DEVELOPMENT AND EVALUATION OF AN ENERGY AND WATER EFFICIENT INTENSIVE CROPPING SYSTEM

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توسعه و ارزیابی یک سامانه کشت متمرکز با بازده بالای آب و انرژی

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Nomenclature			
AccET	*Accumulated ET*	*MPPT*	*Maximum power point tracker*
AW	*Available water*	*PAR*	*Photosynthetically active radiation*
CATIA	*Computer aided three-dimensional interactive application*	*RAW*	*Readily available water*
CELSS	*Controlled ecological life support systems*	*SARCS*	*Solar auto-irrigation rotary cropping system*
CriET	*Critical ET*	*A*	*Solar panel area*
ET	*Evapotranspiration*	P_{AC}	*Photovoltaic panel nominal AC power*
FC	*Field capacity*	P_{DC}	*Photovoltaic panel nominal DC power*
GUI	*Graphical user interface*	R_{yr}	*Yearly peak sun hours*
LED	*Light-emitting diode*	μ_p	*Panel efficiency*
MAD	*Maximum allowable depletion*		

ABSTRACT

The current strategies of crop production beside the current status of energy and water resources are believed to be hardly capable of addressing the increasing global food demand. Using low-input, high-output crop production systems, therefore, could be a good answer to these problems. To address this challenge, a water and energy efficient intensive rotary hydroponic cropping system was developed. Plants in the area of an open-ended rotary drum take water from a chamber beneath the drum and grow inward toward a set of illuminating LEDs embedded at the drum horizontal axis. This system included an embedded irrigation unit which used plants' evapotranspiration fuzzy predictions for irrigating plants based on their water requirements, and an array of solar photovoltaic panels as the main source to supply renewable, clean energy. The system was evaluated in a low-irradiance season by growing lettuce in fuzzy-based and ordinary irrigation modes. According to the results, the average daily lettuce plants' ET in fuzzy mode was about 2.18 L. The solar unit could supply an average of about 52% of annual energy requirement and about 50% of energy requirement in low-irradiance days of winter. To produce one kilogram of marketable lettuce, fuzzy-based mode required 43% less area, 56% less water, and 74% less energy, compared to ordinary mode. Compared to open field method of lettuce planting, plants were 12 times denser and water usage was approximately 15 times less.

چکیده

روش های تولید محصول در حال حاضر در کنار وضعیت انرژی و منابع آب به سختی می تواند نیاز روزافزون غذای جهانی را تامین کند. استفاده از سیستم هایی با نهاده پایین و محصول زیاد می تواند یکی از راه حل های این مساله باشد. با توجه به این مساله، یک سیستم کشت هیدروپونیک دوار با بازده بالای آب و انرژی توسعه داده شد. گیاهان کشت شده در محیط یک استوانه، آب را از مخزن پایین استوانه کشیده و با تامین نور توسط LED هایی که در راستای محور استوانه قرار گرفته به سمت مرکز استوانه رشد می کنند. این سیستم از یک واحد آبیاری که از تخمین فازی مبتنی بر تبخیر و تعرق استفاده می کند تا مقدار آب مورد نیاز گیاه را تشخیص بدهد، تشکیل شده است. یک آرایه خورشیدی برای تامین توان سیستم از انرژی پاک مورد استفاده قرار گرفت. سامانه توسعه داده شده در یک فصل با تابش کم و با کاشت کاهو به دو صورت فازی و روش آبیاری معمولی مورد ارزیابی قرار گرفت. مطابق بررسی ها، مقدار متوسط تبخیر-تعرق، گیاه کاهو روزانه حدود 2/18 L بود. واحد خورشیدی حدود 52% انرژی سالانه و حدود 50% انرژی مورد نیاز را در روزهای کم تابش زمستان فراهم می نماید. برای تولید یک کیلوگرم کاهوی قابل ارائه به بازار، در مقایسه با روش معمول آبیاری، روش مبتنی بر سیستم فازی، 43% مساحت کمتر، 56% آب کمتر و 74% انرژی کمتری نیاز دارد. در مقایسه با تولید کاهو در مزرعه، کشت گیاه 12 برابر متراکم بوده و مصرف آب حدود 15 برابر کمتر است.

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INTRODUCTION

The global increase in food demand and challenges in water, energy and fertile soil resources has made it clear that the current farming practices are no longer effective. So, pursuing new strategies and novel farming methods is an inescapable decision in food safety and sustainable agriculture management. These methods aim at producing maximum yield with minimum inputs and minimum dependencies to seasonal and climatic changes. Among all practices, intensive indoor planting like hydroponic approaches with a potential to increase productivity and easily adaptable to automatic control systems provide opportunities to achieve this objective. In recent decades, intensive production systems have commanded considerable attention. In early 1980’s, hydroponic based production developed rapidly. In 1991, about 5000 ha out of 62600 ha of greenhouses in the European Union was under hydroponic culture (*Roustaee, 2009*).

On the other hand, agriculture, as a major source of water usage, needs to be equipped with water management and water saving strategies. More than 99% of water delivered to plants is said to be lost by evapotranspiration (ET) (*Alizadeh, 2011*). So, prediction of ET can be a suitable measure for irrigation management goals. With the nonlinear and complex nature and dependency on various climatic and vegetal parameters (*Entesari, 2007)*, this phenomenon is very difficult to be estimated precisely (*Alizadeh, 2011*). Therefore, the application of artificial intelligence techniques like fuzzy logic which leads to the development of suitable ET prediction models is appropriately justified. Among all methods, fuzzy inference systems (*Alavian, 2012; Moradi, 2012*), neuro-fuzzy networks (ANFIS) (*Cobaner, 2011; Hashemi Najafi, 2007; Kişi and Öztürk, 2007; Shiri et al., 2013*), fuzzy regression (*Shayannejad, 2008*) and geno-fuzzy methods (*Kişi, 2013*) are more considered by researchers.

Also, some studies have been conducted to implement intelligent irrigation systems using fuzzy logic. For example, Kia designed a fuzzy based irrigation setup in greenhouse such that the Penman-Monteith equation (*Allen et al., 1998*) was employed to measure ET. The differences between actual and optimum soil moisture were considered as the only input and the irrigation valve position was the only output for the fuzzy system (*Kia, 2009*). In another work, a fuzzy irrigation setup was implemented for growing pepper in a protected condition. A fuzzy model with temperature and relative humidity as inputs was responsible for determining irrigation duration to compensate for the lost water which was measured by a soil moisture sensor (*Martha-Rocio et al., 2015*). Finally, a fuzzy controller was employed in a greenhouse to cut the water usage in a drip irrigation system. The greenhouse temperature and the soil moisture were fuzzy inputs whereas irrigation time was considered as the fuzzy output (*Ed-Dahhak et al., 2013*).

