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Thermoelectric-Based Low-Cost Water Chiller via Peltier-Plates

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ABSTRACT

This study aims to design and build a water-chilling device for strawberry irrigation in low-land areas in Malaysia. Strawberries possess better growth in a chilled environment. On that note, a chilling thermoelectric device known as the Peltier plate has been used in this project, which follows an open-cycle system. This process is cost-effective and more convenient than the other methods used for strawberry plantation, such as providing an air-conditioner, which is costly, and using a sprinkler, which may rot the strawberries in wet conditions. Therefore, we propose a low-cost chilling device to chill the water with low-temperature water to be applied in strawberry plants. The plant treated with the water chiller showed better growth with 12 cm of height. The thermoelectric effect has been adopted in this study as the source of chilling since it reduces the temperature on one side and increases it on the other side. The heat is to be discharged using two fans to increase the difference in temperature between the two sides of the thermoelectric device. It involved the Peltier effect, which generates the voltage from the power source to heat/temperature differentials. The obtained result revealed a temperature difference of 5.7 °C between the water-in (27 °C) and water-out (21.3 °C), considered the optimum temperature for strawberries to survive well.

1. Introduction

Malaysia is considered one of the hottest countries; thus, it substantially requires cold conditions. The plantations carried out here also demand suitable light, heat and water to survive regardless of the state of the natural atmosphere. Strawberries are highly treasured, owing to their aromatic nature, upbeat color and harmony [1]. Hence, they need a lot of heat and light to grow well, and they do best in warm, dry circumstances with at least 6 hours of sunlight every day [2]. Thus, strawberries tend to dry out quickly, as they have shallow roots. Therefore, they are required to be watered continuously. Here lies the significance of a chiller since it is also needed to be assured that the plants

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do not get overwatered or suffer from a lack of proper watering, as strawberry plants are pretty sensitive to these kinds of environmental issues [3]. So, this consistent regulation of the plant can be effectively conducted in the greenhouse. Although there is no frost damage in a greenhouse, and strawberries can grow throughout time [4], greenhouses may become quite hot, especially in the summer, necessitating frequent watering. Ali *et al.,* [5] testified the performance analysis of various configurations of evaporative cooling, including a direct evaporative cooling, indirect and falling film in various kinds of weather of Pakistan, including different states. It has been observed that direct cooling systems works best in dry and hot weather for some states.

There are other ways to regulate the temperature of water irrigation for strawberry plants, such as using an air-conditioner [6], as strawberries are adaptable to lower temperatures. However, it is quite challenging to maintain due to higher costs. Moreover, sprinklers are also used to water the strawberries, but they are highly likely to contaminate the plant, and it is not easy to continuously keep applying chilled water. Hence, introducing a water chiller device can be more convenient for the plants to survive well in a condition of reduced temperature. Several researchers have focused on improving the control of chillers and cooling towers to upgrade their performance. However, most of them emphasized either power or water savings without considering the inevitable trade-off between them. Water chillers are commonly built for the refrigeration system. For example, Liu *et al.,* [7] have reported a continuous adsorption water chiller in which silica-gel water was used.

Moreover, Jeon *et al.,* [8] reported the combination of a screw water-chiller with a ground source heat pump to design a hybrid chilling system. On the other hand, some researchers have also implemented a chilling system for plantation purposes. For example, Shigeoki *et al.,* [9] applied a commercial heat pump to cool strawberry plants via a heat exchanger in the greenhouse. However, it supports partial cooling only. A water tube was connected to the chiller tank of the heat pump. However, the heat exchanger length was not appropriate for efficient geothermal energy. On that note, the parameters of a heat exchanger are essential factors. As per the report of Phu and Thao [10], owing to the change in the inclination angle of a flat tube heat exchanger, the overall heat transfer mechanism can change regardless of the heat transfer surface extension (heat transfer performance can increase). One thermal management system involved proton electrolyte membrane fuel cells, which can be replaced by a hybrid nanofluid containing aluminium oxide and silicon oxide as an efficient cooling medium and enhances the heat transfer performance, as reported by Idris *et al.,* [11].

