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Performance Investigation of 18 Thermoelectric Cooler (TEC) Units to Supply Continuous Daily Fresh Water from Malaysia's Atmosphere

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Abstract: In this work, an atmospheric water generator (AWG) system called the medium-scale AWG (MSAWG) was designed, fabricated, and tested in Universiti Sains Malaysia (USM) under the outdoor tropical climate conditions of Malaysia to investigate the amount of fresh water production in successive periods of 24 h. The MSAWG consisted of 18 thermoelectric cooler (TEC) units, 18 internal finned heat sinks, 18 external finned heat sinks, 18 direct current (DC) cooling fans, an air-conditioner mesh air filter, and an axial ventilation fan. It was found from the results that the hourly values of water production of MSAWG were proportional to the hourly rates of relative humidity, but they were inversely affected by the corresponding hourly values of the ambient temperature. Night-time and early morning were the most effective times to produce the highest amount of fresh water from Malaysia's atmosphere using MSAWG, as the increase in the rates of relative humidity and the decrease in the values of ambient temperature occurred over these periods. Based on the varied hourly rates of relative humidity with the ranges between the minimum rate of 55% and maximum rate of 85%, an equation of Y = 0.2285X + 36.675 with R^2 of 0.9404 was achieved from the 48 h experimental work to estimate the water production of MSAWG in Malaysia, where Y and X were indicated as the rate of relative humidity and the value of water production, respectively, in this equation. In conclusion, the MSAWG produced a consecutive cumulative water volume of 3.432 and 6.997 L experimentally in the periods of 24 and 48 h, respectively. The estimated cost per liter for MSAWG was USD 0.466. Some water quality parameters of the fresh water produced by MSAWG were analysed in the laboratory, which showed that they met the World Health Organization (WHO) drinking water standards. Therefore, MSAWG can be employed as a sustainable alternative to generate annual daily fresh water from Malaysia's tropical atmosphere and aid in mitigating the problem of unpredicted water shortage in the country.

Keywords: tropical climate; relative humidity; humid air condensation; thermoelectric cooling; freshwater production

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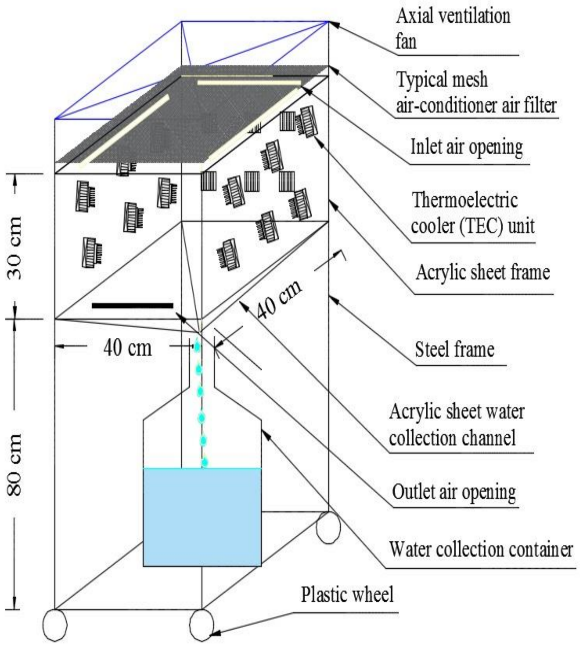
1. Introduction

The world is faced with the problem of scarcity of fresh water. At present, more than 1.2 billion people lack access to clean drinking water. By 2030, almost half the world's population will be living in water-stressed conditions [1]. All tropical countries located on the equator with the latitude of zero degrees (countries in South-East Asia, East Africa, Central Africa, West Africa, the Caribbean, Central America and South America) are known as humid countries due to their high average values of annual rainfall, relative humidity, solar irradiance, and ambient temperature [2]. The humid atmosphere stores a wealth of water, which is affected by the variations in ambient temperature and the relative humidity of the location (Figure 1) [3]. One of these tropical countries is Malaysia, which is located in South-East Asia. Malaysia enjoys varied annual average relative humidity rates from 84% in the dry season to 88% in the wet season, and varied annual average values of ambient temperature, from 23 to 32 °C [4] and 1.0 m^3 of its atmosphere carries about 21 g of water vapor; equivalent to 69×10^9 kg of water vapor within a height range of 10 m that is available in the whole country [3]. Thus, humid tropical countries have a huge volume of fresh water in their atmosphere annually, which is beyond the total amount of available fresh water in marshes, wetlands, and rivers on Earth [5]. Extracting this massive source of fresh water via condensing the humid atmosphere of the tropical zones can solve the problem faced by countries with water-stressed conditions. One sustainable technology used to condense humid air and produce fresh water is the thermoelectric cooler (TEC) unit [6], which has recently drawn significant attention worldwide. A TEC unit is the main component of an atmospheric water generating (AWG) system, which works based on condensing the humid air and extracting water from the atmosphere. Very few researchers have stated the performance of the TEC units in terms of generating water from the atmosphere experimentally under controlled indoor conditions. In 2002, Vian et al. [7] designed and fabricated a thermoelectric dehumidifier using three Peltier modules which were tested under indoor controlled varied rates of input power, ambient air temperature, and relative humidity. The system produced a maximum rate of 0.969 L of water per day under indoor controlled maximum rates of input power and relative humidity. In addition, V. P. Joshi et al. [6] investigated the performance of a thermoelectric fresh water generator (TFWG) under indoor controlled conditions using an air conditioning test rig in the period of 10 h in India. The TFWG comprised 10 Peltier modules, an external heat sink, four cooling fans, an internal heat sink and an axial ventilation fan. The Peltier modules were placed linearly in an array with the distance of 0.02 m on a long external heat sink with the length of 0.70 m and the surface area of 0.7 m^2. Four cooling fans, each having the velocity of 0.025 m/s, were placed at the external heat sink to dissipate the excess heat of the Peltier modules. An internal heat sink with a surface area of 0.2 m^2 was placed at the cold side of the Peltier modules to condensate the air. An axial fan with the maximum air flow rate of 50.4 m^3/h was also used to vacuum the air into the TFWG for accelerating the condensation process. TWFG produced a maximum water yield of 240 mL per 10 h at an indoor controlled ambient temperature of 30 °C and a controlled rate of maximum relative humidity of 90%. In 2020, He et al. [8] designed and fabricated an atmospheric water generator (AWG) using two TEC units in India and the influence of the variations in relative humidity and the air inlet flow rate on the water production of the AWG system under controlled indoor atmospheric conditions was investigated. The total cold surface area over the internal heat sinks was 180 cm^2 [8]. An indoor experiment with a period of 10 h was prepared and controlled under a constant dry bulb at a temperature of 24 °C. The total water yields of 85.5, 135.5, 186.7, 245.8 mL/10 h were obtained within the controlled relative humidity rates of 60, 70, 80 and 90%, respectively, using an air humidifier. The cumulative water production values of 85.5, 94.4 and 109.6 mL/10 h were also gained via vacuuming the air flow rates of 30, 50 and 70 m^3/h respectively into the system. The researchers concluded that the AWG produced the maximum amount of water under the indoor controlled conditions of a relative humidity rate of 90% and an air flow rate of 70 m^3/h in a period of 10 h [8]. In 2013, Tian et al. [9] experimentally studied the parameters affecting the amount of extracted water by a thermoelectric cooler (TEC) unit with a cold surface area of 579.6 cm^2. They obtained 50 mL of water with an average relative humidity of 77% over a short period of 3 h. An atmospheric water generator (AWG) system was fabricated and tested under the outdoor climate conditions of Madrid, Spain in 2012 [10] with the aim to harvest water for young trees using a thermoelectric cooling (TEC) unit powered by a 12 V battery with the capacity of 17 Ah re-charged by a 30 Wp photovoltaic module. The maximum water production of the AWG system was obtained in the morning hours from 5 to 8 a.m. which was found to be the best period of the day for collecting water, as the maximum rate of relative humidity and the lowest value of ambient temperature were observed during this period. The AWG system produced between 2 and 4 mL of water [10] within an hour. A portable water generator using two thermoelectric coolers (TECs) was designed and investigated experimentally under indoor controlled climate condition in China in 2017 [11]. Different inlet air relative humidity and air flow rates were investigated to obtain their impacts on the amount of generated water and condensation rate. The maximum amount of produced water was 25.1 g each hour at a relative humidity rate of 92.1% and ambient temperature of 23.6 °C [11].



