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Harvesting of Water from Atmospheric Air using Electrospun PVP- PVC Nanofibers with TEC Atmospheric Generator

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Abstract

Water scarcity is a worldwide problem. The need for freshwater is increasing as a result of many factors such as population growth, industrial development and climate change. Water treatment methods such as desalination process produce a good amount of water. However, it is costly, require large space and high amounts of energy especially in remote areas. So, alternative water resources, such as air water harvesting must be considered as a possible water source especially for hot and humid regions. In this paper, a prototype of air water generator was designed, built, and tested. The operation of the prototype is based on harvesting water from air using Peltier effect also known as thermoelectric cooling device [TEC]. The system was conducted under different conditions: ambient temperature [28 &29] °C, relative humidity [47, 59, 68, 75, 85, and 95] %. Two collecting surfaces were used, aluminium foil, and electrospun polyvinyl chloride [PVC] combined with polyvinylpyrrolidone [PVP] nanofiber. Based on the results obtained, it was found that using PVC-PVP nanofiber increased the amount of harvested water. At temperature 29°C and RH 95%, the prototype produced an average water of 104.94 mg/cm2.h using nanofiber, and only 89.44mg/cm2.h using aluminium foil surface. The nanofiber is hydrophobic, with water contact angle of 130.25°.

The harvested water was tested for water quality. It is observed that most results comply with Jordanian Drinking Water Standards and World Health Organization. The chemical structures of the nanofibers was characterized by Fourier transform infrared [FTIR], Scanning electron microscopy [SEM] and water contact angle measurement method to determine the morphology and surface hydrophobicity of the nanofiber.

Keywords: Harvesting of Water, TEC Atmospheric Generator, Drinking Water, hydrophobic, PVC-PVP Nanofiber

1. Introduction

Water is a basic requirement for life and a determinant of the standard of living. Although two thirds of Earth's surface areas covered with water, 97% of this water is salty water and only 3% is fresh water. Less than 1 percent of this tiny fraction is usable for drinking, agricultural and industrial uses. The rest is locked in polar ice caps, or underground [1]. As the world's population continues to increase and to achieve a better standard of living, the amount of fresh water needed has increased drastically. With the tiny amount of usable water that exists, the biggest challenge in the future is how to effectively conserve, manage, and distribute this water.

Water scarcity can be defined as lack of freshwater resources to meet water demand. It can be a physical water scarcity or economic water scarcity. Physical water scarcity is a result of inadequate natural water resources to supply a region's demand while economic water scarcity is a result of poor management of the sufficient available water resources [2].

Water scarcity is a worldwide problem. According to the UN, around 1.2 billion people, or almost one-fifth of the world's population lives in areas of physical water scarcity. Five hundred million people are approaching this situation. Another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage. By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water-stressed conditions [3].

Atmospheric water

The atmospheric air is considered as a huge and renewable source of fresh water. The atmosphere contains about 12,900 km3 of fresh water, whereas liquid water resources of inhabited lands are about 12,500 km3 [4].

Dew is the atmospheric water vapor obtained by condensation. It is a natural phenomenon that takes place spontaneously in nature. It requires a cold surface which should be cooler than the

surrounding air. Therefore, for dew formation, a drop in temperature below dew point temperature is needed. This requires a cold surface while a 100% air humidity is not a must [5].
AWG [Atmospheric Water Generator] is an important innovation with a strong potential to combat the problem of pure water scarcity by extracting water from humid ambient air.

Atmospheric Water Generator performance depends on the humidity and temperature in a specific geographical location, and can be designed for agricultural and irrigation purposes, or for drinking by adding water purification systems to the device such as UV, Carbon Filters, cartridge filter, etc] [6].

There are different methods that can accomplish water extraction from the humid atmospheric air:
1) Desiccant method.
2) Cooling condensation method which include:
- Vapour Compression method.
- Peltier Effect [Thermoelectric Cooler TEC].

The use of atmospheric water as source of fresh water has been investigated extensively, but is still underdeveloped [4]. Investigated the effect of air velocity on condensate production by using a finned evaporator coil for a cooling then dehumidification process. He reported that only optimum air velocity can provide the maximum amount of condensation. The condensate production below or above this optimum was diminished due to several factors such as frosting and insufficient evaporator capacity. Proposed water extraction from air using two-stage process. This involved humidity absorption by a liquid desiccant then water desorption by solar -powered desiccant method. Calcium chloride was chosen as the desiccant, and experiments were conducted in Dhahran, Saudi Arabian climate [7,8].