Chaichana *et al.,* [12] also reported on the effect of heat load due to light-emitting diode lightning, but other conditions have also been scrutinized, such as temperature and moisture. However, in order to do that, an air-conditioner has been used. Although it encompassed comfort and controlled process applications and chillers are primarily used here, it is expensive. Herein, a low-cost water-chilling system has been designed for better growth of strawberry plants, which require 10 °C to 26.67 °C) of water temperature [13]. The mentioned temperature condition has been set as the necessary output from the system. The system supports the reduction of the water temperature to meet the required temperature for strawberries, which can be assisted by a thermoelectric effect, which is classified into the Peltier effect and Seebeck effect [14]. The power generated from the heat/temperature difference is known as the Seebeck effect. However, when heat/temperature differentials are generated from the power, it is known as the Peltier effect. This corresponds to one of the significant devices to operate the required temperature of the water, known as Peltier plates. Peltier plates are being applied in camping coolers, spacecraft, and CPUs [15], but have not been thought of being used as a water chiller for plantation yet. Rahman *et al.,* [16] reported on a Peltier-based thermoelectric cooling box followed by its working mechanism as a cooling system, which was proved to exhibit efficient cooling capacity due to faster temperature drop without the presence of any beverage inside the box.

A French Scientist named Jean-Charles-Athanase Peltier discovered the Peltier effect, which denotes that an electric current produces heat or cold at the junction of two different metals based on the direction of current flow [17]. Thus, the Peltier plate is effective in terms of utilizing voltage to produce a temperature gradient. It maintains a consistent balance over temperature by increasing it on one side and decreasing it on the opposite side [14]. Moreover, the temperature difference followed by concentration difference and the presence of various fluids can also lead to thermal and concentration stratifications [16]. Hammad *et al.,* [18] worked on water cooling via the Peltier effect, where he made good use of the advantage of the thermoelectric module. With time, the temperature kept decreasing. However, he constructed a circuit with five transformers to convert alternating current to a direct current of 10 amperes (A) with a voltage of 12 volts (V). Therefore, in this project, one power adapter of 12v and 10 A has been used to power the 6 Peltiers with 2 V each and the fan.

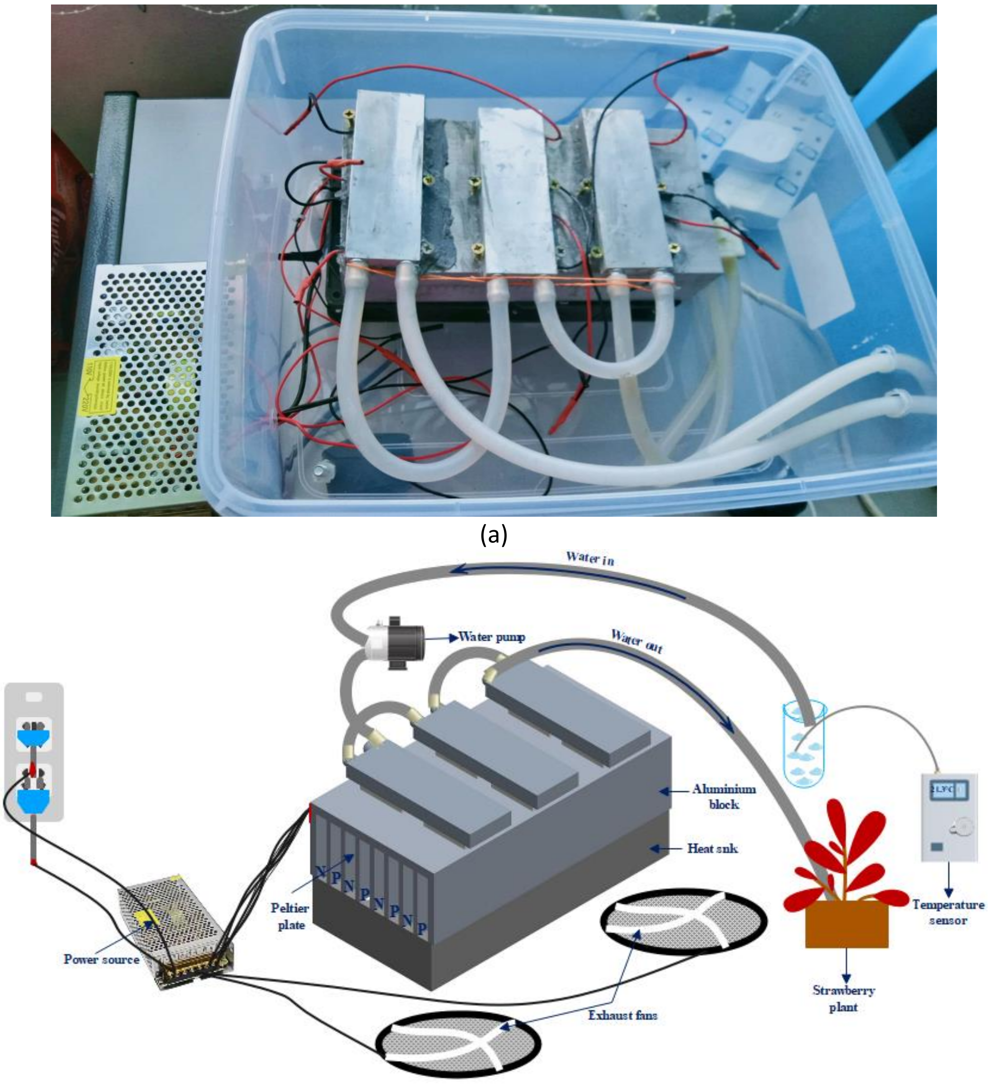
Furthermore, water-chillers are developed so that the water, which is applied to the plants, touches the glue that eventually affects and contaminates the water due to their inflexibility, as they are connected via ordinary solder or sinter bonds between the interconnection and ceramic wafers [19]. In this project, the isolation techniques involved adding thermal grease and silicone glue, which kept the plates in distant locations. The jug with water was placed far away from the Peltier and water pump connection. Moreover, only one tube has been used to transfer the chilled water to the soil, which is effortless and convenient for the whole plantation process, along with the maintenance of safety concerns. Three festival strawberry plants were treated with three different conditions: the water chiller, air-condition and ice, where air-condition and ice have been used to treat the plants with conventional methods. It has been observed that the plant treated with the water-chiller showed enhanced growth with 12 cm of height in one month. Other researchers have implemented the Peltier device for thermoelectric-based systems and utilized the heating and cooling effect to optimize the system. However, the capability of the Peltier effect has not yet been explored for plantation system, which has been attempted to be executed in this work.

