

Deficit Irrigation Using an Evapotranspiration-based Irrigation System

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Various efforts have been made to automate irrigation systems, however, there still exists a problem of an impending water crisis that was reported by the World Bank wherein the Philippines was one of the countries that will be affected. Most irrigation systems that were designed for open field farms require a lot of meteorological data that can only be acquired from weather stations, which are not readily available to some places. For these reasons, the researchers developed an evapotranspiration (ET)-based sensing irrigation system where less meteorological data are required to estimate the ET of a *Capsicum frutescens* plant (siling labuyo). This study covers the development of an automatic irrigation system with control based on the ET of the *C. frutescens* plant, which is also computed by the system software using sensor readings of temperature and water flow. The system was also able to implement a deficit irrigation strategy. The results have shown that the proposed system used up to 20% less water than the ET-based irrigation systems designed to use 100% crop ET, without any significant decrease in crop yield.

1. Introduction

Water is a vital element of life. It is essential for living organisms such as plants, animals, humans, fungi, and micro-organisms. Most of the earth's water is salt water, 2.5% of the water on the earth is freshwater, and only 0.034% of this freshwater is readily available to humans.⁽¹⁾ This includes the water people use for drinking, washing, and agricultural purposes. Agriculture is the largest consumer of the earth's available freshwater. Most of the water usage in agriculture is for irrigation purposes.⁽²⁾ The irrigation process should provide water to soil consistently when it is needed and halt when the soil has enough water. Excess irrigation is not only wasteful but also bad for crops. Because of the high rate of the world's population growth, the demand for drinking water and food produced by agriculture is increasing. Thus, freshwater must be used

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efficiently because it is becoming scarce over the course of time. There are still other sources of fresh water. Water also exists in air as water vapor and in the ground as soil moisture, and is released from plant leaves through transpiration. In general, the sum of evaporation and transpiration is called evapotranspiration (ET). The measurement of ET could help the process of irrigation scheduling by enabling the determination of the time and the amount of water to be applied to crops. To estimate ET, meteorological factors, as well as the soil moisture and the kind of plant, are also considered.

Advanced agricultural systems use the ET sensing process to determine the amount of water needed for the better growth of plants and the proper usage of the water supply. A common method of measuring the ET of crops is to use lysimeters. A lysimeter is composed of inner and outer tanks, loadcell assemblies, and a drain system. In a previous study, a plastic weighable micro-lysimeter is designed and built at a depth of 0.35 m in a soil volume of 6300 cm³. A plastic tube is used to obtain soil from the soil core while the load cell is mounted to it. The load cell then monitors the weight of the soil while the drain system removes the excess water in the micro-lysimeter.⁽³⁾ The amount of water lost by ET can be determined by calculating the difference in weight before and after the precipitation input. A few hundredths of a millimeter accuracy can be achieved using a weighing lysimeter to measure the water loss from the change in mass.⁽⁴⁾ In a previous study, an irrigation system that uses soil moisture sensor readings to regulate water flow in soil without much human intervention while optimizing the utilization of water was proposed. It was concluded that about 50% of water is conserved with the use of sensors compared with the traditional watering of plants.⁽⁵⁾ Aside from soil moisture, additional sensors such as temperature and humidity sensors can be used.⁽⁶⁾ Researchers also developed a capacitance-based soil moisture sensor, and the data obtained were the basis for irrigation scheduling. Results showed that the system can tell whether the soil is over-irrigated or under-irrigated.⁽⁷⁾ In a recent study, an automated infiltrometer that measures the soil infiltration rate was created to control the flow rate of the irrigator.⁽⁸⁾ In another study, a system that used weather sensors, such as DHT11 and an anemometer, to measure the temperature, wind speed and humidity of the environment was presented, and the Penman–Monteith and Hargreaves–Samani equations were compared to identify which would be more effective for the *Capsicum annuum* plant.⁽⁹⁾ Irrigation systems use different techniques. One involves dripping water directly into the soil using plastic pipes that contain small holes or outlets. This is called drip or trickle irrigation.⁽¹⁰⁾ Another is a combination of misting and drip irrigation, called hybrid irrigation. With hybrid irrigation, misting allows the adjustment of the relative humidity in air while drip lines moisten the soil when needed depending on its moisture content.⁽¹¹⁾