(**a**)

(**b**)

Figure 1. (**a**) Sketch of medium-scale atmospheric water generator (MSAWG); (**b**) the experimental photo of the fabricated MSAWG.

The total base areas of the internal heat sinks placed to the cold side of the Peltier modules used in [6,8,9,11] were 200, 180, 579.6 and 180 cm^2, respectively. The maximum amount of water generated over the internal heat sinks of [6,8,9,11]'s AWG systems under the relative humidity rates of 90, 90, 77 and 92.1% were 240, 245.8, 50 and 25.1 mL over the periods of 10, 10, 3 and 3 h using 10, 2, 2 and 2 Peltier modules, respectively. The amount of water produced by each Peltier module per an hour used in [6,8,9,11] exposed to the relative humidity rates of 90, 90, 77 and 92.1% were 2.4, 9.335, 8.33 and 4.18 mL, respectively. The researchers [6,8,9]'s AWG systems also produced the maximum amount of water under the highest rate of vacuumed indoor controlled ambient air throughout the experimental works.

As Malaysia is located on the equator and enjoys varied annual daily average relative humidity rates from 84% in the dry season to 88% in the wet season as well as varied annual daily average values of ambient temperature from 23 to 32 °C [4], and the application of thermoelectric cooler (TEC) units in terms of producing high amount of fresh water requires a high rate of average relative humidity [6–11], the outdoor tropical climatic condition of Malaysia is appropriate for the thermoelectric cooler (TEC) units to be applied to extract water from its atmosphere every day in a year. However, the non-tropical areas pose limitations to the appropriate climate conditions for the thermoelectric cooler (TEC) units to be used for daily fresh water generation due to the long periods of cold and dry seasons in a year. It was also observed in the literature [6,8,9,11] that the majority of the works on water production investigation using thermoelectric cooler (TEC) units were conducted under indoor atmospheric conditions with the controlled rates of relative humidity and ambient temperature. Thus, there is still ample room to conduct research by investigating the application of the thermoelectric cooler (TEC) units in Malaysia's outdoor tropical climate in supplying continuous daily fresh water from the atmosphere. According to the World Health Organization (WHO), a person needs 2–3 L of potable water per day for survival [1], and as each thermoelectric cooler (TEC) unit in [6–11] was able to produce high rate of fresh water from the atmosphere by being exposed to the high rate of relative humidity, therefore, in this work, a medium-scale atmosphere water generator (MSAWG) system comprising 18 thermoelectric cooling (TEC) units (which encompassed 18 Peltier modules, 18 internal heat sinks, 18 external heat sinks, 18 cooling fans) along with an axial ventilation fan and a mesh air-conditioner air filter was designed, fabricated, and tested in subsequent periods of 24 h under Malaysia's outdoor tropical climate and exposed to varied hourly rates of relative humidity and ambient temperature, vacuuming the outdoor tropical climate into the MSAWG system to investigate its ability to supply sufficient and continuous daily amounts of fresh water per capita, which has not yet been reported. The objective of this work is to determine the fresh water production per capita from Malaysia's atmosphere using the MSAWG system. The effects of the varied rates of relative humidity and ambient temperatures of Malaysia's outdoor climate on the amount of water production of MSAWG will be investigated in this work. Furthermore, the cost per litre of the produced water by the MSAWG system and analysis of some water quality parameters of the water produced by the MSAWG system shall also be investigated.

2. Materials and Methods

2.1. MSAWG System Materials and Dimensions

In order to investigate the thermoelectric cooler (TEC) unit's performance in terms of continuous daily fresh water generation per capita from the atmosphere, an atmospheric water generator (AWG) called the medium-scale AWG which included 18 TEC units was designed, fabricated, and tested under Malaysia's outdoor tropical climate conditions. The sketch and photograph of the constructed medium-scale atmospheric water generator (MSAWG) system are presented in Figure 1a,b. The MSAWG in this work comprised an axial ventilation fan, a typical air-conditioner mesh air filter, a frame box made of acrylic sheets, 3 air inlet openings at the top of the acrylic box, 18 thermoelectric cooler (TEC) units, an acrylic sheet pyramid-shaped water collection channel, and a painted steel frame to hold the acrylic sheet frame along with the axial ventilation fan, which are shown in Figure 1a,b.

The typical air-conditioner mesh air filter measuring 40 cm in length and 40 cm in width was placed between the axial ventilation fan and the top layer of the acrylic sheet frame box to avoid dust from the inlet air flowing into the MSAWG system (Figure 1a). The acrylic sheet frame box measuring 40 cm long, 40 cm wide and 30 cm high was used to hold the 18 TEC units at its sides (Figure 1a,b). The top of the acrylic frame was cut to create the inlet air openings on 3 sides to allow the vacuumed air to flow into the MSAWG system. Each inlet air opening had dimensions of 2 cm wide and 30 cm long (Figure 1a). A pyramid-shaped water collection channel made of acrylic sheets with a length of 60 cm, width of 60 cm and height of 30 cm was placed at the bottom of the acrylic frame box to convey the collected water droplets to the water collection container (Figure 1a,b). Eighteen thermoelectric cooling (TEC) units were placed on three sides of the acrylic sheet frame box, with 6 TEC units placed on each side of the frame box (Figure 1a,b). A painted steel frame measuring 40 cm in length, 40 cm in width and 80 cm in height was installed to hold the acrylic sheet frame along with its equipment (Figure 1a,b).

Each TEC unit was made of a Peltier module, with an internal finned heat sink and an external finned heat sink along with a direct current (DC) cooling fan (Figures 2 and 3a,b).

Each Peltier module, internal finned heat sink, external finned heat sink, and DC cooling fan connected to the external heat sink had a surface base area of 0.0016, 0.002, 0.01 and 0.0085 m^2 respectively (Figures 2 and 3b). Each internal heat sink used in the MSAWG included 9 straight fins and each fin had a length of 18 mm, a height of 40 mm and a thickness of 1 mm. The fins stood at the base of heat sink with a spacing of 4 mm from the outer sides of each other. The base of each internal heat sink that was connected to the fins had an effective area of 0.0016 m^2 and a thickness of 4 mm, and was attached to the cold side of a Peltier module (Figures 2, 3a,b and 4).