Energy resources challenge is believed to be as important as water resources issue. This, in turn, has attracted so much attention and the need for clean, renewable sources of energies like solar is undeniable. There are numerous works regarding the utilization of solar energy in agricultural operations. In an attempt, a hybrid solar tractor which could perform some farming practices was designed. The solar system was able to provide up to 18% of total energy required (*Mousazadeh et al., 2010*). In another research, an intelligent fuzzy-based hybrid solar system was developed for heating a poultry hall with promising results (*Mirzaee, 2013*). Also, a solar dryer equipped with recycling air system and desiccant chamber was developed by researchers. The performance of this system was evaluated by drying mint vegetable (*Aghkhani et al., 2013*). An interesting work in this field was about designing semi-transparent photovoltaic modules mounted as roofs on the greenhouse to extract the needed energy of greenhouse from a solar resource (*Yano et al., 2014*). Application of solar energy for the development of an automated fertigation (irrigation + fertilization) control system in a greenhouse was reported in another work. Injectors and irrigation pumps were triggered by three digital timers to mix fertilizers and regulate irrigation cycle. It was calculated that the solar system was able to fulfil the system energy requirement up to seven days without adequate solar radiation (*Salih et al., 2012*).

The main goal of this study was to develop and evaluate an innovative climate-independent, water and energy-efficient indoor intensive vegetable production system. This was based on a rotary hydroponic cropping apparatus equipped with a solar energy extraction system and an ET-based fuzzy fertigation unit.

MATERIALS AND METHODS

The idea of rotational cropping was first innovated by Marchildon (*Marchildon, 2003*). This, in addition to other hydroponic planting systems, has been considered by NASA in the studies on Controlled Ecological Life Support Systems (CELSS) for producing vegetables in space.

The Solar Auto-irrigation Rotary Cropping System (SARCS) which was the base of this work had three major sub-systems; a) rotary hydroponic cropping unit, b) solar energy supply unit, and c) fuzzy-based irrigation unit. This system was developed in such a way to have minimum energy requirement extracted mainly from the clean solar energy resource. The embedded fuzzy-based irrigation unit was responsible for applying water purposefully by estimating ET using fuzzy logic. This, in turn, would cut the water consumption as well as the pumping energy. The schematic of SARCS components depicting the relationship between different parts of the system is shown in the Figure 1. The 3D of the system was modeled in CATIA and then was fabricated on a real scale.

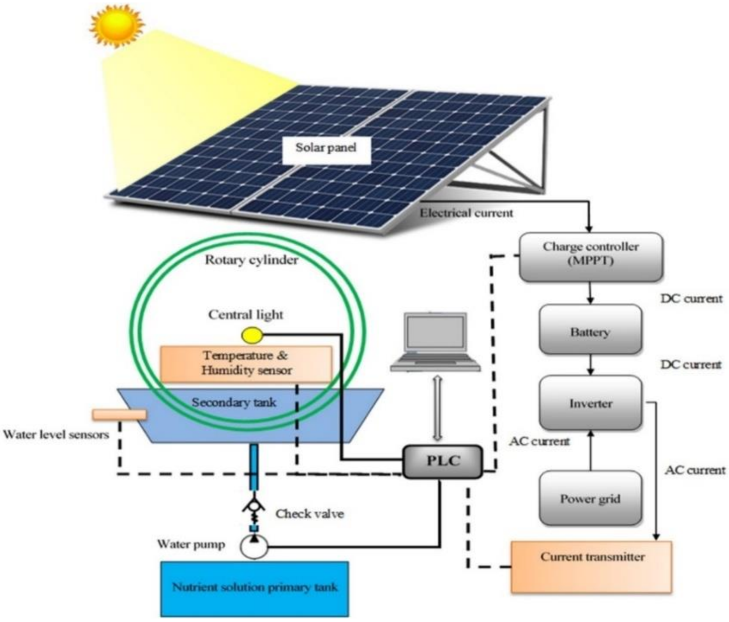

Fig. 1 - Schematic of SARCS components

Rotary planting sub-system

Rotary drum was one part of the system with 100 cm diameter and 80 cm length. These dimensions had influences on the rotation needed power, light received to plants, material costs, and other considerations. Accordingly, the acreage provided by this system was about 2.5 m^2, about 3 times more than flat planting. More than one drum may be positioned above or beside the current one to make more intensive planting structure and produce huge amount of vegetables in a minimum area (*Marchildon, 2003*). Planting trays embedded in a surface area of the drum contained grow bags filled with a mixture of perlite and coco peat to make a suitable substrate (*Hassandokht, 2012a*) for plants. This design caused plants to grow inward toward the drum central line where artificial light was positioned (Figure 2A). With minimum light dispersion to places out of the access of plants, this lighting scheme would ensure all plants get access to light equally and effectively which is more efficient, as compared to the ordinary flat cropping systems.

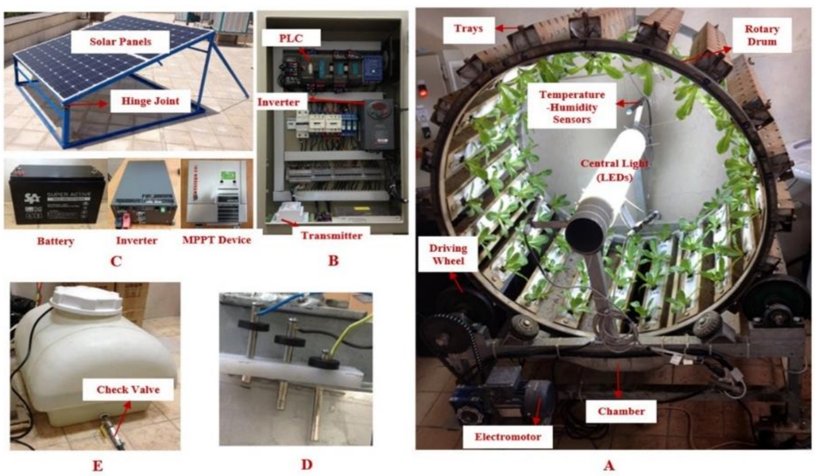

Fig. 2 - SARCS major components

A) Rotary cropping apparatus, B) Electrical parts and control unit, C) Solar unit components, D) Low-cost 3-electrod water level sensor mounted at the inner wall of chamber, E) Primary tank containing a submersible pump.

