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An efficient irrigation based on hargreaves potential evapotranspiration to improve yield for tomato plantation

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Original Research

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Abstract:

With a tropical climate in Malaysia, varieties of vegetables can grow all year round. Nevertheless, during the hot season, watering the plant is challenging, especially for vegetables that are intolerant to heat such as tomato plants. Over-watering or under-watering could decrease the yield and quality of tomatoes. Therefore, in this study, we proposed an efficient irrigation system based on Hargreaves's potential evapotranspiration to improve the yield and quality of tomato plants in Melaka, Malaysia. Using the Hargreaves equation, the correlation between the surrounding temperature and the amount of water needed by the tomato plants is investigated. Three growth stages are considered: early stage ($0-30$ days of planting), middle stage ($31-76$ days of planting), and final stage ($77-105$ days of planting). Based on a 30-day analysis, on average, tomato plants require 45.5 mL/day, 87.4 mL/day, and 60.8 mL/day respectively for the early, middle, and final stages of growth. A mobile monitoring application is also developed using MIT App Inventor for users to monitor the temperature, humidity, soil moisture, pH level, status of water pumps, and the amount of water released to the plants. The proposed system can increase the efficiency of the irrigation process and ultimately, reduce the farming cost.

Keywords: Watering; Tomato plant; Mobile application; Hargreaves equation

1. Introduction

Agriculture consumes an estimated 72% of the amount of freshwater worldwide [1]. It is predicted that water consumption in agriculture activities increases year-by-year as food consumption increases due to the growing population [2]. High water consumption is also contributed by the poor irrigation system which leads to inefficiency and water wastage [3, 4]. As a consequence, it increases the cost of farming and affects the overall yield of the plants. Tomato plants in particular are the type of plant that is easily affected by water stress (i.e., over-watering or under-watering). The tropical climate in Malaysia makes planting of these tomato plants more challenging, especially during the hot season. Hence, an efficient irrigation system is required to improve the quality and yield of the tomato plants, and also reduce water wastage.

Several irrigation systems for tomato plants have been proposed in the past. Rohith et al., [5] proposed an irrigation system for tomato plants mainly controlled using Arduino UNO and NodeMCU ESP8266. The irrigation system has sensors for soil moisture, temperature, and humidity. The irrigation process triggers when temperature, humidity, or soil moisture exceeds the set threshold value. A major drawback of this system is the similar amount of water being released to the tomato plants irrespective of environmental variations and growth stages of tomato plants which could lead to over-watering or under-watering. Similar studies as above were also found in [6–12].

The study of evapotranspiration is therefore important to estimate the amount of water that evaporated to the atmosphere from the soil surface which strongly depends on the variations of ambient temperature. In a study, Hernandez et al., [13] used the adaptive network-based fuzzy inference system (ANFIS) algorithm to estimate the water evapotranspiration of tomato plants for agricultural production in a greenhouse. The results show that the ANFIS algorithm has a 20 g error in evapotranspiration measurement as compared to standard measurement using a lysimeter. Elsewhere, an efficient irrigation system is developed based on the estimation of evapotranspiration through Hargreaves-Samani equation [14]. In another study, Colimba et al., [15] developed an irrigation system based on the estimation of evapotranspiration in the area of Ecuador using the Penman-Monteith equation. Ichwan et al., [16] proposed a more efficient integration system by integrating the estimation of evapotranspiration through the Hargreaves equation and growth stages of tomato plants in the village area of Indonesia. The above studies [13, 15, 16] managed to reduce water consumption significantly and improve the yield of tomato plants. Nevertheless, the developed techniques above are only valid to the defined area of locality.

Elsewhere, a study focused on the impact of potassium level variations and soil moisture during different growth stages on the water use efficiency and the yield of tomato plants [17]. Another parameter that greatly affects the yield of tomato plants is soil pH [18, 19]. Hence, the monitoring system of these important parameters that greatly affect the water use efficiency and the yield of tomato plants is developed in [20, 21]. In a recent study, Bettelli et al., [22] developed a technique to identify the tomato plants that experienced water stress (i.e., under-watering). A similar study investigating the water content or stress in tomato plants is also found in [23].