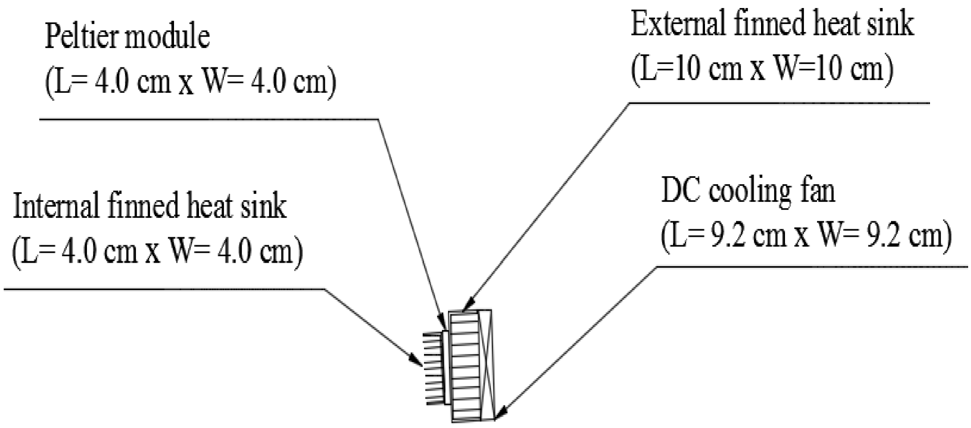


Figure 2. Sketch and the components of a thermoelectric cooling (TEC) unit with the dimensions used in this work.

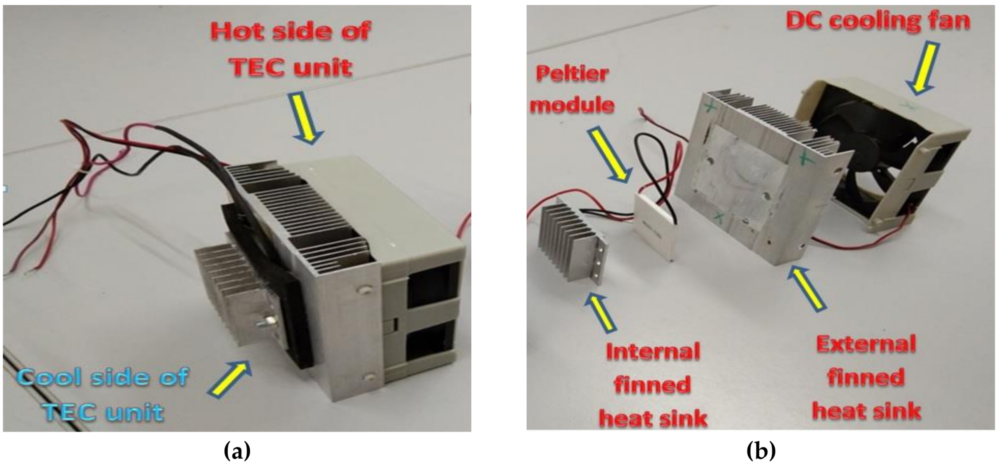


Figure 3. Photographs of (**a**) an assembled set of a thermoelectric cooling (TEC) unit; (**b**) the main components of a thermoelectric cooling (TEC) unit included the internal and external finned aluminum heats sinks, the direct current (DC) cooling fan, and the Peltier module used in MSAWG.

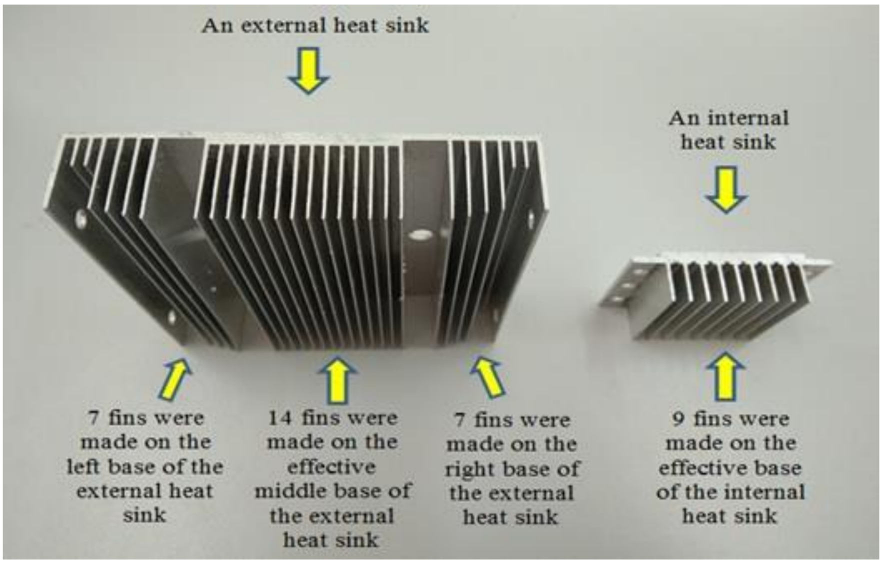


Figure 4. Photograph of the straight fins made on the external and internal heat sinks of a thermoelectric cooling (TEC) unit used in MSAWG.

The base of each external heat sink used in the MSAWG had dimensions of 100 × 100 mm (L x W) (Figures 2, 3a,b and 4), but they had different thicknesses; 40 mm of the width of the external heat sink had a thickness of 4 mm located at the middle side of the base of the external heat sink to aid in dissipating excess heat from the hot side of the Peltier module (Figures 3a,b and 4), and the other 60 mm of the length of the external heat sink located on the right and left sides of the heat sink had a thickness of 2 mm (Figures 3a,b and 4). Each external heat sink used in the MSAWG included 28 straight fins (Figure 3a,b). All the fins had a similar height of 100 mm and thickness of 0.75 mm. However, the length of the fins was set differently to adjust the mould of the DC cooling fan. Fourteen out of 28 fins were made and stood on the middle side of the base of the external heat sink, which had a similar length of 20 mm, with the spacing of 2 mm from each other (Figures 3a,b and 4). Seven out of 28 fins were made and stood on the right side, and the other 7 fins were made and stood on the left side of the inner side of the external heat sink.