In the Philippines, the government is urging farmers to adopt greenhouse technology that will enable them to protect and raise crops all year-round.⁽¹²⁾ A low-technology greenhouse could be a viable option for the initial implementation because it comprises low-cost structures covered with plastic film without any active climatic control systems and also because crops are normally grown on soil substrates.⁽¹³⁾ Agricultural advancement and automation have been researched and implemented worldwide, which has greatly helped to increase agricultural productivity, particularly in the area of precision agriculture. It was also reported that the temperature and radiation-based Hargreaves and Samani model was implemented often in low-technology greenhouses.⁽¹⁴⁾ Also, several research groups studying ET inside greenhouses have

shown that modern estimation methods can closely match actual water loss from crops, demonstrating that ET can be measured even in controlled environments.^(13–15) Their results show that methods such as the Hargreaves, FAO24 Pan, and modified FAO56 Penman–Monteith models can estimate greenhouse reference crop ET (ET_0) even under varying conditions. These findings further support the integration of ET-based approaches into automated greenhouse irrigation systems. Also, in a study⁽¹⁵⁾ conducted using a low-technology/low-cost greenhouse, the Hargreaves and radiation methods were recommended for the calculation of greenhouse ET because of their simplicity. These prior studies have already demonstrated the ET models used in irrigation inside greenhouses that have enabled savings in water consumption. In this regard, we aim to evaluate the performance of an ET-based irrigation system in a low-technology greenhouse and determine whether the implementation of deficit irrigation with 20 and 40% less water is effective in the growth of a particular crop.

Despite the attempt to automate irrigation systems, there still exists the problem of an impending water crisis that was reported by the World Bank, wherein the Philippines is predicted to be one of the countries that will be affected. Another problem is that most irrigation systems use methods that require a lot of meteorological data. Such data can only be acquired from weather stations and thus are not readily available in some places. Furthermore, most of the reported systems were designed for open field farms.

The objective of our study was to develop an ET-based sensing irrigation system that implements a deficit irrigation scheme inside a low-technology greenhouse for crops. Specifically, the aims of this research were to (1) develop a device that dispenses water to a greenhouse through the irrigation system based on ET sensing for cultivating *Capsicum frutescens* (siling labuyo) plants; (2) calibrate the ET-based sensing irrigation system and implement deficit irrigation in a low-technology greenhouse structure; and (3) evaluate the system performance and functionality using the proposed ET-based sensing irrigation system with the implementation of deficit irrigation.

The results of this research will play an important role in monitoring and lessening water usage in irrigation through the use of the ET-based system. Sensing how much water leaves the ground allows the determination of how much water must be added back. Thus, the ET process has been used by irrigation companies to provide irrigation recommendations to growers. The advantage of controlling the crop's environment by establishing protective structures such as greenhouses or net houses will further improve crop production and the quality of the produce. Moreover, these structures will be able to protect crops from pests that are known to damage crops and spread diseases.

This study covers the development of an automatic irrigation system that is controlled on the basis of the ET of the *C. frutescens* plant, which was also computed using the system software using sensor readings of temperature and water flow. A microcontroller was used to control the irrigation scheduling and dispensing of water. This study also covers the implementation and testing of the ET-based irrigation system in a low-technology greenhouse structure. The ET-based sensing irrigation system was tested for applying the deficit irrigation watering strategy. This treatment-imposed application of 100, 80, and 60% crop water requirement was based on ET. The open field application of the system was not covered in this study.