Based on all the above, the previous studies focused on the development of irrigation systems based on the sensed value of temperature, humidity, and/or soil moisture. Some improvements were made in other studies by efficiently estimating the water using the evapotranspiration equation model and growth stages of tomato plants, but all these studies were conducted outside the region of Malaysia. Therefore, this paper focuses on developing an efficient irrigation system to increase the yield and quality of tomato plants in Malaysia.

We present three major contributions in this paper.

1. We present a detailed water estimation analysis based on Hargreaves' potential evapotranspiration for tomato planting in Melaka, Malaysia for three different growth stages which are early stage (0 – 30 days of planting (d.a.p)), middle stage (31 – 76 d.a.p) and final stage (77 – 105 d.a.p).

2. We developed an irrigation hardware system that consists of microcontrollers, a real-time clock (RTC) module, a display module, sensors, water pumps, and relays in which the system can vary the watering amount according to the growth stages of the tomato plants and maximum ambient temperature.

3. We developed a mobile monitoring application for the user to monitor users to monitor the temperature, humidity, soil moisture, pH level, status of water pumps, and the amount of water released to the plants.

2. Methodology

In this section, the methodology to design an efficient irrigation system based on Hargreaves' potential evapotranspiration is described. Fig. 1 illustrates the top level of the proposed irrigation system for tomato plants. The design of the proposed system in Fig. 1 is divided into three main parts which are an investigation of the correlation of water and temperature based on the Hargreaves equation, the development of an efficient irrigation hardware system using a microcontroller, and the development of a mobile monitoring application using MIT App Inventor.

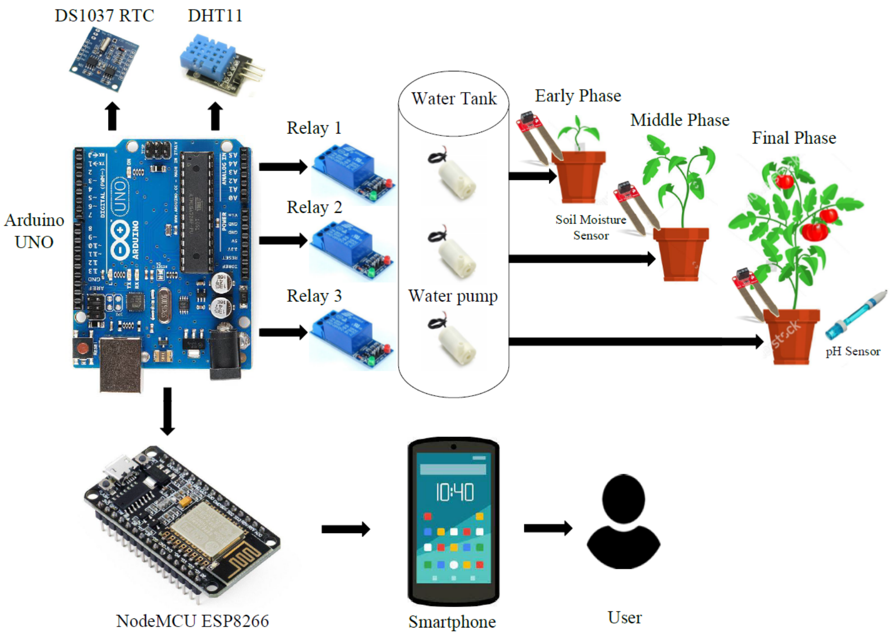

Figure 1. Top level block diagram of an efficient irrigation system for tomato plants.