The length of each of the 7 fins on the right side of the external heat sink was 21, 8, 8, 19, 20, 21 and 22 mm, which stood with a spacing of 2 mm from each other on the inner side of the external heat sink (Figures 3a,b and 4). The length of the other 7 fins on the left side of the external heat sink had similar lengths of 21, 8, 8, 19, 20, 21 and 22 mm with a spacing of 2 mm from each other (Figures 3a,b and 4). Each external heat sink was coupled with a direct current (DC) cooling fan with the dimensions of 92 × 92 × 25 mm (W x L x H) to dissipate the excess heat from the hot side of each Peltier (Figures 2 and 3a,b). The cooling fan was wired to run at a maximum speed of 2000 RPM throughout the experiment and had a rated power consumption of 1.44 W. In total, 18 TEC units were placed vertically on three sides of the acrylic sheet frame box, as 6 TEC units were placed vertically on each side of the box with the distance of 2.5 cm horizontally from each other (Figure 1a,b). The humid air was passed through the three inlet openings at the top of the acrylic frame and directed vertically at all six internal heat sinks (Figure 1a,b). The MSAWG in this work was exposed to the outdoor tropical climate of Malaysia in an open field in 2 successive periods of 24 h, from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020 (Figure 1b). In this work, 18 thermoelectric cooler (TEC) units were used, and each TEC unit included a DC Peltier module, one internal finned aluminium heat sink attached to the cool side of the Peltier module to condensate the injected humid air, and an external finned aluminium heat sink along with a DC cooling fan attached to the hot side of the Peltier module (Figure 3a,b) to dissipate the excess heat released from the Peltier module. Each direct current (DC) Peltier module had a length (L) of 40 mm, a width (W) of 40 mm, and a ceramic plate thickness of 3.80 mm (Figures 2 and 3b), and contained two external ceramic plates separated by semiconductor pellets. Each Peltier module was rated at 12V, 5.8A current and a maximum power consumption of 60W (Table 1). Each Peltier module was fixed to the bases of each internal and external heat sink using micronized silver thermal paste (Figures 2 and 3a,b). One of the plates of the Peltier module absorbed heat (became cooler) and the other plates dissipated heat (became hotter) when a current passed through the semiconductor pellets (Figure 3b) due to the thermoelectric cooling effect [10]. The temperature at the cold side of each Peltier module was constant at 1 °C throughout this research experiment. The total surface areas of the internal finned heat sinks placed to the cold side of the 10, 2, 2 and 2 Peltier modules of [6,8,9,11]'s TEC units were 200, 180, 579.6 and 180 cm^2, respectively, to condensate the surrounding air and generate fresh water over the surface of the internal heat sinks. As an internal heat sink with a larger area than the surface area of a Peltier module needed to be placed next to a larger number of the Peltier modules [6,8,9,11] in order to achieve the lowest temperature, as low as the temperature of the Peltier modules, in this work, the dimensions of the effective base of each internal finned heat sink were considered to be 40 × 40 mm (L x W). And each internal heat sink had an effective base area of (4 cm × 4 cm) 16 cm^2, which was similar to the surface area of each Peltier module (Figures 2 and 3a,b). The reason for the similarity of the surface areas of each internal heat sink and each Peltier module at the cold side of the TEC unit was to increase the reduction in temperature of the internal heat sink attached to the cold side of the Peltier module exposed to the vacuumed ambient air so that the temperature of the internal heat sink reached 1 °C, similar to the temperature of the cold side of the Peltier module, to condense the humid air effectively. The total cold surface area of the 18 internal heat sinks used in the MSAWG was (4 cm × 4 cm × 18) 288 cm^2 (Figures 1a,b, 2 and 3a,b).

Table 1. Specifications of electrical components of the direct current (DC) Peltier module, DC cooling fan, alternating current (AC) axial ventilation fan, and DC to AC converter used in this work.

Parameters	Values of a DC Peltier Module	Values of a DC Cooling Fan	Values of the AC Axial Ventilation Fan	Values of a Power Supply of DC to AC Converter (Input)	Values of a Power Supply of DC to AC Converter (Output)
Working current (Imax)	5.8A	0.12A	0.20A	1.46A	33A
Rated Voltage	12V	12V	220V	90V	12V
Maximum Voltage	15V	12V	265V	275V	12V
Pmax	60 W	1.44W	55W	400W	400W

2.2. Experimental Set-Up

In the experiment, the MSAWG was placed in an open field at the River Engineering and Urban Drainage Research Centre (REDAC) laboratory in Universiti Sains Malaysia (USM) to expose it to Malaysia's outdoor tropical climate conditions. Outdoor experiments were conducted in 2 consecutive periods of 24 h from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020 using the MSAWG system (Figure 1b) to investigate the effects of a constant flow rate of humid air flowing into the system and the variable rates of relative humidity and variable values of ambient temperature on the amount of water condensed on the surfaces of the system's internal finned heat sinks. The experimental setup of the MSAWG comprised three main things, namely 6 converters of direct current (DC) to alternating current (AC) power supply, 18 thermoelectric cooler (TEC) units, and the axial ventilation fan (Figure 1a,b). The MSAWG was tested in 2 consecutive periods of 24 h in the outdoor tropical climate conditions of Malaysia with varied rates of relative humidity and varied values of ambient temperature. Electric power was supplied to the 18 Peltier modules and 18 cooling fans by six DC to AC power converters in a manner in which each power source was responsible for powering three Peltier modules and three cooling fans in series (Figure 1b). The axial ventilation fan with a maximum spinning speed of 1050 RPM was powered directly using the alternating current (AC) power supply.

He et al. [8] were able to produce maximum water by vacuuming controlled indoor air with a flow rate of 70 m^3/h into their AWG system. Therefore, in this work, outdoor humid air of Malaysia's tropical climate with a similar constant flow rate of 70 m^3/h was vacuumed into the MSAWG system throughout the experiment using an axial ventilation fan. Each Peltier module, DC cooling fan, axial ventilation fan, and DC to AC power converter had the rated current, voltage and the maximum output power of 5.8A, 12V, and 60W, 0.12A, 12V, and 1.44W, 0.25A, 220V, and 55W and 33A, 12V, and 400W, respectively (Table 1). The total fabrication (fixed) cost of the MSAWG with 18 TEC units was around RM 1228.10 or USD 291.01 (Table 2). The annual variable maintenance cost of the MSAWG was expected to be 30% of the total fixed fabrication cost of the electronic appliances in the MSAWG (Table 3), which was around RM 368.00 or USD 87.20, whereas the annual cost of power consumption of the MSAWG in Malaysia was expected to be RM 1752.00 or USD 415.17, considering USD 0.047 for the cost of each KWh consumption charged by the utility company, Tenaga Nasional Berhad (TNB) in Malaysia (Table 4). Table 5 shows the different experiment instruments, namely the digital multimeter, digital humidity meter, anemometer, and measuring cylinder, as well as their accuracies to measure the values of ambient temperature, rates of relative humidity, mass flow rate of humid air flowing through the MSAWG system, and the amount of water production.

Table 2. Fixed fabrication cost of the MSAWG.

Items	Quantity	Unit Cost (RM)	Cost (RM)
Acrylic sheet	1.5 m2	3.00	4.50
TEC unit	18	30.00	540.00
Axial ventilation fan	1	60.00	60.00
Silicon glue	2	5.00	10.00
Power supply of DC to AC converter	6	100.00	600.00
Metal Frame	6 m	2.00	12.00
Wooden box	0.32 m2	5.00	1.60
Total fixed cost			1228.10

US$ 1 ≈ RM 4.22.

Table 3. Expected annual maintenance cost of the MSAWG with consideration of replacing 30% of the total electrical items.