2. Data, Materials, and Methods

2.1 Conceptual framework

Figure 1 shows the conceptual framework of the deficit ET-based irrigation system. The system has input from two sensors: an ambient temperature sensor and a water flow sensor. Other inputs come from RTC and SD card modules. The inputs were processed by a microcontroller. The system obtains samples of temperature every 30 min and computes the average temperature daily. This average temperature is used to compute ET_0 . The crop ET (ET_c) can be computed by the system using the ET_0 and crop coefficient (K_c) values. ET_c is the basis of how much water to be dispensed by the system on Row 1 (100% ET_c drip line) per day. Deficit irrigation is applied for the two remaining rows (80 and 60% ET_c drip lines). For other outputs, the liquid crystal display (LCD) shows the temperature reading, water flow rate, date, time, and system messages. Temporary data and the log file are saved in an SD card. The system is also set to produce sound as an indicator by sending signals to a buzzer.

2.2 Development of the system hardware

Figure 2 illustrates the hardware block diagram of the deficit ET-based irrigation system. The main component of the system is the Arduino Mega microcontroller. It is powered by a 12 V DC power supply. The microcontroller receives the input of the temperature inside the greenhouse from the temperature sensor. The real-time clock module is used by the microcontroller to get the current date and time. When watering, the microcontroller produces output signals for the relay modules that turn on the solenoid valves. The solenoid valves use the same power source as the Arduino Mega microcontroller. This microcontroller uses the LCD to output different information about the system, such as current date, time, temperature and other processes performed. A buzzer is connected to the microcontroller to produce different indications and warning sounds. The SD card module is used to read and write temperature readings and the daily watering data log.

Figure 3(a) shows a photograph of the prototype installed inside the greenhouse. The main electronic components, such as the Arduino Mega microcontroller, LCD, SD card module, RTC module, relay modules, and buzzer, were housed inside an acrylic case. The ambient temperature

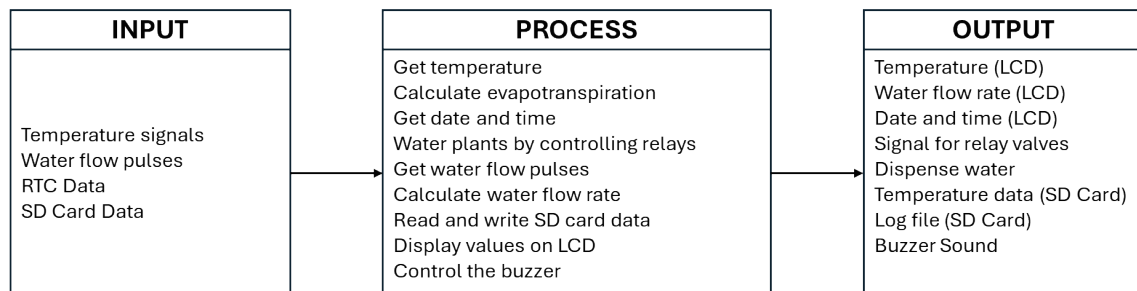


Fig. 1. Conceptual framework of the system.

2.3 Development of the controller software

Figure 4 shows the flowchart of the ET-based deficit irrigation system. First, the system checks for saved data in the SD card. Then, it checks the time. If it is 6:45 AM (defined watering time), the system then calculates ET_c for the past 24 h, waters the plants on the basis of ET_c , writes the log into the SD card, and then restarts the system. Aside from the watering time, the system checks if the time-minute mark is equal to 00 or 30. This enables the system to get temperature samples every 30 min. By default, the system displays the date, time, and temperature.

To calculate the amount of water needed, also known as ET_c , the system must first compute ET_o . The simplified formula for ET_o is⁽¹⁶⁾

$$ET_o = 0.0135 (KT) (Ra) (Tmax - Tmin) 0.5 (TC + 17.8), \tag{1}$$

where TC is the average daily temperature in degrees Celsius ($^{\circ}C$); KT is the empirical coefficient; Ra is the extraterrestrial radiation; and $Tmax$ and $Tmin$ are the maximum and