2. Methodology

The list of apparatus used for the project is depicted in Table 1. The design prototype and the overall work procedure of the water-chilling system are illustrated in Figure 1(a) and (b), respectively. Open-cycle system type has been used to build the prototype to maintain low cost. Six Peltier plates are connected in series with a set of three on one side and the other three on another side. The Peltier plates were reduced from 10 m to 8 m to avoid the heat produced by each plate affecting the chilling from the other plates. They are positioned between aluminum blocks and heat sink. There are three aluminum blocks, and each contains two Peltiers. The aluminum blocks potentially benefit the system for its thermal properties since it cools the water directly and supplies into the jug [4]. Below the heat sink, two exhaust fans are located below the heat sink, which circulate air to the heat sink to reduce the temperature. The lower portion of the Peltier is hot, so the heat sink dissipates heat from the bottom part [20]. For isolation, the Peltier plates are attached to the heat sink via thermal grease and silicon glue.

Table 1
List of materials for building low-cost water-chiller

Materials	Quantity
Wires	1 (8 m)
Cutter	1
Electric tape	1
Welding pen + Solder	1
Voltameter	1
Knife Cutter	1
Wire heat isolator	1 (1 m)
Peltier plate	8
PC fan	2
Aluminium heat sink	1
LCD thermometer	1
AC-DC adaptor	2
Switch	2
Basket (case)	1
Hose	1 (8 m)
Pan	1



(a)

(b)

Fig. 1. (a) Design prototype of the water-chilling system (b) Schematic of the work procedure

A suitable-sized basket was used as a case, as it has an opening for air to flow in and out to achieve an effective heat removal process. The fans and the Peltiers have different power supply adaptors (a total of two) since the plates take most of the power and do not allow the fans to be turned on, which increases the heat produced. This, in its way, affects the heat difference between both sides of the Peltier plates. Each Peltiers is powered with a voltage of 2 V, thus 12 V in total and 10 A of current. The power is applied for 15 minutes to operate and reduce the temperature. The water is pumped from and into the jug to circulate through the cooled aluminum blocks to initiate the water-chilling process. The chilled water is applied onto the strawberry plant soil via a tube used in the system for the purpose of watering out. The temperature change has been noted from the temperature sensor.