The drum rotates slowly by the aid of a chain drive and an electromotor. A driving wheel which was in contact with the drum, transmit the rotation to that (Figure 2A). A chamber was located beneath the drum so that the rotating plants take irrigation water while entering to it. This chamber is filled occasionally with nutrient solution by a submerged pump in a primary tank (Figure 2E). This method of irrigation removed the need for pipes, droppers, sprinklers, etc. which are common in irrigation systems.

Light and darkness periods for plants growth (photoperiod) was provided by automatic regulation of the light On/Off status. Central LEDs with low power requirement, water proof property and minimum heat generation were chosen to be applied as the artificial lighting unit instead of some ordinary sources like metal halide or sodium lamps. These, in addition to higher amount of power required, need more complex setup including a glass cover for droplets protection and also a fan to blow the produced hot air out of the system.

Provision of plants needed light spectrum which is defined by Photosynthetically Active Radiation (PAR) was the main factor for choosing LEDs. Different spectra with different number and arrangement of LEDs were tested in various literatures (*Chang and Chang, 2014; Morewane, 2014; Shimokawa et al., 2014; Wen et al., 2011; Yanagi et al., 1996*). The SARCS selected lighting system was comprised of 17 meters of strip LEDs thoroughly twisted around a 10-centimeter diameter cylinder. These provided white light with 150 W total power requirement and no need for fan or covering glass (Figure 2A).

Solar energy supply sub-system

Two 300 W mono-crystalline photovoltaic panels were connected in series to make a 600 W solar unit to serve the system (Figure 2C). The grid-tied panels were south-oriented and positioned on a frame with manual tilt angle changing mechanism to assure the maximum absorption of irradiance. The extracted solar energy was then saved on batteries after passing through a charge controller which tracks the maximum power point and is called MPPT device (Western, WRM30) (Figure 2C). The MPPT device uses a search algorithm for finding the maximum power point, regardless of load voltage and its charging condition *(Mousazadeh and Javanbakht, 2010)*. Since the current from panels was DC while loads needed AC power, an inverter (COTEK, ST1000-248) was employed (Figure 2C). This device also switched between the serving sources of energy (solar or grid power) when required. Four 12 V- 100 Ah sealed lead acid batteries in series were responsible for supplying solar energy. Solar irradiance was considered as the main source of energy supply when was adequate on batteries. Otherwise, grid power was employed by the inverter. So, this is a so-called “on-grid” solar unit. An AC single-phase transmitter (TM-1510-M) was used to measure the energy consumption of various parts of SARCS (Figure 2 B).

Estimation of the system energy requirement was the first step in designing the photovoltaic system. This was calculated by integrating each part’s power consumption on a daily basis. For SARCS, the power consuming parts including electromotor, lamp, water pump and other parts (electronic and controlling devices) used a total amount of 4600 Wh day^{-1} which, in turn, implied 1679 kWh year^{-1}. The next step of the solar system design accounted for determining the solar irradiance in the research location (Karaj, Iran: 35° 82′ N, 50° 97′ E). For this purpose, the concept of ‘peak sun hours’ (R_{yr}) was employed. The irradiance (kWh m^{-2} day^{-1}) is equivalent to ‘the number of daily pick hours (h day^{-1})’ in one Sun (kWh m^{-2}) *(Masterss, 2004*). To determine this parameter, the Karaj daily irradiance data were averaged over the year 2016 which was about 5.23 kWh m^{-2} day^{-1}. Thus, in standard condition (one Sun) the amount of irradiance was about 5.23 h day^{-1}. So, the AC power provided by the solar array in a standard solar irradiance (P_{AC}) was calculated by the Equation (1):

$$Energy\ (kWh/yr) = P_{AC}\ (kW) \times R_{yr}\ (h/day) \times 365\ (days/yr) \Rightarrow P_{AC} = \frac{1679}{5.23 \times 365} = 0.88\ \text{kW} \quad (1)$$

In order to include the effects of temperature, inverter efficiency, module inconsistency and dirt on DC to AC power conversion, a conversion efficiency of 0.75 was taken into account (*Masterss, 2004*). Therefore, the array nominal DC power in standard condition (P_{DC}) was calculated according to Equation (2):

$$P_{DC} = \frac{0.88}{0.75} = 1.17\ \text{kW} \quad (2)$$

In the next step, for the selected type of crystalline silicon modules, an efficiency of 12.5 ($\mu_p = 12.5$) was considered (*Masterss, 2004*). So, the theoretical needed panel area for standard condition was calculated by the Equation (3):

$$P_{DC} = 1\ \frac{kWh}{m^2} \times A\ (\text{m}^2) \times \mu_p \Rightarrow A = \frac{1.17}{0.125} = 9.36\ \text{m}^2 \quad (3)$$

Since each selected panel had 300 W of nominal power and a total amount of 1170 W of DC power was needed in standard condition, the total of 3.9 or 4 panels were needed to fulfil the annual SARCS energy requirement. Application of two solar panels in SARCS each with the 1.98×0.99 m^2 area would provide 3.92 m^2 area and the total energy provided would be calculated by the Equation (4):

$$Energy = 2 \times 0.3\ kW \times 0.75 \times 5.23\ (h/day) \times 365\ (days/yr) = 859.03\ kWh/yr \quad (4)$$

In another word, the SARCS solar sub-system was able to provide 51.16% of SARCS total annual energy requirement.

Fuzzy-based irrigation sub-system and the fuzzy model

The concept of irrigation in SARCS refers to water pumping to chamber in order to facilitate the access of rotating trays to water. Two irrigation modes were applied in SARCS. The first one (ordinary or non-fuzzy irrigation mode) was based on the water level in the chamber according to the low-cost, 3-electrode water level sensor (Figure 2D). This sensor represents high, low, and base level of water. Water pumping to the chamber terminates when the maximum desirable (touchable) water volume was sensed by the pre-set high-level sensor. Inversely, the pump was not triggered until water level dropped to the pre-set low-level sensor. In the second mode of irrigation (fuzzy mode) the irrigation event was predicted according to the ET-based plant water requirement estimations (regardless of the water level related to low-level sensor), so the pump was triggered to fill the chamber up to the high-level sensor. This mode of irrigation had variable frequency and variable duration, since the water level in the chamber differs in each irrigation event. Since substrate-filled grow bags were used to support the plants, there was no soil evaporation and, therefore, ET was limited to plant transpiration. 5-second intervals were considered for ET estimations. Estimated ETs were then accumulated/summed (AccET) until reaching critical ET (CriET), which, in turn, was considered as an equivalent to the substrate ‘readily available water’ (RAW). RAW, which ruled the irrigation time (pump triggering) was related to field capacity (FC) by Equation (5) (*Alizadeh, 2011*):

$$RAW = (2.3 + 0.37\ FC) \times MAD \quad (5)$$

where MAD was ‘maximum allowable depletion’. Greenhouse Romaine lettuce (Lactuca sativa L.) with MAD=0.3 was considered for SARCS performance evaluation. This parameter indicates that when ET causes substrate to lose 30% of water content between its FC and ‘crop extractable water’ (CEW), irrigation (water pumping) was needed to prevent plant water stress (*Alizadeh, 2011*). By applying a mixture of equal percent of perlite and coco peat (measured FC = 60.89%) as substrate, RAW was 7.45%. Considering the dimension of cropping trays in SARCS, the maximum root development depth was 6.8 cm and 7.45% of that was 5 mm. Since ET was based on a 0.84 m^2 area in the rotating drum, 5 mm depletion of water was equivalent to 4.22 L which implied the lost RAW. As a conservative decision, a depletion of 4 L was considered as CriET to trigger the irrigation pump.