Items Are Expected to Be Replaced Annually	Expected Quantity of the Items to Be Replaced Annually	Unit Cost (RM)	The Annual Maintenance Cost of Items (RM)	Total Annual Maintenance Cost (RM)
Peltier modules	6	10.00	60.00	368.00
DC cooling fans	6	8.00	48.00	
Axial ventilation fan	1	60.00	60.00	
Power supply of DC to AC converters	2	100.00	200.00	

Table 4. Annual power consumption cost of the MSAWG in Malaysia.

Cost of 1 KWh Power Consumption in Malaysia in 2020 (RM)	The Hourly Power Consumed by MSAWG (KW.hr)	Total Cost of the Power Consumed by MSAWG Annually (RM)
0.20	1.0	1752.00

Table 5. Experimental instruments with range and accuracy used in this work.

Instruments	Range	Accuracy
Digital multimeter	0–100 °C	±1 °C
Digital humidity meter	10–99%	±5%
Anemometer	0.2–30 m/s	±0.015 m/s
Measuring cylinder	±0.5 ml	0–50 ml

2.3. Mechanism of Generating Fresh Water by MSAWG

An axial ventilation fan was placed at the top end of the MSAWG, which generated suction of humid air (moist air) into the system. The humid air passed through the 3 inlet air openings on the top of the acrylic sheet frame (Figure 1a,b). Thereafter, the humid air entered the MSAWG and hit the 18 internal finned heat sinks. The method we designed included extracting water from the air using the thermoelectric effect. The internal finned heat sinks were made of aluminum (Figures 3b and 4) and were attached to the cold side of the Peltier modules (Figure 3b). The Peltier module contained several thermocouples combined between two ceramic plates and connected thermally in parallel and electrically in series. One of the plates of the Peltier module would absorb heat (became cooler) and the other plates would dissipate heat (became hotter) as the current passed through the semiconductor pellets (Figure 3b) due to the thermoelectric cooling effect [10]. The temperature of each internal heat sink was constant at 1 °C due to it being attached to the cold side of the Peltier modules. This caused the ambient temperature to drop to the dew point and the humid air started to condense on the surface of the internal finned heat sinks of the TEC units (Figures 1a,b and 5). Finally, the excess air escaped from the outlet air opening, which was made by cutting the acrylic sheet at the bottom of the acrylic frame box (Figure 1a,b). The condensed air in the form of water droplets over the fins of the internal heat sinks (Figure 5) started to flow downward to the pyramid-shaped acrylic sheet water collection channel and into the water collection container due to gravity (Figure 1a,b).

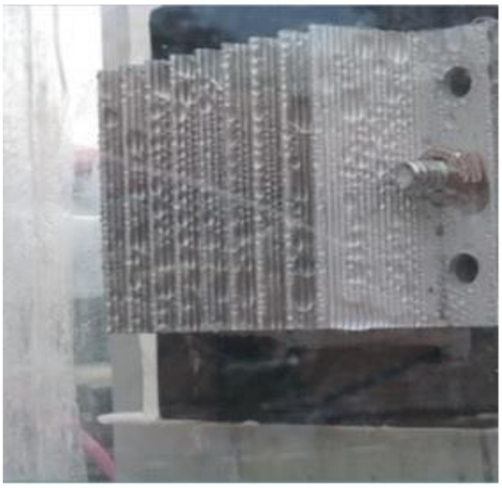


Figure 5. Photograph of the condensed humid air in the form of water droplets on the surfaces of the fins of an internal heat sink of the MSAWG.

3. Results

3.1. Impact of the Rates of Relative Humidity and Ambient Temperature on Water Production of the MSAWG

The performance of the medium-scale atmosphere water generator (MSAWG) system was investigated in a 48 h period from 8 p.m. on 18 March 2020 to 8 p.m. on 20 March 2020 in Malaysia's tropical outdoor climate conditions. The values of ambient temperature, water production, and rates of relative humidity were measured hourly within the 48 h period (2 successive periods of 24 h), as shown in Figures 6 and 7.

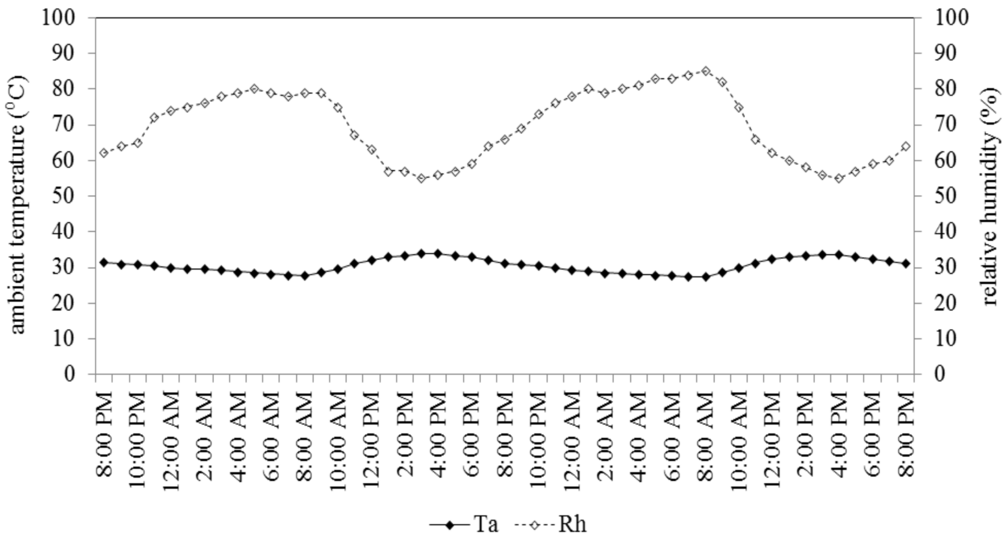


Figure 6. Values of ambient temperature versus the relative humidity rates in Malaysia from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020.

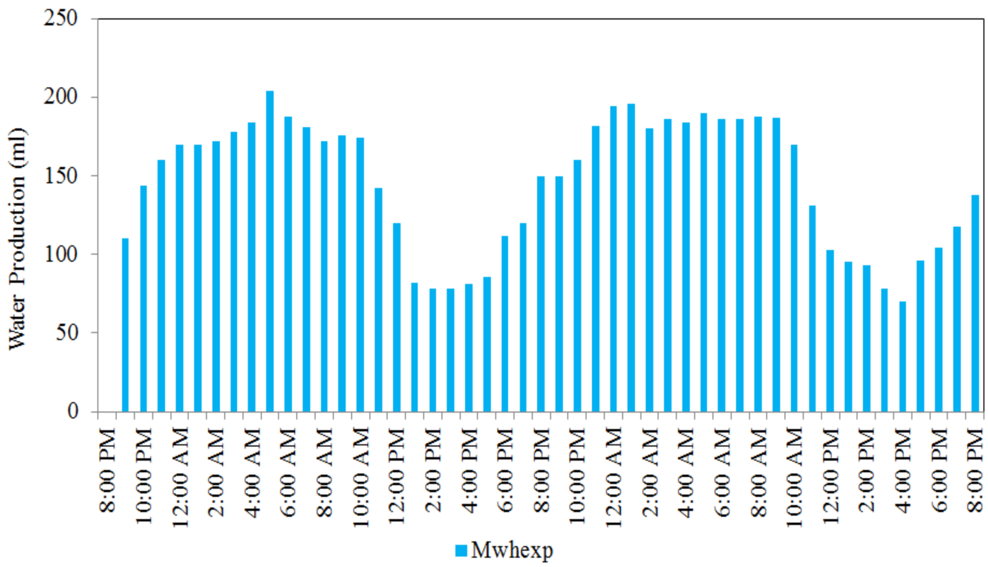


Figure 7. Values of hourly water production (Mwhexp) of MSAWG in a 48 h period from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020.