First, the Hargreaves equation is studied to correlate the ambient temperature and the amount of water required by the tomato plants. The Hargreaves equation is derived from the Penman-Monteith formula [24] and it is given as:

$$ETo = 0.000939(T_{\max} - T_{\min})^{0.5}(T_{ave} + 17.8)Ra \quad (1)$$

where ETo represents potential evapotranspiration (mm/-day), Ra represents extraterrestrial radiation, $T_{\max}$, $T_{\min}$, and T_{ave} represent a daily maximum, minimum, and average temperature (°C), respectively. Ra value can be estimated based on the location's latitude/longitude and calendar day of the year and it is given as follows:

$$Ra = \frac{(60)(24)}{\pi} \times Gsc \times dr[Ws.\sin(\theta)\sin(\delta) + \cos(\theta)\cos(\delta)\sin(Ws)] \quad (2)$$

where Gsc represents a solar constant which is equivalent to 0.0820 MJ.m^{-2}/min, dr represents an inverse relative distance from the earth to the sun, Ws represents a sunset hour angle (in radians), θ represents a latitude (in radians), and δ represents a solar declination (in radians). Based on the ETo value, the amount of water needed by the tomato plants can be computed using the following equation:

$$ETc = Cc \times ETo \quad (3)$$

where ETc represents estimated water requirement (mm/-day) and Cc represents crop coefficient (d.a.p). Three growth stages are considered in this study; early stage $(0-30$ d.a.p), middle stage $(31-76$ d.a.p), and final stage $(77-105$ d.a.p). The crop coefficient of tomato plants depends on the stage of growth. $Cc = 0.6$ for an early stage, $Cc = 1.15$ for a middle stage, and $Cc = 0.8$ for a final stage [16, 25]. For water estimation computation, 1 mm/day is defined as 1 L of water per 1 m^2 of ground area evaporated to the atmosphere in a day [26]. In our study, we used a poly bag with a diameter of 15.24 cm. The area of a poly bag is calculated using πr^2 and it is equivalent to 0.0182 m^2.

Next, based on the Hargreaves equation above, the irrigation system is developed using Arduino UNO, NodeMCU ESP8266, DS1307 RTC module, liquid crystal display (LCD), DHT11 sensor, soil moisture sensor, pH sensor, water pumps, relays, and water tank in which the system able to vary the watering amount according to the growth stages of the tomato plants and maximum temperature. DS1307 RTC module is used to keep track of the current time such that the irrigation process can be performed exactly at 7 pm. The environmental parameters such as pH level, humidity, temperature, and soil moisture are sensed by the sensors and processed by the Arduino UNO to be displayed in LCD. The measured environmental parameters are also sent to the mobile monitoring application using a built-in WiFi module in NodeMCU ESP8266.

The mobile monitoring application is developed by using MIT App Inventor [27, 28]. First, the user interface of the login page is designed. Subsequently, the interface of the main menu page is developed which consists of the display of temperature, humidity, soil moisture, and pH level. This monitoring feature is designed to alert the user about the environmental conditions that affect the amount of water released to the tomato plants. The mobile application also displays the total amount of water that has been released to grow the tomato plants. Once the login page and menu page are successfully designed, the mobile application is linked to the hardware to sync and display all the required data in the mobile application.

3. Results and discussion

3.1 Forecast-potential evapotranspiration analysis

As described in section 2, the Hargreaves equation requires a set of temperature data per day to calculate the amount of water required by the tomato plants. Therefore, the observation on temperature was conducted from 17th April 2023 until 16th May 2023 (30-day duration) for Malacca city by referring to https://www.timeanddate.com/weather/malaysia/malacca-city. The temperature was observed every 1 hour in a day. Based on 24 readings of the temperature in a day, the $T_{\max}$, $T_{\min}$, and T_{ave} were computed. Fig. 2 illustrates the distribution of $T_{\max}$, $T_{\min}$, and T_{ave} for a 30-day duration.