A fuzzy logic approach was employed to estimate ET in 5-second intervals. Since SARCS was intrinsically an indoor cropping system, wind speed was negligible and the central light (LEDs) was the major lighting system. Therefore, ambient temperature and relative humidity (Rh) in addition to the light On/Off condition were considered as inputs to the fuzzy model, while 5-second ETs were its only output. The averaged readings of three integrated ambient temperature-humidity sensors which were tube-shaped (model SHT11) positioned in the rotary drum at 35-cm above the plants base (Figure 2A) was considered as two inputs. The third input (light condition) was basically dependent on photoperiod settings. Accordingly, 6:00 and 22:00 were respectively used for automatic switch on and off for the lights; this set a 16/8 photoperiod for lettuce planting. So, light had a 2-input mode to the fuzzy model.

Due to accuracy and generality of the triangular and trapezoidal membership functions, these were employed for the input and output parameters in the fuzzy model (*Teshneh Lab et al., 2013*). The membership functions and their range were depicted in Figure 3, where VL, L, M, H, and VH are stand for very low, low, medium, high, and very high, respectively. The principal properties of the developed fuzzy model are shown in the Table 1. MATLAB R2015a software was used for model development.

Table 1

Some properties of the developed fuzzy model for the prediction of 5-second ET

Model type	AndMethod	OrMethod	ImpMethod	AggMethod	DefuzzMethod
Mamdani	min	max	min	max	centroid

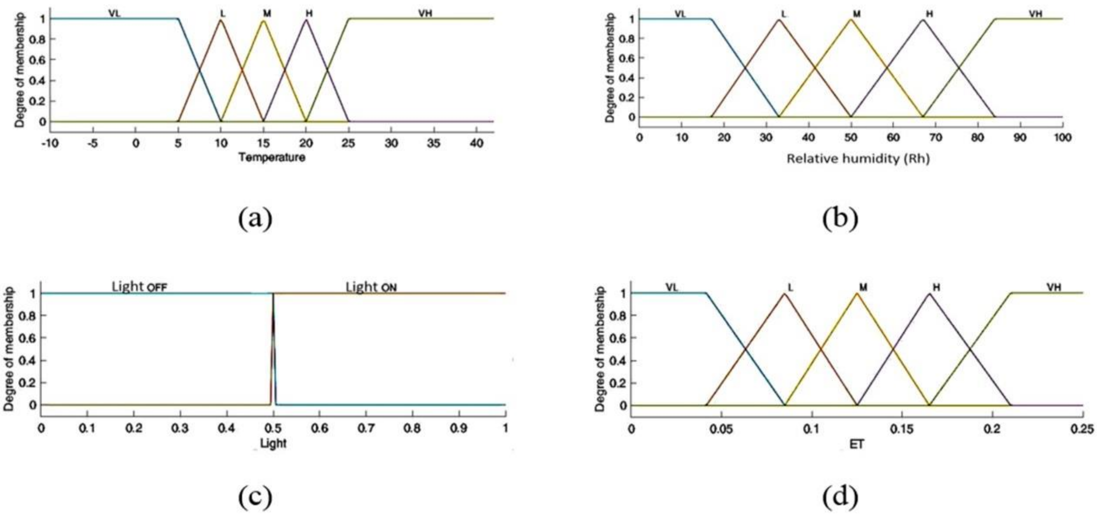

Fig. 3 - Membership functions of the fuzzy model inputs and an output;
(a): Temperature, (b): Relative humidity (Rh), (c): Light, and (d): 5-second ET.

Due to the choice of 5, 5, and 2 membership functions for temperature, relative humidity and light respectively, a maximum of 50 fuzzy rules could be considered which are presented in the Table 2. These rules were based on parameters evaluations, effects of inputs on output, experimental findings, experts' opinion etc.

Table 2

Fuzzy rules of the developed model for the prediction of ET

		Temperature-VH	Temperature-H	Temperature-M	Temperature-L	Temperature-VL
Light On	**Rh-VL**	ET-VH	ET-VH	ET-H	ET-H	ET-M
	Rh-L	ET-VH	ET-H	ET-M	ET-M	ET-M
	Rh-M	ET-H	ET-M	ET-L	ET-M	ET-L
	Rh-H	ET-M	ET-M	ET-L	ET-L	ET-L
	Rh-VH	ET-M	ET-M	ET-L	ET-L	ET-L
Light Off	**Rh-VL**	ET-VH	ET-H	ET-H	ET-M	ET-M
	Rh-L	ET-H	ET-H	ET-M	ET-M	ET-L
	Rh-M	ET-M	ET-M	ET-L	ET-L	ET-L
	Rh-H	ET-M	ET-L	ET-L	ET-VL	ET-VL
	Rh-VH	ET-L	ET-L	ET-L	ET-VL	ET-VL

The fuzzy model controlling surface for the prediction of 5-second ET is depicted in Figure 4. This figure illustrates the trends and the relationships between the fuzzy model inputs and output, according to the fuzzy rules.

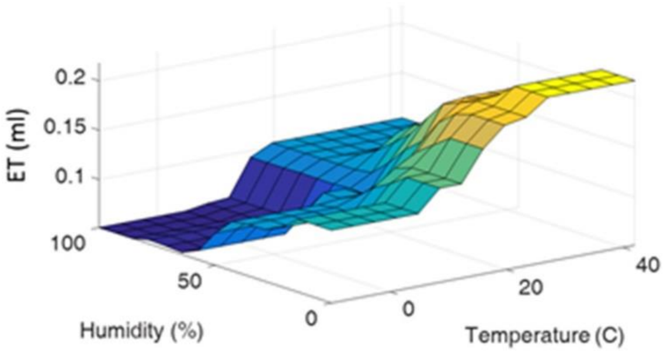

Fig. 4 - The output of fuzzy model controlling surface for the prediction of ET

Performance evaluation of SARCS

In order to test the different SARCS parts and sub-systems, lettuce with 3-5 leaves were transplanted in SARCS in low-irradiance season (Dec. 2016 to Feb. 2017) and two irrigation modes (fuzzy-based and ordinary) with a same predefined photoperiod were separately tested.