Figure 6 shows that the rate of relative humidity (Rh) increased from 62% at 8.00 p.m. on 18 March 2020 to 80% at 5.00 a.m. the next day, or 19 March 2020. Afterward, it reduced gradually to the minimum rate of 55% at 2.00 p.m. on 19 March 2020, before it increased to 66% in the afternoon from 2.00 p.m. to 8 p.m. on 19 March 2020. However, the values of ambient temperature decreased gradually from 31.5 °C at 8 p.m. on 18 March 2020 to 27.8 °C at 8 a.m. the next day, 19 March 2020 (Figure 6). It increased slowly from 27.8 °C at 8 a.m. to 33.8 °C at 2 p.m. on 19 March 2020, and then it registered a decline of 2.2 °C from 2 p.m. to 8 p.m. (Figure 6). It can also be observed in Figure 6 that similar patterns were noticed for the rates of relative humidity and the values of ambient temperature for the next 24 h from 8 p.m. on 19 March 2020 to 8 p.m. on 20 March 2020.

It is shown that with the increase and decrease in the values of ambient temperature, the rates of relative humidity fell and rose, respectively, in a period of 48 h (Figure 6). Thus, there is an inverse relationship between the hourly rates of relative humidity (Rh) and the hourly values of ambient temperature (Ta) in Malaysia (Figure 8). Therefore, an equation of Y = −4.7416X + 214.73 with R^2 of 0.9584 was obtained from the data collected and, as shown in Figures 6 and 8, to ascertain the estimated hourly rate of relative humidity based on the hourly values of ambient temperature with the ranges between a minimum value of 27.5 °C and a maximum value of 33.8 °C in Malaysia, where Y and X are indicated as the rate of relative humidity and the value of ambient temperature, respectively. The hourly values of water production of the MSAWG system increased from 110 mL/h at 9 p.m. (night) on 18 March 2020 to 204 mL/h at 5 a.m. (early morning) on 19 March 2020, when the corresponding rates of the relative humidity increased from 62 to 80% and the values of ambient temperature decreased from 31.5 to 28.5 °C, respectively. Afterward, the productivity of MSAWG decreased from 204 mL/h at 5 a.m. on 19 March 2020 to 120 mL/h at 12 p.m. (noon) on 19 March 2020 when the corresponding rates of the relative humidity decreased from 80 to 63% and the values of ambient temperature increased from 28.5 to 32 °C, respectively.

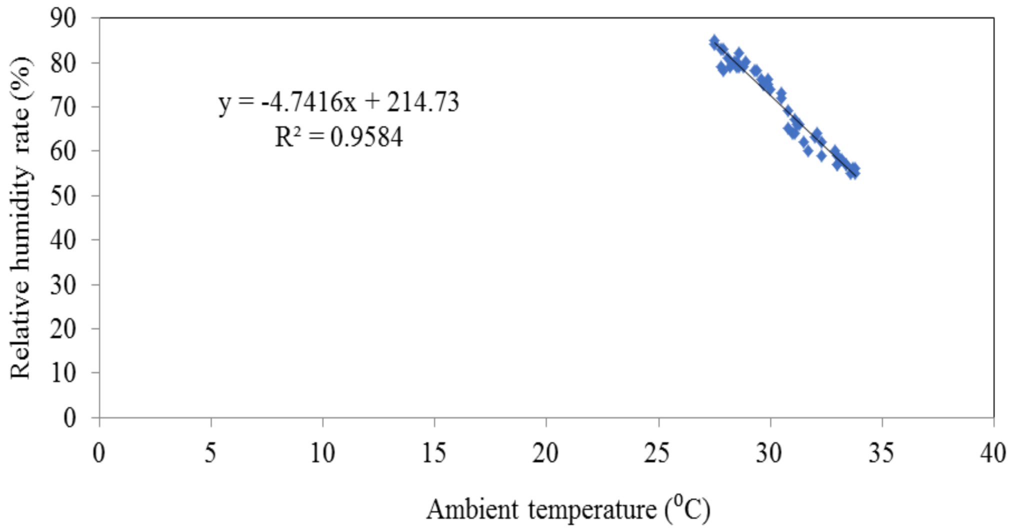


Figure 8. Adverse relationship between the rates of relative humidity and the values of ambient temperature in Malaysia in a 48 h period from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020.

The yield of MSAWG decreased from 120 mL/h at 12 p.m. (noon) on 19 March 2020 to 78 mL/h at 3 p.m. (afternoon) on 19 March 2020 when the corresponding rates of relative humidity decreased from 57 to 55% and the values of ambient temperature increased from 32 to 33.8 °C, respectively. The productivity of AWG increased from 78 mL/ at 3 p.m. to 150 mL/h at 8 p.m. on 19 March 2020 when the corresponding rates of humidity rose from 56 to 66% and the values of ambient temperature decreased from 33.8 to 31.2 °C, respectively. It can also be observed in Figures 6 and 7 that similar patterns were noticed for the values of water production, the rates of relative humidity and the values of ambient temperature for the next 24 h from 8 p.m. on 19 March 2020 to 8 p.m. on 20 March 2020. It was found in the 48 h experimental period that the hourly values of water production of MSAWG increased by 80% from 8.00 p.m. on 18 March 2020 to 5.00 a.m. the next day (on 19 March 2020) and by 79% from 8 p.m. on 19 March 2020 to 5 a.m. on 20 March 2020, respectively, due to the increase in the corresponding hourly rates of relative humidity by 18 and 17% and the decline in the corresponding hourly values of ambient temperature by 3 and 3.3 °C, respectively (Figures 6–8). The hourly values of water production of MSAWG decreased by 71 and 69% from early morning at 5.00 a.m. to the evening at 5.00 p.m. for two days on 19 March 2020 and 20 March 2020, respectively, due to the growth in the corresponding hourly values of ambient temperature by 4.9 and 5.1 °C and the decline in the corresponding hourly rates of relative humidity by 23 and 26%, respectively (Figures 6–8). From 5 p.m. to 8 p.m. on the 19th and 20th of March 2020, the hourly yields of MSAWG increased by 74.41 and 43.75%, respectively, while the corresponding hourly values of ambient temperature reduced by 2.2 and 1.9 °C and the hourly rates of relative humidity increased by 9 and 7%, respectively (Figures 6–8). It was also revealed that the increase in the hourly water production of MSAWG heavily depended on the rise in the corresponding rates of relative humidity throughout the experiment (Figures 6–8). It was observed that with the highest and lowest hourly rate of relative humidity during the night and at noon, the medium-scale AWG produced the highest and lowest hourly rates of water, respectively (Figures 6, 7 and 9). The relationship rate (R^2) of 0.9404 was obtained between the rates of hourly relative humidity and the hourly values of water production, which determined that the relationship between them was approximately linear and showed that the value of hourly water production heavily depended on the available rate of the relative humidity (Figure 9). Thus, an equation of Y = 0.2285X + 36.675 achieved from the experimental work could be applied for estimating the projected values of water production of MSAWG based on the corresponding rates of relative humidity, with the varied relative humidity rates in the ranges between the minimum rate of 55% and maximum rate of 85% in Malaysia while Y and X are indicated as the rate of relative humidity and the value of water production respectively. However, the hourly values of water production of the system showed an adverse relationship with the values of ambient temperature throughout the experiment (Figure 10) and there was a contrary relationship between the ambient temperature and the water production which showed that the high values of ambient temperature during the day caused the reduction in the rates of relative humidity and hence, the decrease in water production (Figures 6–10). Therefore, an equation of Y = −0.0466X + 37.334 with R^2 of 0.9092 was obtained from the data in Figures 6, 7 and 10 to figure out the projected hourly values of water production based on the varied hourly values of ambient temperature with the ranges between the minimum value of 27.5 °C and the maximum value of 33.8 °C in Malaysia, where Y and X are indicated as the value of ambient temperature and the value of water production, respectively, in the above equation.