Three strawberry plants (festival plants) [21] have been chosen to be monitored under three different conditions. The first plant is provided with chilled water from the water chiller (with water chiller). Another is kept in an air-conditioned room, putting ice on the surface of the soil (conventional (air-conditioned)). The third plant is kept at room temperature by putting ice on the surface of the soil (conventional (room-temperature)). The ice cubes melt gradually, and the plant gets chilled water. All the plants were controlled simultaneously for 30 days to identify their growth conditions. The plants were being watered every morning. Initially, the plant with the chilled water was started to be grown until it reached the height of 5 cm, then the other plants were started to be grown considering 5 cm as the origin. The plants were given plant growth lights combining three red, two blue, and one white. The heights were measured by placing a ruler beside the plant and estimating the distance from the surface of the soil to the tip of the plant.

3. Results

The working mechanism of the thermoelectric effect-based device has been illustrated in Figure 2. It involves two semiconductors, known as positive-type (P-type) semiconductors and negative-type (N-type) Bismuth telluride semiconductors [21], and a heat source. The semiconductors are connected to a metallic bridge, as seen from the diagram. This setup is known as a thermocouple [22]. N-type semiconductor contains excess electrons, whereas P-type semiconductor lack electrons. So, when heat is applied, electrons in the N-type semiconductor gain heat energy [23], which gets converted to kinetic energy, and they start moving haphazardly. Owing to the random movement of electrons for the accumulation of surplus heat, they tend to move to the cooler side. Since the P-type semiconductor has sufficient space to accept electrons, the electrons with heat energy occupy the space. Thus, this flow of electrons produces an electrical current. Now, if the voltage or the potential difference is to be measured across the semiconductor, it is measured in terms of the temperature difference between the hot and the cold side. Since the voltage of the temperature difference is measured, it is quite little in amount for each thermocouple. On that note, to generate more functional power, the thermocouples can be assembled together.

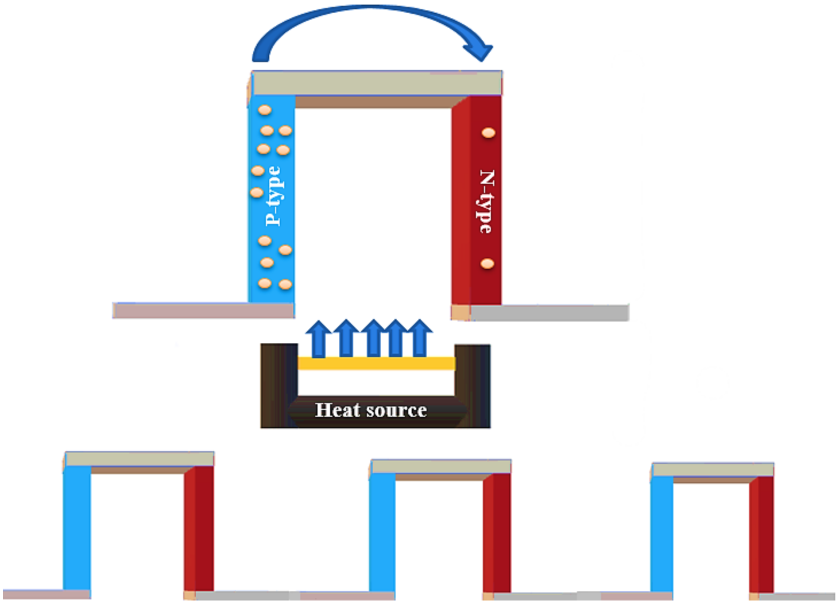


Fig. 2. Working principle of thermocouple

Therefore, Peltier plates function the same way as a thermocouple. The detailed configuration of Peltier has been represented in Figure 3(a), and the structure of the Peltier and vapor compression unit has been illustrated in Figure 3 (b) [24]. It follows the exact mechanism. When the current flows through the junctions of the two conductors, heat is removed from one junction and deposited on the other, and chilling occurs. As an alternative to the heat source mentioned above, if a voltage is applied to the Peltier plates, supposedly from a battery, it responds in the same way as in the thermocouple, which refers to the thermoelectric effect [25]. Hence, upon applying a voltage to the Peltier plates, basically, heat is transferred from the hot side to the cold side, as according to the third law of thermodynamics, heat is usually transferred from an object with a higher temperature to that with a lower temperature [26]. Hence, when the power is generated from the source to the pettier in this thermoelectric device system, it produces heat, which rises the temperature of the water. That high temperature from the water is taken out and transferred to the top part, where air flows to discharge heat from the heat sink, and thus the water temperature cools down. This method refers to the discovery of thermoelectric cooling and temperature control, today's most widely used thermoelectric applications [22]. Budiyanto *et al.,* [27] reported on the analysis of the application of a thermoelectric cooler to control the room temperature of unmanned surface vehicles to keep stable. The mechanism, in general, is explained in Figure 3 [28]. The temperature of the water produced in the device was 27°C, and the output attained was 21.3°C. Thus, 5.7°C of drop in temperature has been observed due to the chilled water provided to the plant from the water chiller. The direction of water flow through the Peltier plates has been depicted in Figure 4.