Hoagland nutrient solution was prepared for supplementing plant needed elements. A total number of 80 lettuce transplants (4 in each tray), were transplanted in each treatment and fuzzy treatment was launched just after ordinary treatment products were harvested. Both treatments lasted 33 days and investigations on environmental parameters as well as evaluations of fuzzy ET estimations, water, and energy use efficiencies, and crop yields were conducted based on the measurements and acquired data by GUI (Figure 5).

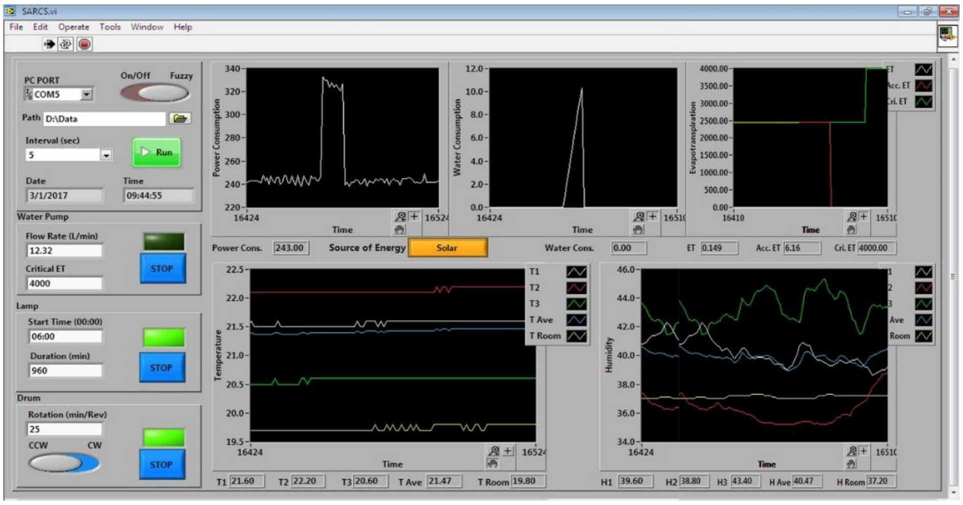

Fig. 5 - The GUI for SARCS performance settings, monitoring and data collection

RESULTS

The variations of temperature and relative humidity (Rh) of indoor environment and plant canopy (cylinder interior) in both ordinary and fuzzy treatments are summarized in Table 3. These parameters, which were not controlled during the experiments, have influences on lettuce growth parameters and water demand behaviours (especially in fuzzy treatment). However, the results of this table suggest that day/night ambient temperatures were almost in accordance with greenhouse lettuce recommended conditions (*Hassandokht, 2012a*).

Table 3

Variations of temperature and relative humidity of room and cylinder interior (canopy) in the two treatments

			Ordinary treatment				Fuzzy treatment			
			Max	Min	Ave.	SD	Max	Min	Ave.	SD
Day	Room	Temp. (°C)	21.84	16.35	19.04	1.31	20.71	14.78	18.33	1.53
		Rh(%)	61.71	27.80	44.33	9.10	57.41	29.84	39.85	6.29
	Cylinder	Temp. (°C)	23.45	17.54	20.26	1.59	22.41	17.31	20.02	1.59
		Rh(%)	69.43	27.38	48.14	11.47	65.50	29.93	43.44	8.86
Night	Room	Temp. (°C)	19.70	15.75	17.78	0.93	19.91	13.63	17.20	1.67
		Rh(%)	69.26	30.10	49.09	9.48	54.33	32.53	41.86	6.04
	Cylinder	Temp. (°C)	21.18	15.16	18.00	1.37	20.38	13.96	17.64	1.65
		Rh(%)	77.13	31.15	56.90	13.22	65.51	34.36	47.06	8.13

The other factor that affected the performance of SARCS was daily solar radiation. Figure 6 shows the variations of this parameter during the two treatments (ordinary and fuzzy). This Figure proves that SARCS experienced low-irradiance days during the tests, implying that in high-irradiance days of year the solar unit would be more efficient in serving the system.

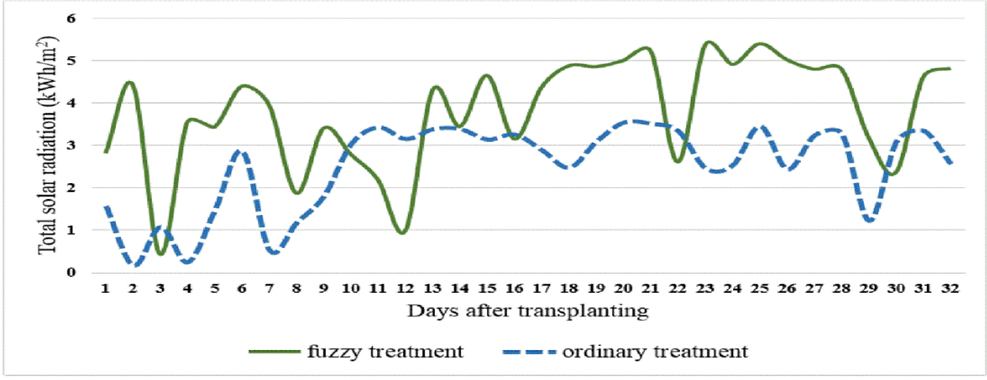

Fig. 6 - Variations of total daily solar radiation in ordinary and fuzzy treatments in Karaj climate

The variations of the estimated 5-second fuzzy ETs with its inputs (temperature, relative humidity, and light condition) in 24 hours (00:00 to 24:00) of a typical day during the fuzzy treatment are depicted in the Figure 7. As shown in this figure, at the time of light turning on (06:00) the ET increased and at its turning off time (22:00) ET decreased. Also, at any time of the day, when the temperature was high and/or relative humidity was low, ET experienced its high magnitudes. Conversely, ET was in its low magnitudes when the temperature was low and/or relative humidity was high. These results are in agreement with the principles of evapotranspiration. Estimation of plants ETs throughout the lettuce growth period in fuzzy treatment demonstrated that about 69.5 L water was lost due to plants ET which implies 2.18 L in each day.