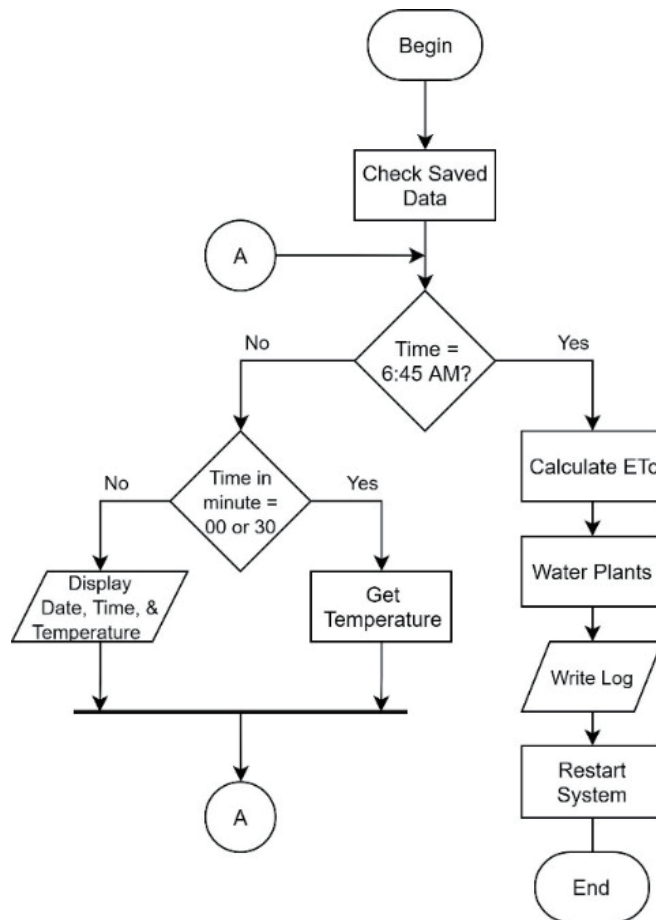


Fig. 4. System flowchart.

minimum temperatures, respectively. The value that can be used for KT is 0.162 for interior regions or 0.19 for coastal regions. For values of extraterrestrial radiation (Ra), refer to the table in Ref. 17. The table shows the exact extraterrestrial radiation determined from the relationship between time (in month) and location (in latitude).

In this study, the plant used is *C. frutescens*. It has a different Kc value for each of its corresponding growth stages. The crop coefficient is determined to be 0.4 for the initial stage, 0.6 for the development stage, 1.1 during the mid-season, and 0.9 at the time of harvest or late season.

Knowing the values of ET_o and Kc , ET_c was computed. To determine ET , the crop coefficient method was used. The temperature values recorded inside the greenhouse were used to compute the reference crop ET (ET_o). The Kc of *C. frutescens* in each development stage was also used. In this method, the equation used to compute ET_c is

$$ET_c = Kc \times ET_o . \quad (2)$$

In this study, there are three rows of plants to be watered. Each row has five plants. The unit of ET_c is millimeter per day. To convert it to a volume unit such as milliliters, the equation below can be used:

$$ET_c = ET_c (0.1) (A) , \quad (3)$$

where A is the plot area of the five plants. In the setup of this study, the total area for a single row is 3716.12 cm².

After the determination of ET_c , the system then waters the plants. The first row was watered with 100% of ET_c . The second row was watered with 80% of ET_c (20% deficit irrigation). The third row was watered with 60% of ET_c (40% deficit irrigation). While watering, the system also monitors water flow to determine whether the amount of water dispensed is correct. The system records a log file containing the date, time, and amount of water used for each row. After all these processes, the system then deletes the temporary data and starts again.

3. Results

Table 1 shows the average height, number of leaves, and number of branches per week for each of Row 1, Row 2, and Row 3. Row 1 was watered with 100% of the plants' water requirement, Row 2 was watered with 80% (20% deficit), and Row 3 was watered with 60% (40% deficit).

T-tests were conducted to compare the average plant height, number of leaves, and number of branches between three rows of plants watered at different deficit irrigation levels: 100% (Row 1), 80% (Row 2), and 60% (Row 3) of the plants' daily water requirement. For plant height, Row 1 had an average of 47.54 cm, Row 2 had 41.08 cm, and Row 3 had 37.64 cm. A statistical comparison between Rows 1 and 2 yielded a test statistic of 0.74347, and between Rows 1 and 3, 1.2226. Both values were lower than their respective critical values, indicating no significant

Table 1
Weekly average and overall average for plant height, number of leaves, and number of branches.