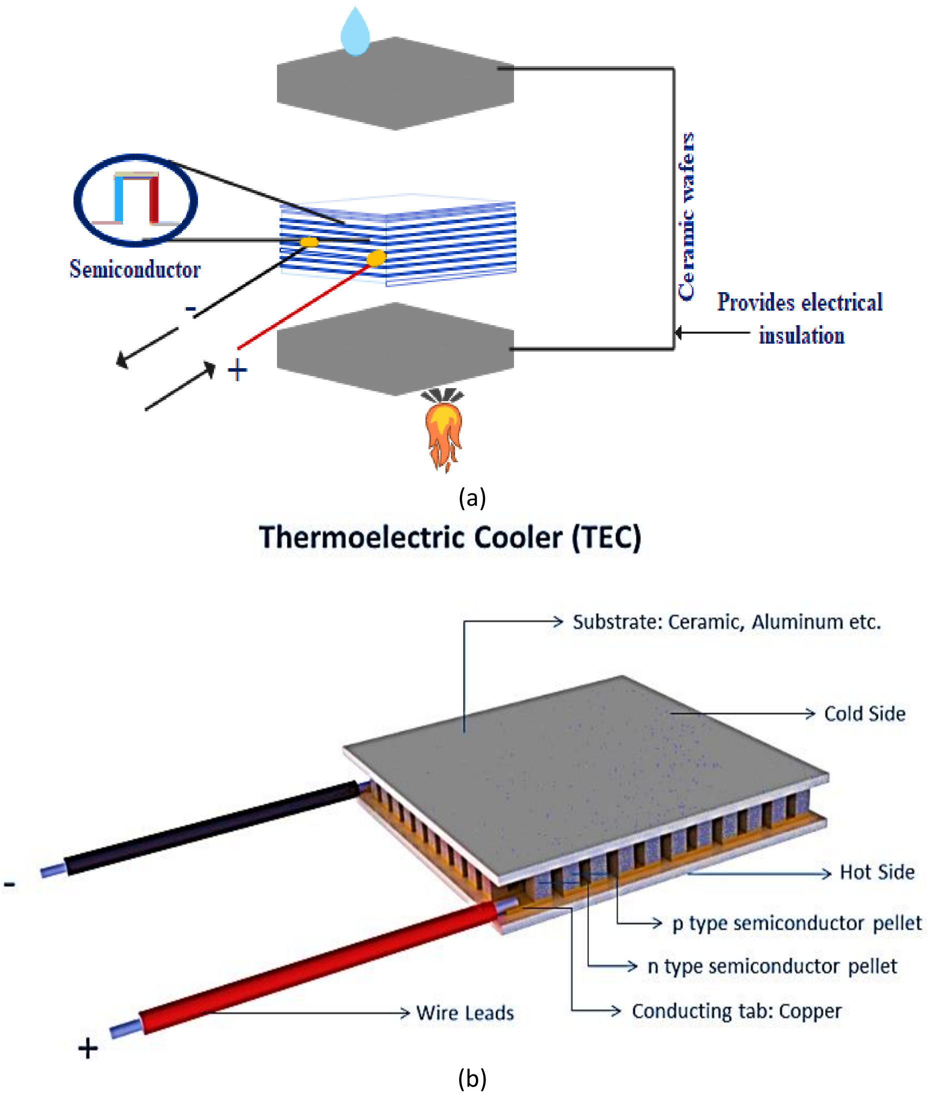


Fig. 3. (a) Detailed configuration of Peltier (b) Main structure of Peltier [30]