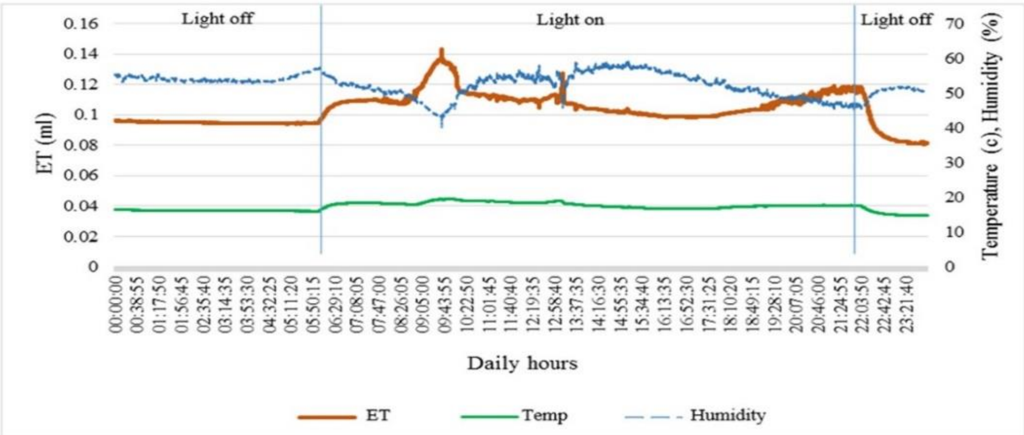

Fig. 7 - Variations of the estimated 5-second ETs and its inputs in a sample day

Figure 8 shows the variations of AccET in fuzzy treatment. As seen in this figure, AccET had naturally an ascending trend until reaching 4000 ml (CriET) at which irrigation pump was triggered. Then, AccET dropped to zero for the next irrigation event. This process repeated over time, but the ascending slopes and zero time intervals were not necessarily the same, meaning that the irrigation frequency was variable.

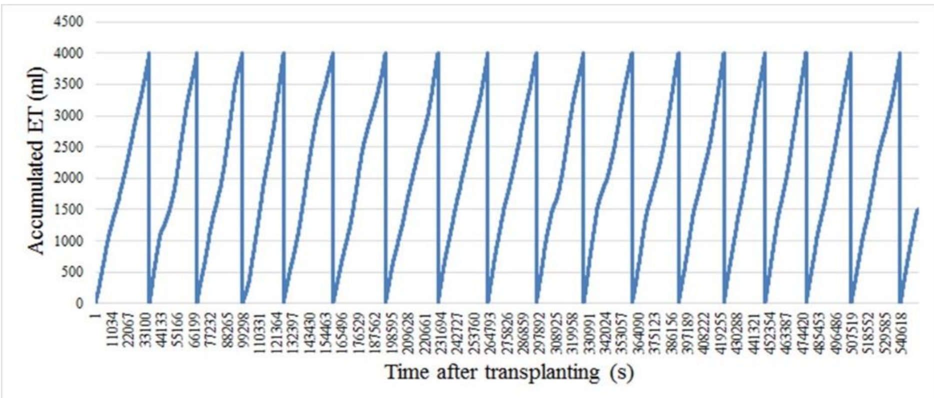

Fig. 8 - Variations of the accumulated five-second ETs implying pump performance when drops to zero

The total amount of irrigation water pumped to the chamber on different days of the two treatments is depicted in Figure 9. In the ordinary treatment, which was based on the operator pre-set settings of level sensors, the amount of applied water in each event was based on the instant capacity of the substrate in addition to the chamber surface water evaporation rate. These two factors, especially the former, caused the pump to be triggered more than once in some days like days 2 and 23. In the fuzzy treatment, the irrigation was governed by substrate water depletion related to CriET, which can be set by the GUI (Figure 5). Therefore, the differences between the amounts of irrigated water in each event could be attributed mainly to the different predicted water requirement of lettuce during the growth period. So, this treatment showed less fluctuations in irrigation water pumped (Figure 9).

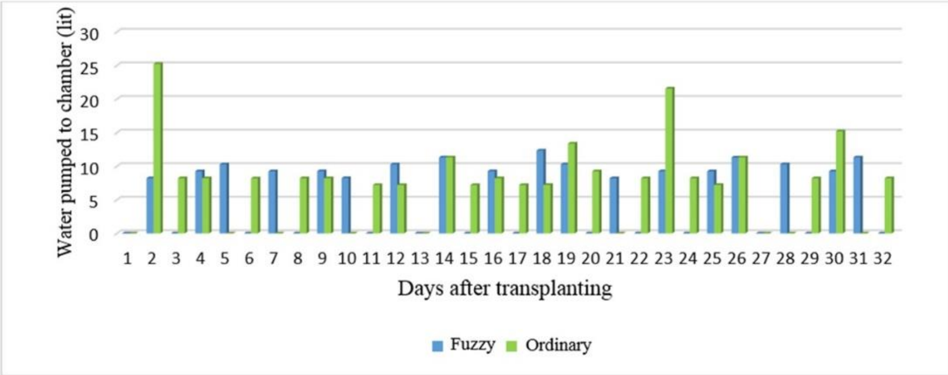

Fig. 9 - Water pumped to chamber in the two treatments

Table 4 summarizes some SARCS performance parameters in fuzzy and ordinary treatments. Since 80 lettuce were grown in both treatments and the area occupied by rotary cropping sub-system was about 1.2 m^2, the crop density in this system was about 66 plants m^{-2}. Field lettuce is planted in 25-40 cm distances in rows and 40-75 cm between rows (*Hassandokht, 2012b*) which implies 3.5-10 plants m^{-2}. This parameter is about 11-25 plants m^{-2} of lettuce in greenhouse (*Hassandokht, 2012a*). These results suggested that the SARCS plant density was on average, 12 times more than field lettuce and about 4 times more than greenhouse lettuce. From Table 4 it was also shown that the total lettuce product in fuzzy treatment was 74.47% more than ordinary mode and the product yield per area was about 3.42 and 1.96 kg m^{-2} in fuzzy and ordinary treatments, respectively. Since this parameter for field lettuce is about 3.2 kg m^{-2} (*Hassandokht, 2012b*) the fuzzy approach could improve that.

According to the Table 4, in ordinary and fuzzy modes, 232.47 and 176.76 L water was consumed meaning that for growing a lettuce plant in ordinary and fuzzy treatments 2.91 and 2.21 L water was needed, respectively. This showed 24% reduction of water usage in fuzzy mode. A field lettuce needs 14 to 48 L water in its growing period (*Peivast, 2009, Hassandokht, 2012b*) which was on average 15 times more than SARCS performance.