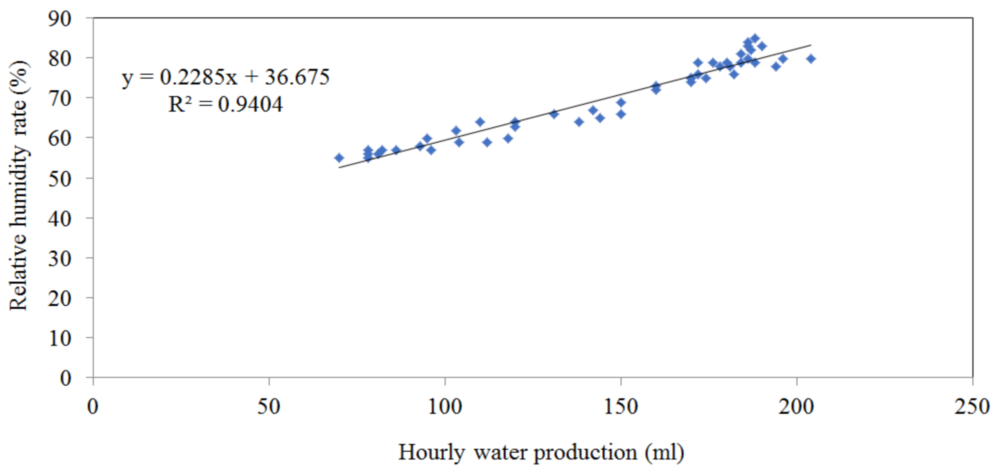


Figure 9. Linear relationship between the rates of relative humidity and hourly values of water production of MSAWG in a 48 h period from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020.

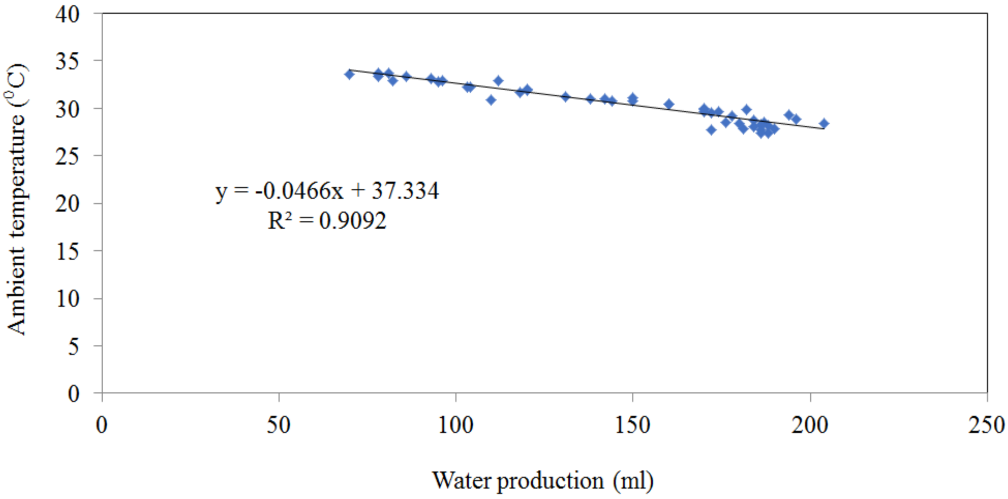


Figure 10. Adverse relationship between the values of ambient temperature and the values of water production of MSAWG in a 48 h period from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020.

3.2. Cumulative Water Production of MSAWG

The cumulative water production value of the medium-scale atmosphere water generator (MSAWG) was about 6997 mL in a 48 h period from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020, with the varied relative humidity rates in the range between the minimum rate of 55% and maximum rate of 85% and with the varied values of ambient temperature in the range between the minimum value of 27.5 °C and maximum value of 33.8 °C in Malaysia (Figure 11).

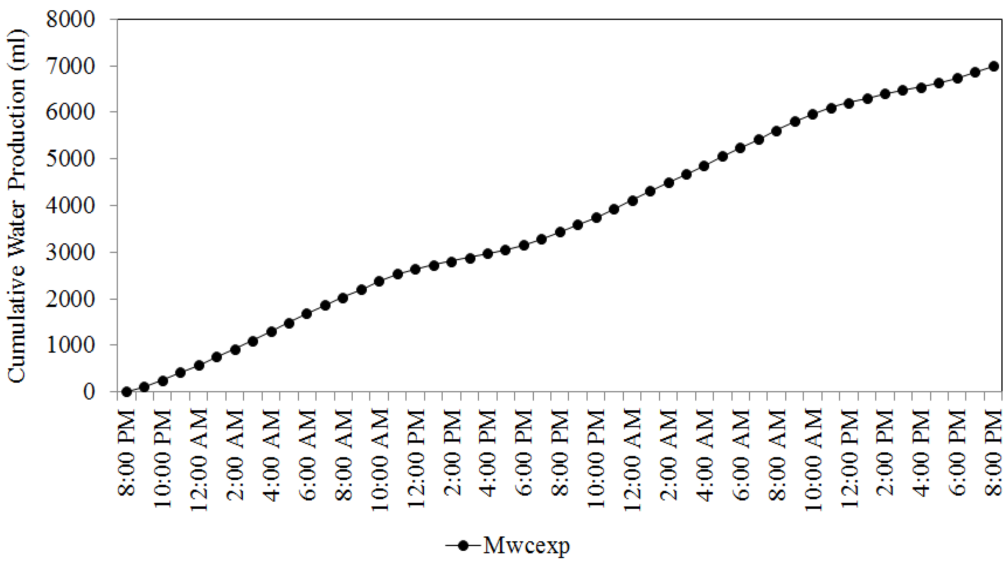


Figure 11. Values of experimental cumulative water production (Mwcexp) of MSAWG in a 48 h period from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020.