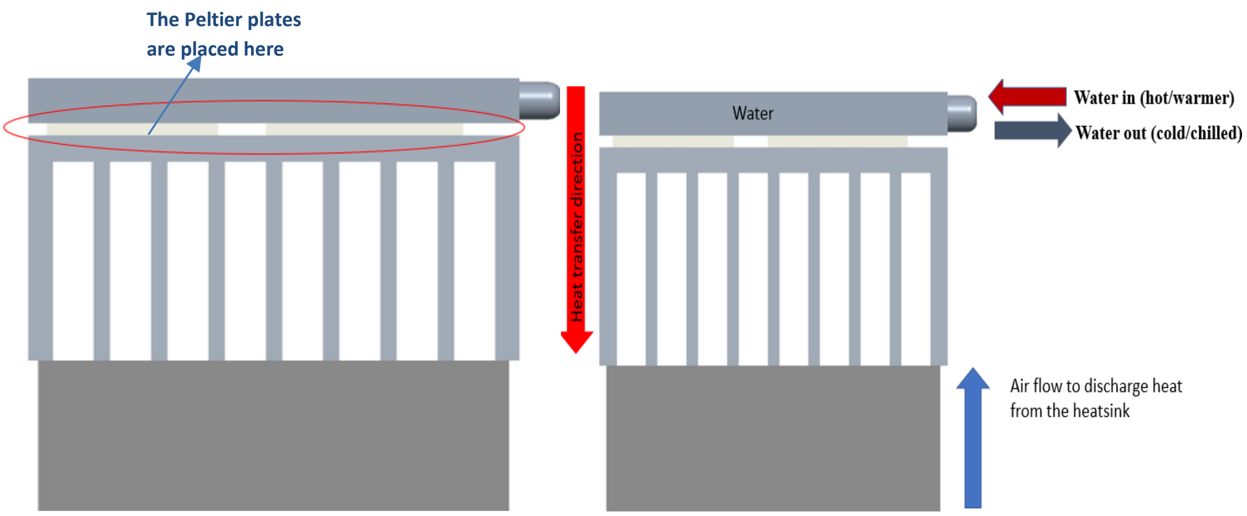
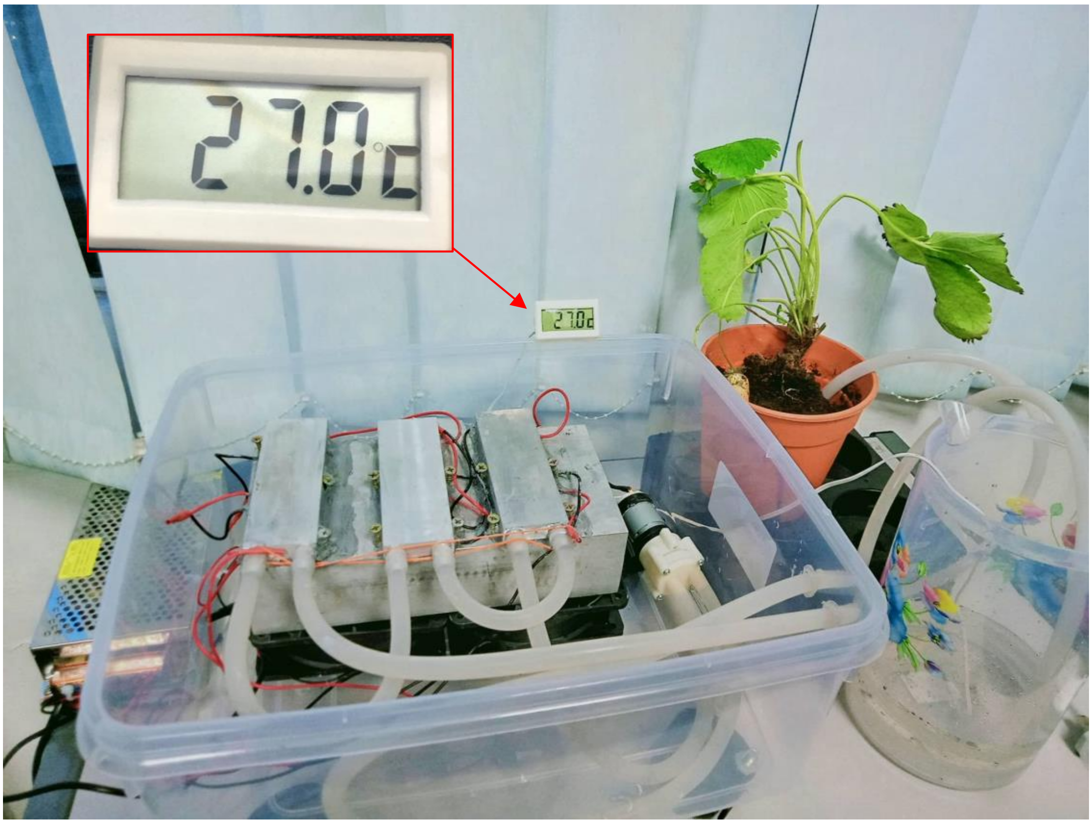