Table 4

Performance parameters in fuzzy and ordinary treatments

Performance and yield-related parameters	Treatments	
	Fuzzy	ordinary
Total fresh shoot weight (kg)	4.104	2.35
Total dry shoot weight (kg)	0.156	0.0998
Total fresh biomass weight (kg)	4.805	2.81
Total dry biomass weight (kg)	0.207	0.135
Area occupied (m^2)	1.2	1.2
Total water consumption (L)	176.76	232.47
Mean fertigation frequency (hr)	41.5	22
Number of irrigation events	18	34
Total energy consumption (kWh)	147.61	147.33
Solar energy consumption (kWh) and its contribution (%)	86.81 (58.81%)	71.32 (48.41%)
Power grid energy consumption (kWh) and its contribution (%)	60.80 (41.19%)	76.00 (51.59%)
Yield per area (kg m^{-2})	3.42	1.96
Plant density (plant m^{-2})	66.67	66.67
Total dry biomass per area (kg m^{-2})	0.172	0.112

From energy aspect, Table 4 shows that in both treatments energy consumption was the same and about 147 kWh which was expected due to the similar growth period and similar photoperiods. But due to the higher yield in fuzzy mode than in ordinary one, the energy needed per kg lettuce product in fuzzy treatment was less than ordinary. In ordinary and fuzzy treatments which were both performed in winter, 48.41% and 58.81% of total required energy was extracted from solar panels, respectively. Higher solar energy utilization in fuzzy mode was, in part, attributed to higher solar irradiance. These results proved the efficient energy usage in SARCS and implied that in high irradiance periods of the year the solar system could provide a higher percentage of SARCS energy requirements.

According to the Table 4, in ordinary and fuzzy modes, the amount of total produced dry biomass was about 0.112 and 0.172 kg m^{-2}, respectively. In a similar work where lettuce was hydroponically grown in a controlled growth chamber under white LED lighting system, an amount of 0.037 kg m^{-2} of dry biomass was produced (*Poulet et al., 2014*) which was about one-third of ordinary and one-fifth of fuzzy treatments in SARCS. Table 4 shows that for producing one kg dry biomass of lettuce in ordinary treatment, an amount of 1091 kWh energy was consumed which reduced to 713 kWh in fuzzy mode. In the experiment of Poulet, this parameter was 790 kWh (*Poulet et al., 2014*) which was less than ordinary mode but more than fuzzy treatment.

Finally, comparison of inputs required for producing edible lettuce product, as depicted in Table 4, showed that one kg of lettuce product in fuzzy mode needed 43% less area, 56% less water and 74% less energy, as compared to ordinary mode.

Analysis of variance for some lettuce growth parameters in ordinary and fuzzy treatments are summarized in the Table 5. According to the results, all parameters were significantly higher in fuzzy mode than in ordinary one ($P<0.05$).

Table 5

Analysis of variances for some lettuce growth parameters in fuzzy and ordinary treatments

Growth parameters	Source of variations	Degree of freedom	Sum of squares	Mean of squares	F	P
Number of leaves	Treatment	1	512.20	512.20	75.20	<.0001*
	Error	158	1076.13	6.81		
	Total	159	1588.33			
Total fresh weight (g)	Treatment	1	24796.39	24796.4	81.81	<.0001*
	Error	158	47888.758	303.1		
	Total	159	72685.152			
Total dry weight (g)	Treatment	1	31.67	31.67	73.17	<.0001*
	Error	158	68.40	0.43		
	Total	159	100.08			
Plant sum of leaf area (m^2)	Treatment	1	0.1013	0.1013	87.47	<.0001*
	Error	158	0.183	0.00116		
	Total	159	0.284			

* *Significant at 5 percent probability level*

In addition, the results of Tables 4 and 5 clarify that purposeful irrigation based on plant water requirement predictions could save water, energy, and acreage and improve input usage efficiencies. This strategy, in turn, improved performance parameters and crop growth properties.

CONCLUSIONS

In this study, a rotary hydroponic intensive cropping system was developed for indoor planting. This was equipped with a fuzzy-based irrigation unit for applying water based on plant water requirement predictions and a solar unit for providing energy for its different working elements. Two valid tests i.e. fuzzy-based and ordinary irrigation modes were considered for SARCS evaluation which was performed in low-irradiances season.

Results of the SARCS performance evaluation are summarized as follow:

- Evaluation of water use showed that in fuzzy treatment lettuce plants consumed 24% less water than in ordinary one.
- In both treatments, the total amount of energy consumption was the same and about 147 kWh, as expected. The solar unit supplied an average of about 50% of the system annual required power

which was about 51.16% in winter. This implies that in high-irradiance seasons this will be much more efficient.

- The results of lettuce yield in the two treatments revealed that a) lettuce planting in SARCS with 66 plants m^{-2} density would be 12 and 4 times more intensive than the field and greenhouse lettuce, respectively. b) The application of fuzzy-based irrigation improved plant weight yield so that the sum of edible lettuce in fuzzy treatment was 74.47% more than ordinary one. The results of plant growth properties in the two treatments revealed that all these properties were significantly higher ($P<0.05$) in fuzzy mode, than in ordinary one.

In addition, results showed that the development of such intensive cropping approaches with water and energy consumption advantages could play an important role in food safety and sustainable production of agricultural products. This is due to the fact that current agricultural production strategies suffer from land, water, and energy challenges.

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REFERENCES

[1] Aghkhani MH, Abasspour-Fard MH, Bayati MR, Mortezapour H, Saedi S.I et al., (2013), Performance analysis of a solar dryer equipped with a recycling air system and desiccant chamber. *Journal of Agricultural Machinery,* vol.3, pp. 92-103. (article in Farsi with an abstract in English);

[2] Alavian S, Jahanshahi M, Tamanalu M., (2012), Design of Sugeno and Mamdani fuzzy inference system for the estimation of daily reference evapotranspiration. In: *Proceedings of the congress on electrical computer and information technology engineering*; Mashhad, Iran. (article in Farsi with an abstract in English);

[3] Alizadeh A., (2011), *Soil, Water and Plant Relationship*: Emam Reza University Press. (In Farsi);

[4] Allen RG, Pereira LS, Raes D, Smith M., (1998), Crop evapotranspiration - Guidelines for computing crop water requirements. *FAO Irrigation and drainage paper 56*. Pp. 3. FAO, Rome 300(9): D05109; ISBN 92-5-104219-5;

[5] Chang C-L, Chang K.P., (2014), The growth response of leaf lettuce at different stages to multiple wavelength-band light-emitting diode lighting. *Scientia Horticulturae,* vol.179, pp.78-84. doi: 10.1016/j.scienta.2014.09.013;