Week	Row 1 (100% <i>Etc</i>)			Row 2 (80% <i>Etc</i>)			Row 3 (60% <i>Etc</i>)		
	Average plant height (cm)	Average number of leaves	Average number of branches	Average plant height (cm)	Average number of leaves	Average number of branches	Average plant height (cm)	Average number of leaves	Average number of branches
1	4.94	5.80	0.00	3.66	5.00	0.00	3.40	5.00	0.00
2	5.94	7.20	0.00	4.28	5.00	0.00	3.58	5.40	0.00
3	7.58	7.00	0.00	5.34	5.60	0.00	4.40	5.40	0.00
4	9.14	6.00	0.00	7.20	5.60	0.00	6.06	6.60	0.00
5	12.30	8.80	0.00	8.76	8.80	0.20	8.70	9.00	0.00
6	18.64	11.00	0.00	13.78	9.00	0.40	13.58	11.20	0.20
7	26.34	14.40	0.00	17.20	10.40	0.40	20.90	14.40	0.60
8	36.60	18.40	0.00	25.20	15.60	1.40	31.50	19.00	2.80
9	47.80	28.20	13.20	33.60	23.20	5.00	40.80	49.20	4.60
10	56.40	86.20	20.00	42.40	53.40	9.60	45.40	75.40	15.60
11	59.40	215.20	42.40	50.90	126.80	20.80	46.74	168.60	30.40
12	61.44	95.80	34.60	50.60	110.80	24.80	45.92	22.60	30.40
13	61.76	142.80	36.40	52.00	191.60	32.20	45.92	86.40	31.80
14	63.76	238.40	52.80	54.80	245.00	52.00	46.60	194.40	48.80
15	64.00	235.20	38.80	56.10	258.60	49.60	47.20	161.00	28.20
16	64.50	235.80	42.20	58.30	250.60	53.60	48.30	148.40	25.60
17	67.60	249.40	42.80	61.40	292.20	61.80	52.80	150.00	25.60
18	71.80	221.80	61.40	67.60	269.80	74.40	59.70	139.40	27.40
19	79.10	287.40	121.20	75.20	313.20	118.40	68.00	195.80	99.00
20	86.00	246.00	100.60	82.80	250.80	99.20	72.20	206.40	74.20
21	93.40	331.00	103.60	91.60	341.60	115.20	78.80	263.80	96.60
Overall average	47.54	128.18	33.81	41.08	132.98	34.24	37.64	92.26	25.80

difference. For the number of leaves, the averages were 128.18 for Row 1, 132.98 for Row 2, and 92.26 for Row 3. The test statistics on comparing Row 1 with Row 2 (0.12752) and Row 1 with Row 3 (1.1404) also fell below critical values, indicating no significant difference. Similarly, in terms of the average number of branches, Row 1 had 33.81, Row 2 had 34.24, and Row 3 had 25.80. The t-test between Rows 1 and 2 (−0.0359), and that between Rows 1 and 3 (0.7561) both showed no statistically significant difference.

Figure 5 shows the daily water usage of the irrigation system. The period of observation ranges from 1st week to 21st week. The system was set up and installed in a greenhouse located in Bulacan, Philippines. It automatically waters the *C. frutescens* plant daily considering the crop coefficient for the three growth stages: the development stage, mid-season, and late season.

Also, the total number of harvested fruits per row was recorded. Row 1 had a total of 226, Row 2 had 221 and Row 3 had 103. Figure 6 shows a photo of plants taken on the 21st week.

4. Discussion

Throughout the study—from vegetative growth up to the early fruiting stage of *C. frutescens*—plants were subjected to three levels of irrigation based on *Etc*: 100, 80, and 60%.