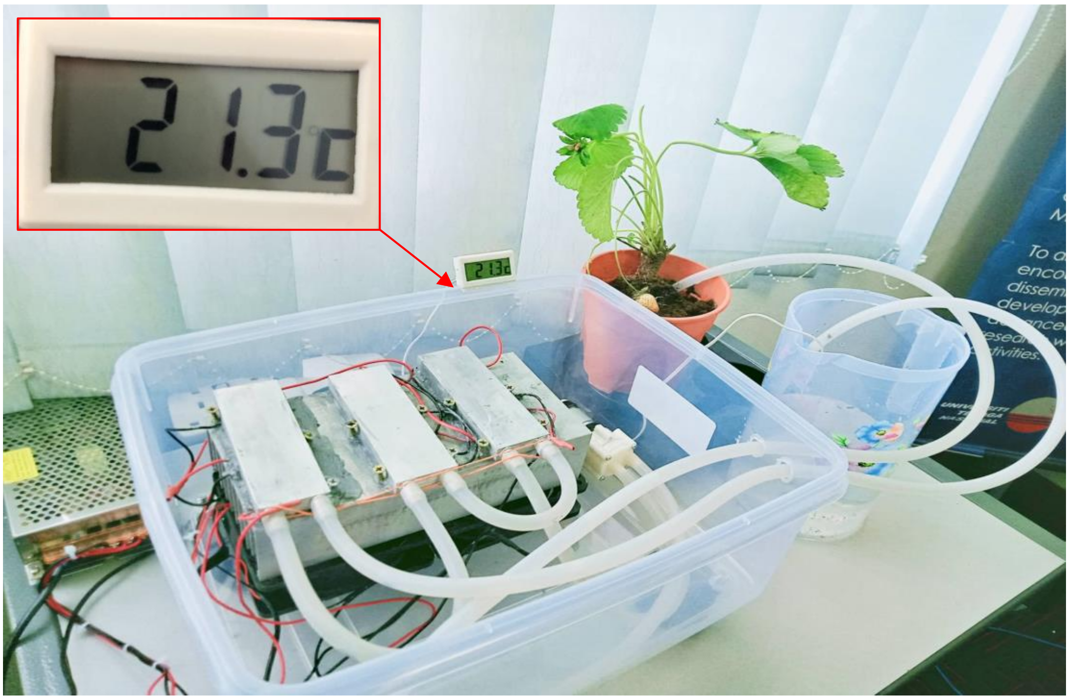
Fig. 4. Water flow operated via Peltier plates

In order to continuously keep one side of the Peltier cool, an exhaust fan is used, which contains a thermoelectric generator [29] that attains the Seebeck effect. It is connected to each of the plates, and when voltage is applied simultaneously, the thermoelectric generator in the fan receives the voltage applied from the power source. That voltage generates a charge to operate the fan, which flows air and attains the Seebeck effect. If both the top and bottom sides of the fan hold the same temperature and that held by both sides of the Peltier plates, then the fan will not be charged since it follows the Seebeck effect, which works with temperature differentials. That is why the top half of the fan is always required to remain cooler by radiating as much heat as possible relative to the bottom section. To increase the temperature differentials, the base plate of the fan is required to occupy a greater surface area to absorb heat.

On the other hand, the top side of the fan should have a larger surface area to emit maximum heat away, which aids in keeping the top section of the Peltier fan cooler than the bottom section. The voltage produced in the Peltier plates depends upon the heat/temperature difference. If the heat difference is lower, the voltage would also be lower. Hence, to maximize the voltage generated in the system, Peltier plates are grouped together, as shown in Figure 2, to increase the heat difference and hence, more power is generated. Thus, to monitor the temperature, a thermometer has been used. It consists of a probe, which is exposed to the water and heated initially. If the probe senses greater heat being induced by the water, which is much different from the outside, a larger voltage is generated. Thus, higher temperature difference is observed, which is calculated by the thermometer. So, to apply the voltage to transfer the heat, the Peltier effect is applied, which produces a thermoelectric cooler. On that note, the heat sink plays an important role, which moves excess heat away from the source. Peltier has been widely used due to its simple structure, less noise and low weight and size [18]. Its mechanism follows that, as long as the voltage is applied, each side of the chip is opposite of the other side, and as per the requirement, the cooling side will be used to cool the water. The overall design of strawberry plant with the initial and final temperatures of the water have been displayed in Figure 5(a) and (b).