3.3. Cost Study and Analysis of the Medium-Scale AWG (MSAWG) in This Work

The fabrication cost of MSAWG is USD 291.01, which is assumed as the fixed cost. In order to obtain the average value of the cost of the condensed output of MSAWG, it is assumed that n is the expected lifetime, F is the fixed cost, M is the expected maintenance cost of the electrical items which must be replaced annually and assumed at 30% of the fixed cost of the electrical items. M is calculated and shown in Table 3 as USD 87.20. E is the total annual cost of the power consumption of MSAWG, which is USD 415.17 and is shown in Table 4, and C is the total cost. Thus, the total cost of the MSAWG in this work is

$$C = (F + (M + E) \times n) \quad (1)$$

Thus, the total cost of MSAWG, assuming the expected lifetime of five years, is:

$$C = (291.01 + (87.20 + 415.17) \times 5) = \text{USD } 2802.86 \quad (2)$$

The average daily water production of MSAWG as estimated from the experimental days (Figure 7) was obtained as 3.432 L/24 h, assuming that MSAWG operates 350 days in the year. The total productivity (M) of MSAWG during the system life is MMSAWG = 6006 L.

Therefore, the cost per litre from the MSAWG = 2802.86/6006 = USD 0.466.

3.4. Water Quality Analysis

The average quality parameters of the water as generated by the MSAWG in this experimental study and the standards of the WHO and Malaysia class I drinking water guidelines are shown in Table 6. The values of pH, total suspended solids (TSS), ammonia nitrogen, nitrate, chemical oxygen demand (COD), and turbidity of the generated water by MSAWG were 7.38, 1 mg/L, 0.33 mg/L, 0.2 mg/L, 0 mg/L, and 0.37 NTU, respectively. This indicated that the above quality parameters of the generated water in this work were within the permitted ranges of the drinking water standards of the World Health Organization (WHO) [12].

Table 6. Performance evaluation of the MSAWG used for extracting water from the atmosphere in this work at the REDAC campus, USM, Malaysia.

Water Quality Parameter	Generated Water from the MSAWG	WHO Drinking Water Standards [12]
pH	7.38	6.5–8.0
Total suspended solids (mg/L)	1	<250
Ammonia nitrogen (mg/L)	0.33	<1.5
Nitrate (mg/L)	0.2	<50
Chemical oxygen demand (mg/L)	0	<10
Turbidity (NTU)	0.37	<5

4. Discussion

In this work, the MSAWG system produced the highest and lowest hourly amount of fresh water in subsequent 24 h periods while being exposed to the outdoor tropical climate conditions of Malaysia with the highest and lowest rates of relative humidity and corresponding lowest and highest values of ambient temperature, while ambient air was vacuumed at a constant flow rate of 70 m^3/h. The highest and lowest hourly productivity of the other AWG systems tested by [6,8,9,11] occurred when exposed to the highest and lowest rates of relative humidity, but they were tested under indoor controlled conditions.

Night-time (between 8 p.m. and 5 a.m.) and early morning (from 5 a.m. to 8 a.m.) were the most effective times to generate the highest amount of fresh water from Malaysia's atmosphere using MSAWG, as the peak rise in the rates of relative humidity and the highest decrease in the values of ambient temperature occurred at these times. However, the lowest amount of water was generated by the MSAWG at noon and in the afternoon, while the peak reduction in the rates of relative humidity and the highest growth of the values of ambient temperature also occurred at these times. The best time to generate water using AWG under the outdoor climate of Madrid, Spain was also in the early morning, from 5 a.m. to 8 a.m., as stated by [10].

The outdoor tropical climate of Malaysia was condensed on the cold surfaces of the 18 internal heat sinks of MSAWG with a total base area of 288 cm^2. It was also observed from the above results that the highest amount of hourly water production of 204 mL was achieved when Malaysia's tropical humid air was vacuumed at the constant flow rate of 70 m^3/h over the 18 internal heat sinks of MSAWG and the outdoor relative humidity rate was 80%. The maximum amount of water produced by each Peltier module of MSAWG with the base surface area of 16 cm^2 attached to its corresponding internal heat sink with the similar base area of 16 cm^2 was found to be (204 mL/18 TEC units) 11.33 mL when exposed to the relative humidity rate of 80%**.** It was shown that using an internal heat sink with a base area similar to the surface area of a Peltier module (16 cm^2) placed next to the cold side of the Peltier module in MSAWG seemed to be more productive compared to each of the Peltier modules employed in [6,8,9,11]'s AWG systems, which was attached to the internal heat sink with larger base area than the surface area of the Peltier module. The MSAWG supplied a continuous cumulative fresh water yield of 6.997 L in two successive 24 h periods from Malaysia's tropical atmosphere at a cost per litre of USD 0.466.

5. Conclusions

A medium-scale atmospheric water generator (MSAWG) model was designed, fabricated, and tested in Malaysia's outdoor climate for two subsequent periods of 24 h from 8.00 p.m. on 18 March 2020 to 8.00 p.m. on 20 March 2020 through vacuuming a constant rate of 70 m^3/h of humid air into the system exposed to the varied hourly rates of relative humidity and ambient temperature which produced consecutive cumulative water yields of 3.432 and 6.997 L experimentally in the periods of 24 and 48 h, respectively. Malaysia's atmosphere has the potential to generate fresh water via the condensing of its humid air using the MSAWG. The MSAWG would be able to supply sufficient and continuous fresh water per capita from Malaysia's atmosphere in 24 h at a cost per litre of USD 0.466, which can ensure national clean water resources and food security for rural development in Malaysia, which is targeted as one of the outlines of the Malaysia National Water Resources Policies. Night-time and early morning were found to be the most productive times to generate the highest amount of fresh water from Malaysia's atmosphere using the MSAWG, as the increase in the relative humidity rates and decrease in ambient temperature values occurred over these two periods. The maximum amount of produced water per each Peltier module of MSAWG with the base surface area of 16 cm^2 attached to its corresponding internal heat sink with the similar base area of 16 cm^2 was found at 11.33 mL. An internal heat sink with a base area similar to the surface area of a Peltier module (16 cm^2) placed next to the cold side of the Peltier module used in MSAWG was more productive compared to each internal heat sink with a larger base area than the surface area of the Peltier module, which was attached to the cold side of each Peltier module. Some water quality parameters of the water produced by the MSAWG were also analysed, showing that they met WHO drinking water standards. Therefore, the MSAWG can be employed as a sustainable alternative to generate annual daily fresh water from Malaysia's tropical atmosphere and aid in solving the problem of unpredicted water shortages in the country. In addition, the application of an internal heat sink with a base area similar to the surface area of a Peltier module placed next to the cold side of the Peltier module as well as the supplementary removal of the excess heat from the hot side of a Peltier module to achieve the additional decrease in the temperature of the internal heat sink attached to the cold side of the Peltier module are recommended for the future research on improvements to AWG systems using TEC units.

Author Contributions: A.R. designed the MSAWG system and wrote the original draft of the manuscript; N.A.Z. and M.R.R.M.A.Z. designed the MSAWG system, supervised the project and edited the manuscript; S.S. and M.F.Y. investigated the MSAWG system performance, collected the data, discussed the results and edited the manuscript; N.M.N., M.Z.M.A., A.M.J., M.M.I., M.Z.M., M.A.R. edited the manuscript and prepared the research funding. All authors have read and agreed to the published version of the manuscript'.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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