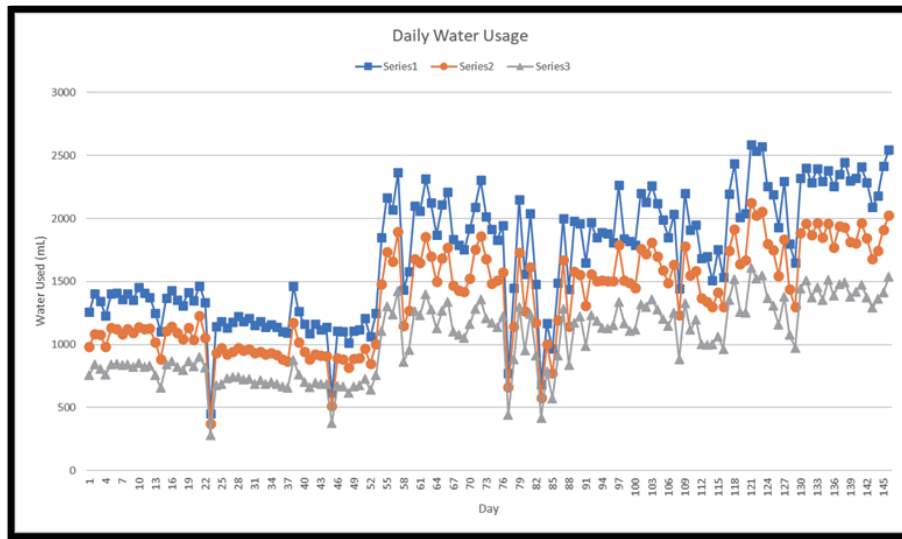


Fig. 5. (Color online) Graph of daily water usage.



Fig. 6. (Color online) Actual plants on the 21st Week.

Interestingly, the results showed no statistically significant differences in plant height, the number of leaves, or the number of branches among the three treatments. This indicates that *C. frutescens* can physiologically adapt to moderate water reductions, especially during the early and middle stages of growth, maintaining healthy structural development even under water stress.

This aligns with the principle of deficit irrigation, where less than the full water requirement is applied to crops to conserve water, without significantly compromising growth. The fact that plants receiving 80% *ETc* performed comparably to those receiving 100% *ETc* suggests that a 20% reduction in irrigation may be feasible for this crop, potentially offering water savings without sacrificing the plant structure.

However, when looking beyond vegetative growth, the number of harvested fruits reveals an important consideration; while plant height, leaf production, and branching were not significantly affected, the number of harvested fruits—or bearings—dropped sharply under the 60% *ETc* treatment. In fact, the reduction in the number of harvested fruits was more than 50% compared with those in the 100% and 80% *ETc* treatments. This significant decrease highlights a critical trade-off in deficit irrigation strategies: while the plants may appear healthy externally, their reproductive output—and thus economic yield—can still be compromised under more severe water stress.

5. Conclusions

In this study, we investigated the effects of deficit irrigation on the growth and fruit production of *C. frutescens* by comparing three levels of water application based on crop ET (*ETc*): 100% (full irrigation), 80% (20% deficit), and 60% (40% deficit). Results showed that plant height, the number of leaves, and the number of branches were not significantly affected by reducing irrigation to either 80 or 60% *ETc*. This suggests that the plant can tolerate moderate water stress in terms of vegetative growth.

However, a significant decrease in the number of harvested fruits was observed under the 60% *ETc* treatment, with a reduction of more than 50% compared with those of the 100% and 80% *ETc* groups. This indicates that while *C. frutescens* may maintain its physical appearance and structural growth under water-limited conditions, its reproductive capacity is much more sensitive to severe water deficits.

Therefore, while deficit irrigation at 80% *ETc* appears to be a promising strategy for conserving water without negatively impacting either the vegetative or reproductive performance, irrigation at 60% *ETc* is not recommended because of its substantial impact on fruit yield. These findings highlight the importance of balancing water use efficiency with crop productivity, especially in regions where water resources are scarce. In future studies, the impact of deficit irrigation on fruit quality and total yield may be further explored to better clarify irrigation management practices for chili pepper cultivation.

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