(a)



(b)

Fig. 5. Overall work design with (a) Initial temperature (b) Final temperature

Based on the experiment on identifying the plant's growth concerning the conditions mentioned above, it has been observed that the strawberry plant occupied an average height of 12 cm in 30 days upon applying the water-chiller system. However, the heights were more or less in a similar level of variation, whereas the usage of a water-chiller has been determined to be relatively a more controlled condition, as the plants could continuously receive chilled water, which aided in making the growth rate faster. The growth of each plant under different conditions has been illustrated in Figure 6, which shows the change in height concerning the number of days. The tastes of all the berries from the plants are the same, although the one treated with the water-chiller has been observed to be taller than the other plants. The average plant heights in conventional (air-conditioned) and conventional (room-temperature) with ice were determined to be 7.39 cm and 7.09 cm, respectively.

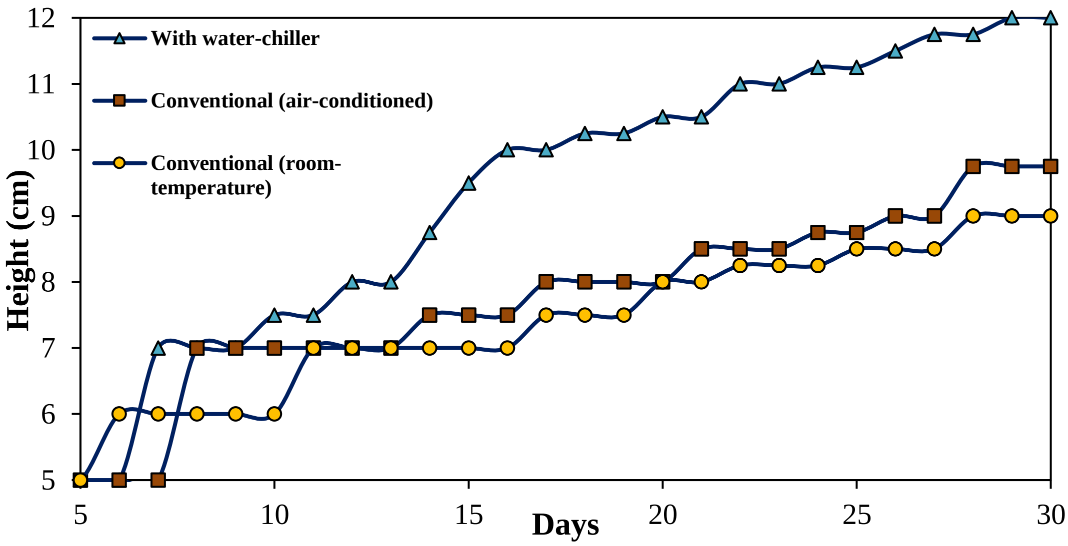


Fig. 6. Average plant height for each plant treatment

4. Conclusion

In conclusion, the prototype has met the strawberry requirements based on the mechanism constructed for adjustable water temperature via a water chilling system. An open-design cycle system has been built, which is much more adequate to the system's needs. Since water is directly dropped into the plants, reducing the components used for the system is advantageous. Moreover, the application of the designed water-chiller has turned out to be advantageous for the improved growth of the strawberry plant occupying 12 cm of height, which was greater than the heights of the other two plants, as the plant could receive continuous chilled water. Therefore, an open-cycle system is productive in terms of cost. However, future work, including a control system, can be executed to control the temperature produced by the system. Smaller-sized heat sinks can be used to be attached to the Peltier plates to enhance the cooling process, as the heat absorption by the heat, which is transferred to the fan, gets limited due to the larger size of the heat sink. Moreover, the heat sink should be compatible with aluminum blocks for efficient heat transfer. For *e.g.,* Jowsey *et al.,* [31] investigated the heat and flow profile of nanofluid flow in a multilayer microchannel heat sink, where aluminum oxide nanofluid was confirmed to be better in terms of heat transfer compared to water. Additionally, the isolation method can be improved to reduce the cooling time. Furthermore, one of the fundamental precautions needs to be taken, that is, the current & voltage supplied into the Peltier plates should be stable for the system to operate efficiently [18].

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