Water absorption rate of 2.11 L/m2 /day and 1.15 L/m2 /day were obtained depending on the desiccant flow rate. Developed a solar-assisted sorption dehumidifier added to a heat exchanger for air dehumidification in order to reduce energy consumption. They found that a low energy, small- scale, silica gel dehumidification system can produce about 5.2 L /day of freshwater in Sydney [9]. Presented a solar thermoelectric cooling system for fresh water production. They studied different parameters, electric current between 1 and 3.5 A, air mass flow rate between 0.005 and 0.012 kg/s, inlet air temperature between 25 and 34℃ and relative humidity between 70 and 90%. They used five TEC channels, each channel consists of twenty 20 TEC units to produce10 L /day [10 hours per day] of water in summer months in Beirut [10]. Reported a system for collecting atmospheric water for young trees using Peltiers powered by solar energy to maximize water condensation using minimum energy. The system generated electricity that was stored it in battery which was then used to generate water when air humidity and temperature were at optimal conditions [11]. Developed a water condensation system based on using thermoelectric Peltier [TEC] device powered by solar energy.

They collected around 1 L/hr of water during the day light in highly humid regions [12]. Proposed a Peltier device use to increase the temperature difference between evaporating and condensing zones. Fresh water produced from three different climate regions [Arab gulf, Red Sea, and south Europe] in summer was obtained using four parameters: the ambient temperature, pressure drop over the flow bath, humidity, and water productivity /m2. They reported a water productivity of 3.9 L/h.m2. Air fan power was only up to 9.1 w [13]. Reported the development of an AWG prototype based on Peltier device which used 12 V DC.

They tested the output of the prototype for several Peltier modules and different airflow conditions. Using 4 Peltier at 190 CFM inlet air flow and power consumption of 125.5 w, the maximum amount of water was produced was 0.61 L/hour. The average ambient conditions were 26oC and 60% RH [14]. Reported that the quantity of water generated by TEC is directly proportional to three parameters: electric current, air mass flow rate and humidity of air [15]. Reported the development of a portable drinking water system consisting of a TEC unit powered by a photovoltaic hybrid system. They reported that 1L/day of drinking water can be produced at a temperature between 10 and 30 °C and a relative humidity between 60 and 80% [16]. Developed a small-scale atmospheric water generator using 4 TEC units they studied the impact of humidity, airflow velocity, TEC current on the water production rate they concluded that increasing the current of the TEC and increasing RH increased water generation rate.

They produced 66 ml/h at 33℃ and 80 RH% [17]. Designed a portable atmospheric water generator with two TEC modules. They investigated the effect of the inlet air flow rate and the relative humidity. They found that that the water amount increased with rising air flow rate and relative humidity [18]. Designed and manufactured solar-powered TEC air water generator. They concluded that water harvesting can be done with solar-power Peltier modules [19]. Proposed a small scale prototype based on using one TEC device, driven by a solar panel module.

They investigated the effect of air temperature, humidity, and airflow rate. They reported that water production rate increased with increasing relative humidity and air flow rate. The maximum amount of water produced was 20 ml /hour at ambient conditions 31oC and 75% RH , with a maximum airflow velocity of 1 m/s [20]. Developed a medium-scale atmospheric water generator consisted of 18 [TEC] units. They tested the production of the prototype in Malaysia at different relative humidity between 55% and 85%, ambient temperatures between 27.5℃ and 33.8 ℃, air flow rate of 70 m3/h. They reported water harvesting rates were between 3.432 L in 24 h of operation, and 6.997 L in 48 h of operation [21].

Nanofiber and dehumidification

Many kinds of bioinspired water collection methods have been developed by modelling the nano structure, wettability and morphology of organisms such as spider silk, cactus and desert beetles [22]. Investigated water ability collecting of the bioinspired artificial spider silks. They fabricated it from a uniform nylon immersed into a polymer solution, poly methyl methacrylate [PMMA] [23]. Fabricated hydrophobic PVDF-HFP electrospun nanowebs with and without impregnation with lubricants for harvesting fog from the atmosphere.

They found that water harvested from the nano-mat was around 88 mg/cm2 .h and with oil impregnation [Krytox-1506] was 118 mg/cm2.h at 20 °C and 70% RH [24]. Studied water harvesting capacity by electrospun polyvinylidene fluoride [PVDF] membranes with and without expanded graphite [EG] inclusions. When EG was included, water harvesting efficiency was improved by 63.4% from 103.1 mg per hour per unit area of virgin PVDF membrane to 168.5 mg per hour per unit area of composite membrane [25]. Fabricated a water harvester inspired from desert beetle and spider silk by electrospinning. They used Polyacrylonitrile [PAN] and expanded graphite [EG] to form the bicomponent nanofibers.