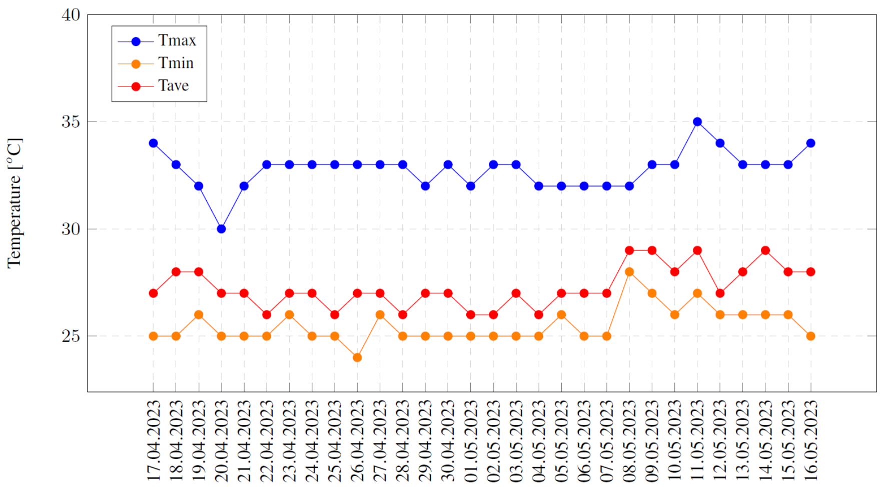

Figure 2. Temperature distribution over 30-day in Melaka.

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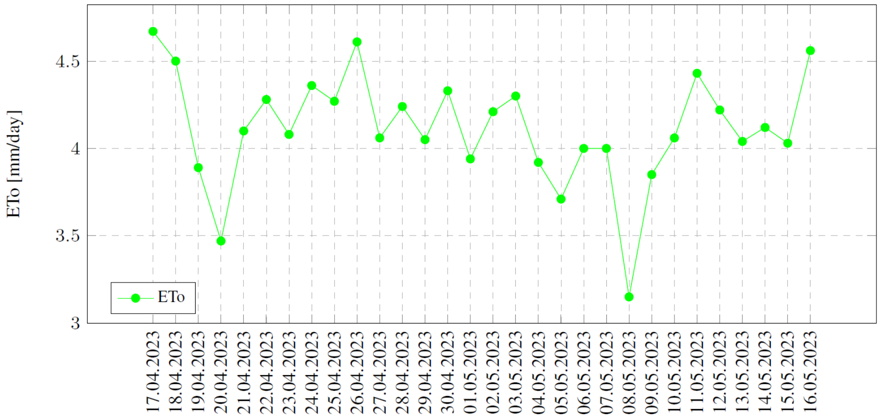

Figure 3. Distribution of ETo for 30-day.

Based on the temperature distribution over the 30-day duration, the potential evapotranspiration can be computed using the Hargreaves equation, Eq. (1). Fig. 3 depicts the distribution of ETo for the 30-day duration. The ETo values vary from 2.82 to 4.67 mm/day depending on the ambient temperature and Ra values. Notice that the maximum potential evapotranspiration occurred on 17th April 2023 which is 4.67 mm/day.

The development of an irrigation system based on the Hargreaves equation can be quite complex as the system has to process several data including $T_{\min}$, T_{ave}, $T_{\max}$, and Ra values to compute ETo. The computation of ETo can be simplified by using regression analysis to find out which temperature ($T_{\max}/T_{\min}/T_{ave}$) has a significant impact (i.e., dependency) on ETo. Hence, eliminating the requirement to compute Ra and the other two temperature values. Fig. 4 illustrates the relationship between ETo and temperature ($T_{\max}/T_{\min}/T_{ave}$).

Based on the linear regression analysis, $ETo - T_{\max}$ produces the highest R^2 which indicates that the ETo and $T_{\max}$ are highly correlated. The $ETo - T_{\max}$ correlation can be represented by a following simplified equation:

$$y = 0.2544x - 4.2216 \tag{4}$$

where y represents the $ETo - f$ (mm/day) which is forecast-potential evapotranspiration, and x represents the maximum temperature of the day, $T_{\max}$ (°C). For water estimation analysis, the value of ETo in Eq. (3) can be replaced by the value of $ETo - f$ and becomes the following:

$$ETc = Cc \times ETo - f \tag{5}$$

As discussed above, the $ETo - f$ (mm/day) or forecast-potential evapotranspiration highly depends on $T_{\max}$. Hence, by measuring only the $T_{\max}$ during the day, one can determine the water requirement for three different growth stages of tomato plants. Based on $T_{\max}$ values in Fig. 2, the ETc values for three different growth stages can be calculated using Eq. (4) and (5). For example, Fig. 5 illustrates the ETc distribution calculated over a 30-day duration for early-stage tomato plants. For middle and final growth stages, the ETc distribution shares a similar pattern as an early stage with a different level of ETc on the y-axis as Cc for the middle stage is 1.15, and Cc for the final stage is 0.8 as compared to early stage, $Cc = 0.6$. Based on the above analysis, the ETc value for tomato plants on average is 2.5 mm/day in the early phase, 4.8 mm/day in the middle phase, and 3.34 mm/day in the final phase.

According to [26], 1 mm/day is defined as 1 L of water per 1 m^2 of ground area evaporated into the atmosphere in a day. In this study, we used poly bags with a diameter of 15.24 cm. The soil's surface that is exposed to the ambient can be calculated using πr^2 and it is equivalent to 0.0182 m^2. Hence, based on the average values of ETc for three different growth stages, the average amount of water needed

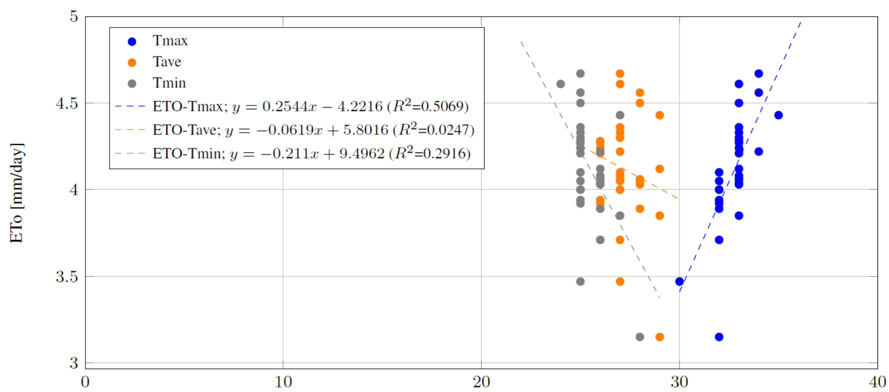

Figure 4. Correlation between ETo, $T_{\max}$, $T_{\min}$, and T_{ave}.

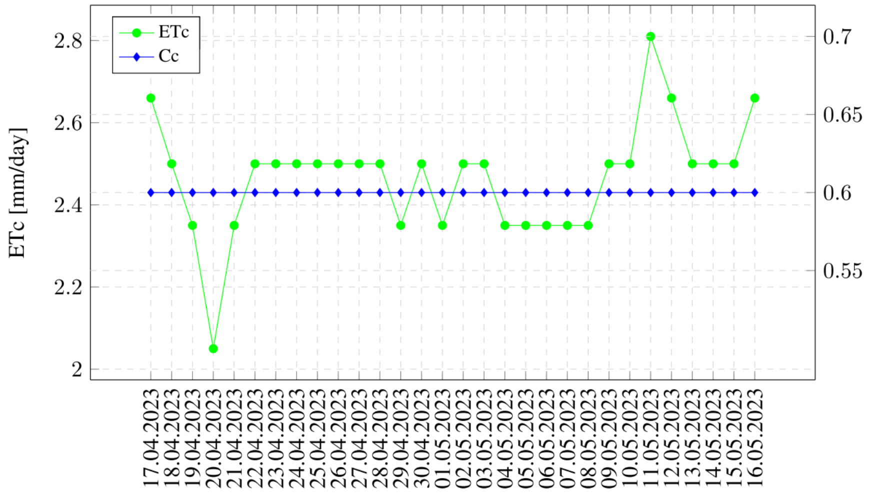

Figure 5. ETc distribution for the early stage of tomato plants over 30-day duration.

by tomato plants daily is 45.5 mL, 87.4 mL, and 60.8 mL, respectively for early, middle, and final growth stages. Further, our irrigation system is developed based on Eq. (4) and Eq. (5) above which are discussed in the next sections.