[6] Chen X., Guo W., Xue X., Morewane MB., (2014), Effects of LED Spectrum Combinations on the Absorption of Mineral Elements of Hydroponic Lettuce. *Spectroscopy and Spectral Analysis,* vol.34(5), pp.1394-7. doi: 10.3964/j.issn.1000-0593(2014)05-1394-04;

[7] Cobaner M., (2011), Evapotranspiration estimation by two different neuro-fuzzy inference systems. *Journal of Hydrology,* vol.398(3), pp.292-302, doi: 10.1016/j.jhydrol.2010.12.030;

[8] Ed-Dahhak A, Guerbaoui M, ElAfou Y, Outanoute M, Lachhab A et al., (2013), Implementation of fuzzy controller to reduce water irrigation in greenhouse using LabView. *International Journal of Engineering and Advanced Technology Studies*, vol.1(2), pp.12-22;

[9] Entesari M, Heidari N, Kheirabi J, Alaei M, Farshchi A et al., (2007), *Water use efficiency in greenhouse production. Iranian National Committee on Irrigation and Drainage (IRNCID)*. (In Farsi);

[10] Hashemi Najafi F, Palangi JA, Azbarmi R., (2007), Estimation of reference evapotranspiration (ET_o) using neuro-fuzzy networks (ANFIS). In: *Proceedings of the 9th national conference on irrigation and evaporation reduction*; Kerman / Iran. (article in Farsi with an abstract in English);

[11] Hassandokht M., (2012). *Greenhouse management (technology of greenhouse crops production)*. Selseleh pub. (In Farsi);

[12] Hassandokht M., (2012), *Vegetables Production Technology;* Selseleh pub. (In Farsi);

[13] Kia PJ, Far A T, Omid M, Alimardani R, Naderloo L., (2009), Intelligent control based fuzzy logic for automation of greenhouse irrigation system and evaluation in relation to conventional systems. *World Applied Sciences Journal*, vol.1(6), pp.16-23;

[14] Kişi Ö., (2013), Applicability of Mamdani and Sugeno Fuzzy Genetic Approaches for Modeling Reference Evapotranspiration. *Journal of Hydrology,* vol. 504, 160-170, doi: 10.1016/j.jhydrol.2013.09.043;

[15] Kişi Ö, Öztürk Ö., (2007), Adaptive neurofuzzy computing technique for evapotranspiration estimation. *Journal of Irrigation and Drainage Engineering*, vol.133(4), pp.368-79;
[16] Marchildon T., (2003), *Rotary Plant Apparatus*. United States of America patent 6604321B2;
[17] Martha-Rocio C, Juan-Luis G, Oscar-Antonio P, Mónica-Karel H, Rivas D, Erazo M., (2015), Fuzzy system of irrigation applied to the growth of Habanero pepper (Capsicum chinense Jacq.) under protected conditions in Yucatan, Mexico Ceballos. *International Journal of Distributed Sensor Networks;* doi: 10.1155/2015/123543;
[18] Masterss GM., (2004), *Renewable and Efficient Electric Power Systems.* John Wiley & Sons, Inc. publication;
[19] Mirzaee E, Omid M, Keyhani A, Javadikia P., (2013), Forecasting the Thermal Load for Implementing Solar Energy in a Model Poultry House. *Journal of Agricultural Engineering and Biotechnology*, vol.1(2), pp.30-6;
[20] Moradi H, Ansari H, Alizadeh A, Hasheminia S, Naderianfar M., (2012), Modeling gross evapotranspiration under non-standard using fuzzy inference system, *Journal of water and soil (agricultural science and technology),* vol.26 (2), pp.507-494. (article in Farsi with an abstract in English);
[21] Mousazadeh H, Javanbakht S., (2010), *Photovoltaic: Iran agricultural science*. (In Farsi);
[22] Mousazadeh H, Keyhani A, Javadi A, Mobli H, Abrinia K et al., (2010), Optimal power and energy modeling and range evaluation of a solar assist plug-in hybrid electric tractor (SAPHT). *Transactions of the ASABE* vol.53(4), pp.1025-35. doi: 10.13031/2013.32586;
[23] Peivast G., (2009), *Growing Vegetables.* Danesh Pazir Publication. (In Farsi);
[24] Poulet L, Massa G, Morrow R, Bourget C, Wheeler R et al., (2014), Significant reduction in energy for plant-growth lighting in space using targeted LED lighting and spectral manipulation. *Life Sciences in Space Research,* vol2, pp.43-53, doi: 10.1016/j.lssr.2014.06.002;
[25] Roustaee A., (2009), *The vegetables crops above ground (Les cultures vegetables hors sol)*. Iranian Student Book Agency. (In Farsi);
[26] Salih J.M., Adom A, Shaakaf AM., (2012), Solar Powered automated fertigation control system for cucumis melo L. cultivation in green house. *APCBEE procedia*. vol.4, pp.79-87;
[27] Shayannejad M, Saadatinejad S.J, Fahmi H., (2008), Determination of evapotranspiration by using Fuzzy regression method. *Journal of Iran-water resources research*, vol.9, pp.1-9. (article in Farsi with an abstract in English);
[28] Shimokawa A, Tonooka Y, Matsumoto M, Ara H, Suzuki H et al., (2014), Effect of alternating red and blue light irradiation generated by light emitting diodes on the growth of leaf lettuce. bioRxiv: 003103.
[29] Shiri J, Nazemi AH, Sadraddini AA, Landeras G, Kisi O et al., (2013), Global cross-station assessment of neuro-fuzzy models for estimating daily reference evapotranspiration. *Journal of Hydrology*, pp.480, pp.46-57. doi: 10.1016/j.jhydrol.2012.12.006;
[30] Teshneh Lab M, Saffar Pour N.D.A., (2013), *A Course in Fuzzy Systems and Control.* Tehran. Khajeh Nasir University of Technology. (In Farsi);
[31] Wen J, Yang Q, Wei L, Cheng R, Liu W et al. (2011). Influence of combined lighting with different red and blue LED on photosynthetic characteristics and quality of lettuce and evaluation of energy consumption. *Acta Horticulturae Sinica,* vol.38(4), 761-9;
[32] Yanagi T, Okamoto K, Takita S (1996). Effects of blue, red, and blue/red lights of two different PPF levels on growth and morphogenesis of lettuce plants. *Acta horticulturae*, pp.440, pp.117-22. doi: 10.17660/ActaHortic.1996.440.21
[33] Yano A, Onoe M, Nakata J (2014). Prototype semi-transparent photovoltaic modules for greenhouse roof applications. *Biosystems Engineering*. 122:62-73. doi: 10.1016/j.biosystemseng.2014.04.003.