The water harvesting capacity of their membrane was 744 mg per hour per unit area, which was higher than the virgin PAN membrane by 91% [26]. Fabricated fibres via electrospinning with diameters in the range 150-400 nm. They used block copolymer polystyrene-b-dimethylsiloxane, dimethylformamide and tetrahydrofuran. The non-woven fibrous mats were super hydrophobic, with a contact angle of 163°[27]. Fabricated a super hydrophobic fluorinated polyacrylonitrile [PAN] nanofibers. They reported a fog harvesting capacity of 335 mg/m2.h, and the contact angle was 159°.

They found that water harvesting increased with increasing the reaction [preparation of fluorinated –PAN nanofiber]: time, temperature, flouroamine compound amount, the distance between the humidifier and the nanofiber mat. The optimum reaction conditions were: reaction time 3 hours, flouroamine concentration 8%w/w and a temperature of 95**°C** [28]. Designed a star-shaped wettability patterns surface inspired from spider silk and desert beetles using TiO2 slurry. They collected 278 mg/cm2.h [29]. Used electrospinning to produced super hydrophilic polyvinyl chloride [PVC] and polyacrylonitrile [PAN] nanofiber mats mixed with different hydrophilic polymers of polyethylene glycol [PEG] and polyvinylpyrrolidone [PVP] at different weight

Percentages of 0, 4, 8, 16 and 32%. They found that PAN and PVP without any addition could absorb water up to 10% of their weight, however adding hydrophilic polymers [16%, 30% wt] raised this percentage to 69 %, with contact angle less than 5° [30].

In this work, AWG prototype using two TEC, was built and experimentally tested to extract water from atmospheric air using different collecting surfaces aluminium foil and electrospun PVC-PVP nanofibers, under different conditions ambient temperature 28 °C and 29 °C, relative humidity between 47% and 95%.

Experimental

AWG Prototype setup

The outer casing is made from Plexiglass with dimensions of 60cm x80cm x120cm and 5mm thickness and wood which are light and cheap materials and easy to work with. Two thermoelectric cooling Peltier devices[TEC- 12706] were used. Two CPU fans with heat sinks as cooling units were attached directly to the Peltier devices by thermal paste to ensure the Peltier devices adequate cooling, which is needed for proper working of the Peltier devices. For electrical work, two power supplies [24 volts, 5 A], DC to DC convertor [15 A, step down] and 3A DC to DC convertor were used. An atomizer device and hot plate were used to adjust humidity and temperature.

The prototype of AWG consisted of:

Table

Item		Quantity
1.	TEC thermoelectric cooler units	2
2.	Fan (CPU fan as cooling devises for TEC)	2
3.	Humidity meter	1
4.	Thermometer	1
5.	Wires and electrical	1
6.	Case	1