3.2 Hardware integration

Fig. 6 depicts the hardware configuration of the irrigation system for three different growth stages of tomato plants (i.e., three poly bags). Each poly bag is equipped with a temperature sensor, soil moisture sensor, and pH sensor. The Arduino UNO is programmed to measure the $T_{\max}$, soil moisture, and pH level. All the measured parameters are displayed on the LCD and sent to the mobile monitoring application by using NodeMCU ESP8266 via a WiFi connection. Based on the measured $T_{\max}$, Arduino UNO is also programmed to compute the amount of water based on Eq. (4) and Eq. (5). The irrigation system in Fig. 5 is also equipped with relays and water pumps to release the water to each poly bag.

3.3 Water estimation analysis

Fig. 7 depicts the amount of water released by the irrigation system at 33 ℃ maximum temperature for tomato plants at the early, middle, and final stages of growth. 15 readings have been measured to verify the variations in the released amount of water. On average, the amount of water released is 45.87 mL/day, 85.6 mL/day, and 59.27 mL/day, respectively for the early stage, middle stage, and the final stage.

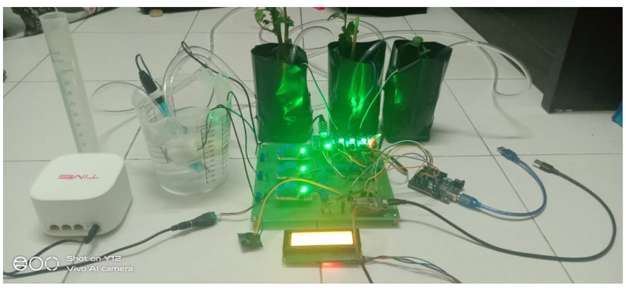

Figure 6. An irrigation system of tomato plants.

As compared to the theoretical values calculated by using Eq. (4) and Eq. (5), the amount of water released for the early stage is 45.57 mL/day, the middle stage is 87.35 mL/-day, and the final stage is 60.77 mL/day. Based on root mean squared error (RMSE) analysis, an error of 1.13 mL, 4.1 mL, and 3.7 mL between theoretical and measured values, respectively for early, middle, and final growth stages. Insignificant differences have been observed between theoretical and measured values. Hence, it proves that the developed irrigation system is able to release a consistent amount of water based on the $T_{\max}$ value.

It is observed from the above analysis that tomato plants require less water during the early stage of their growth. During this stage, the plants are still in the vegetative phase. Tomato plants reach the generative phase when they enter the middle stage of growth. At this stage, tomato plants are growing and require more water for the photosynthesis process. Tomato plants begin to bear fruit in the generative phase. In the final stage of the tomato plant's growth, less water is required since the plant approaches the conclusion of its biological age, especially when the fruit ripening time.

3.4 Mobile monitoring application

A mobile monitoring application is also developed in our study by using MIT App Inventor. Fig. 8 depicts the mobile application interface before 7 pm. Users can monitor the

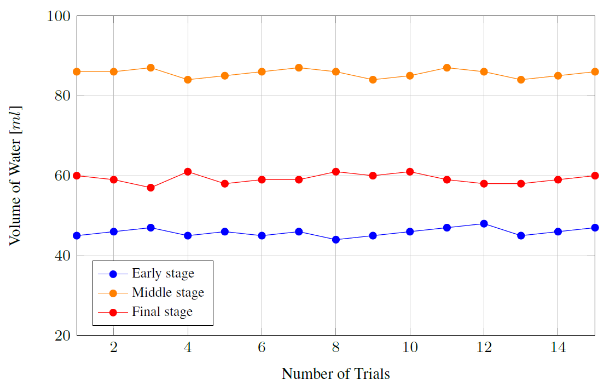

Figure 7. Water release variations at a maximum temperature of 33 ℃.

