the Arduino code.

```

SerialPort conectar = new SerialPort ("COM4", 9600);
conectar.Open( );
while (!_shouldStop)
{
    if (conectar.BytesToRead > 0)
    {
        string t = conectar.ReadLine( );
        string h = conectar.ReadLine( );
        string m = conectar.ReadLine( );
        string texto;
        t = t.Replace("\r", "");
        resp_text.Text = t;
        hume_text.Text = h;
        mov_text.Text = m;
        if (t.StartsWith("Temperatura: "))
        {
            Texto = t;
            t = t.Replace("Temperatura: ", "");
        }
        else{ resp_text.Text = ""; }
        if (h.StartsWith("Humedad: "))
        {
            texto = h;
            h = h.Replace("Humedad: ", "");
        }
        else{ hume_text.Text = ""; }
    }
}

```

ALGORITHM 3: Application connection.

according to the graphic that shows the comparison between the volume of water from the system and the manual or traditional volume, gives us a difference of 79.8% over the best result shown in Pérez-Gutiérrez et al. [19], which shows that the system can efficiently manage water and that incorporation of the expert knowledge in fuzzy rules allows irrigation scheme without using the pan evaporation or calculating the volume associated with irrigation, as they can be automatically supplied without the crop being adversely affected in its development. Saving water is about 152482.3 m<sup>3</sup> for a crop of 1000 plants in an 85-day cycle, causing transplantation at the 30th day. The microclimate conditions generated by the infrastructure of shadow house are not exploited by the lack

of modernization, that is, a producer who does not have the ability to use technology to irrigate their crops, generally only considered during the morning or afternoon, which does not guarantee the product quality, since plants could fall in either water stress or excess moisture. However, the proposed system allows for irrigation supply data from three common sensors (temperature, relative humidity, and soil moisture), allowing similarly for reducing infrastructure costs.

### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

```

public void bd.tempe( )
{
    SqlConnection con = new SqlConnection();
    con.ConnectionString = @"Data Source=DAVIDSERVER\SQLEXPRESS;
Initial Catalog=ARDUINO;Integrated Security=True";
    try
    { con.Open( ); }
    catch (SqlException ex)
    {
        MessageBox.Show(ex.Message);
        throw;
    }
    string tiempo = DateTime.Now.ToString( );
    SqlCommand instruccion = con.CreateCommand( );
    instruccion.CommandText = " insert into tempe(hora,temperatura)
values ('" + tiempo + "',' " + txt.tempe.Text + "')";
    instruccion.ExecuteNonQuery( );
    con.Close( );
}

```

ALGORITHM 4: Database connection.

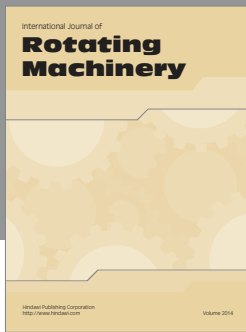
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