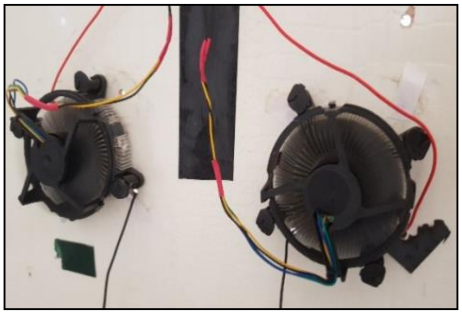

Figure 1: CPU Fan

Figure 2: Thermo-electric cooler TEC

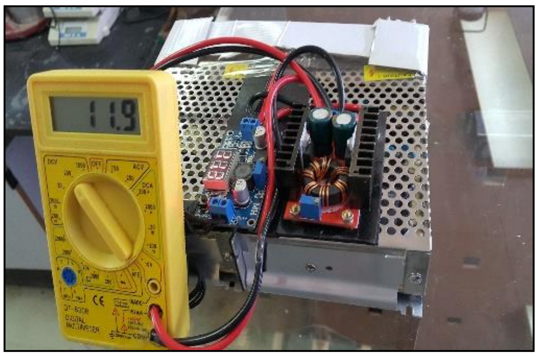

Figure 3: Power supply &connection

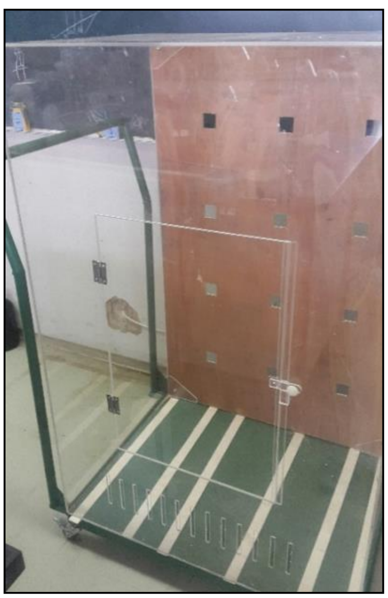

Figure 4: Casing

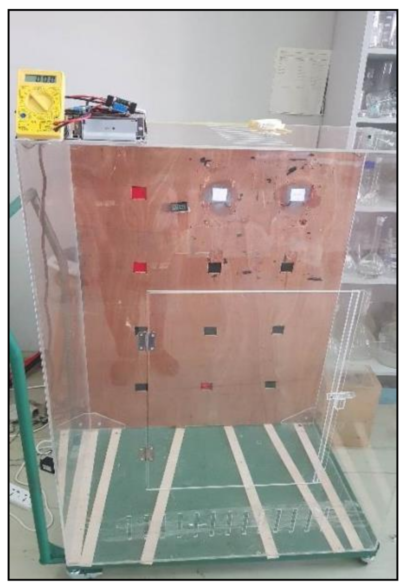

Figure 5: AWG prototype

2. Material

Chemicals used for nanofiber fabrication by electrospinning: Polyvinylchloride [PVC] high molecular weight from Sigma-Aldrich. Polyvinylpyrrolidone [PVP] average Mw from Sigma- Aldrich, N, N-dimethylformamide [DMF] from Tedia Company.

3. Method of Synthesis of Electrospun Nanofiber

DMF was used to dissolve PVC and PVP [60g DMF, 5g PVC, and 0.9 g PVP], the solution was stirred and heated for 2 hours at 400 rpm and 70**℃**. Electospininng was used to electospun nanofiber on the aluminium foil which was wrapped on a rotating drum used as the collector. The solution was fed into 5 ml syringe fitted with 22 gauge needle. Electrospinning was performed at voltages of +18 and -2.5kV, 10% relative humidity, flow rate of 0.7 ml/h.

The distance between the positive electrode and the ground collector was 15 cm. Finally, the obtained nanofiber sheet was placed in oven at 70**℃** for 2 hours to complete the drying process of the nanofibers.

Characterization of Nanofibers

The produced nanofiber was characterized using standard characterization techniques, Scanning Electron Microscope SEM [Quanta FEG 450 [FEI, USA]], Fourier transform infrared spectroscopy [AlPha II Compact FTIR], and Contact angle [Theta Lite contact angle Meter [Biolin Scintific, UK]].

Characterisation of Harvested Water

The harvested water was characterized using :PH meter [Seven Compac Due S213 [Mettler Toledo,USA]], Conductivity meter [Seven Compac Due S213 [Mettler Toledo,USA]],Total dissolved solid TDS meter [DIST1[Hanna Meter,Italy]], Inductive Couple Plasma [ICP] [iCAP Q ICP-MS ICAP [Thermo Scintific,Germany]], and Membrane Filtration Test for the Microbial Test: :water is drawn through a special membrane designed to trap microorganisms larger than 0.45 µm using a filter funnel and vacuum system, then the membrane filter was placed in a Petri dish and Incubated at the proper temperature for the appropriate time finally the numbers of colonies on the Petri plate was counted. The suggested sample volume: 1.0 ml, growth medium: Plate Count Agar, Incubation time: 48–72 h, Incubation temperature: 30°–35° for 3-5 days [31].

AWG harvesting experiments

The AWG prototype was tested under different operating conditions, relative humidity [RH] levels ranging from 45% to 95% different RH levels were controlled by the humidifier, and different temperatures 28 °C and 29 °C. Two collecting surfaces were used enhanced to the TEC cold side: aluminium foil, and PVC-PVP nanofiber. All the tests were repeated Three times, and the test results were averaged for each data point.