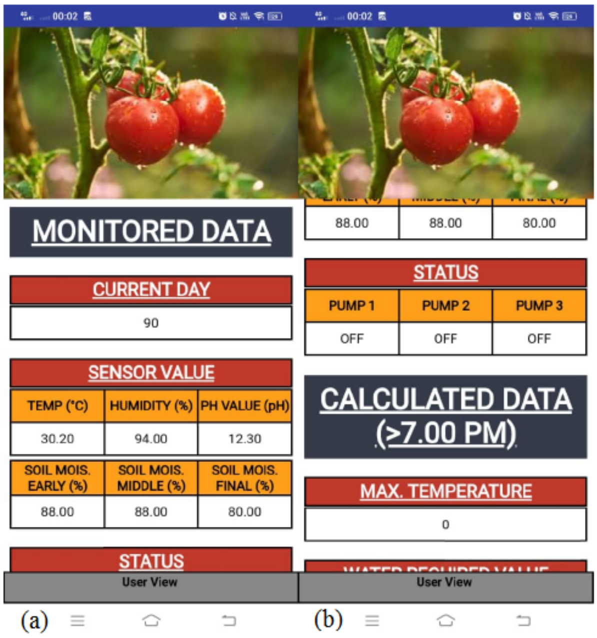

Figure 8. Mobile application interfaces before irrigation process starts at 7 pm.

temperature, humidity, pH level, soil moisture, and status of water pumps (i.e., ON or OFF) in mobile applications. There are three water pumps for three different poly bags which are indicated as PUMP 1, PUMP 2, and PUMP 3 in the mobile application interface. PUMP 1 supplies water for an early stage, PUMP 2 supplies water for a middle stage, and PUMP 3 supplies water for a final stage of tomato plants. The temperature measurement occurs from 7 am to 7 pm in a day. Within this time frame, the water pump is in an OFF state. After 7 pm, the system calculates the maximum temperature of the day and releases the water, and the amount of water is determined based on Eq. (4) and Eq. (5). Fig. 9 illustrates the mobile application interface at 7 pm where the irrigation process began. The T_{max} is displayed, and all three water pumps are in the ON state. The released amount of water is also displayed in the mL unit.

4. Conclusion

In this study, an efficient irrigation system based on Hargreaves's potential evapotranspiration has been developed to improve the yield and quality of tomato plants for the tropical climate in Malaysia. Based on the analysis of evapotranspiration using the Hargreaves equation, the amount of water can be estimated by using the maximum temperature of the day and the crop coefficient (i.e., tomato growth stages). Three growth stages are considered for the tomato plants which are the early stage (0 – 30 days d.a.p), middle stage (31 – 76 d.a.p), and final stage (77 – 105 d.a.p). Based on a 30-day analysis, on average, tomato plants require 45.5 mL/day, 87.4 mL/day, and 60.8 mL/day respectively for the early, middle, and final stages of growth. A mobile monitoring application is also developed in which the user can monitor the environmental parameters that can affect the growth of tomato plants such as temperature, humidity, soil moisture, and pH level. Overall, the developed irrigation system increases the efficiency of the irrigation process, reduces the farming cost, and improves the yield and quality of tomato plants. In the future, the system can be improved by integrating it with a water-soluble fertilizer dispenser system.

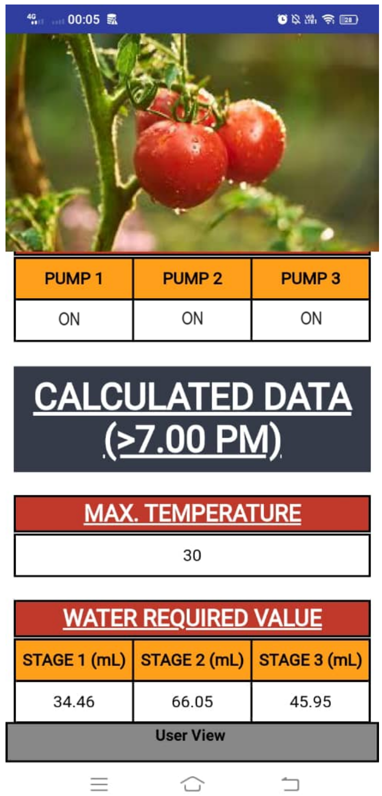

Figure 9. Mobile application interface at 7 pm.

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Authors Contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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