4. Result and discussion

Scanning Electron Microscopy [SEM]

The morphology and surface topography of PVC-PVP nanofibers are shown in Figures [6,7]

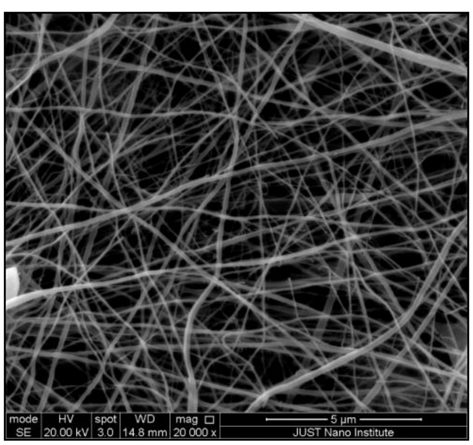

Figure 6: SEM image of PVC-PVP nanofiber (5µm).

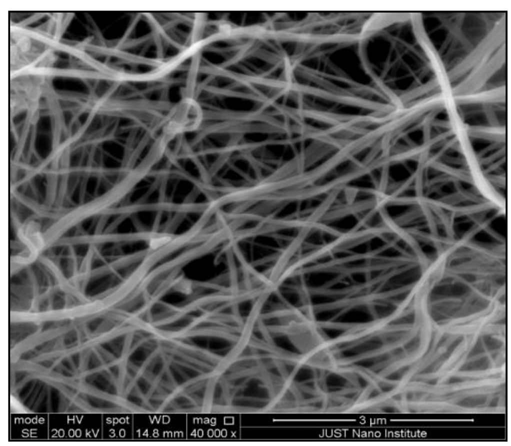

Figure 7: SEM image of PVC-PVP nanofiber (3µm).

Fourier-transform Infrared Spectroscopy [FTIR]

FTIR spectroscopy of PVC-PVP nanofiber is shown in Figure 8. The absorbance peak at 2907cm^{-1} corresponds to CH-CL stretching. The band at 1663 cm^{-1} represents C=O modes. The band at 1252 cm^{-1} corresponds to the stretching mode of C-N, and that at 1428 cm−1 indicates CH2 bending. The band at 611.27 cm^{-1} for corresponds to C-CL stretching, and at 833 cm^{-1} is attributed to the vibrations of the C-C stretch [32, 33].

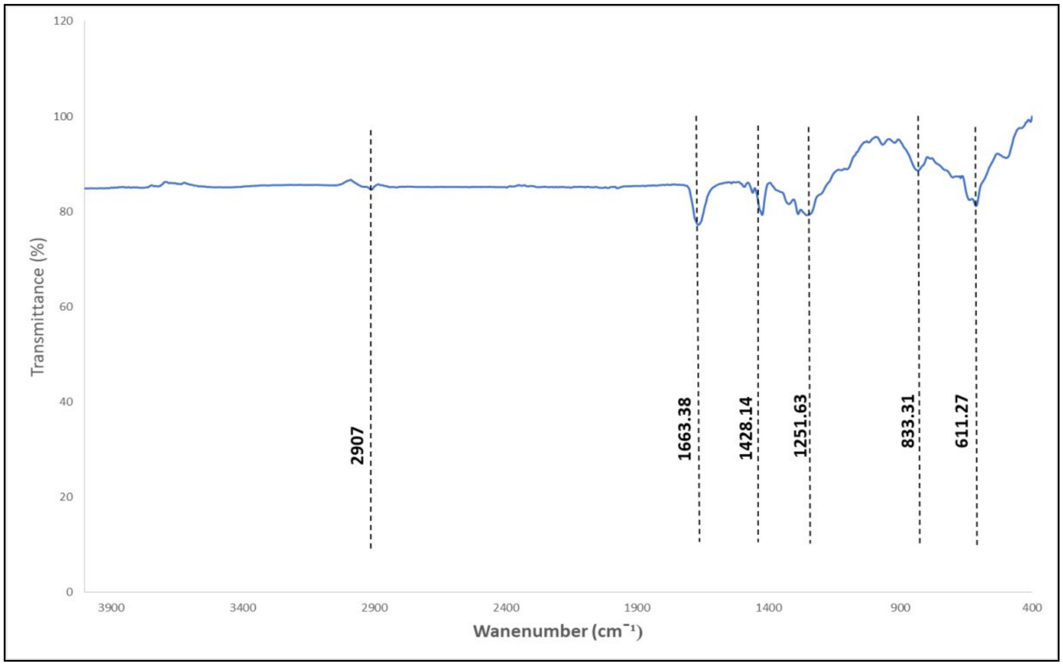

Figure 8: The FTIR spectrum PVP-PVC nanofiber.

Contact angle

The static water contact angle indicates whether a solid surface is hydrophobic or hydrophilic. The surface is described as hydrophobic if the contact angle is more than 90 degrees, and hydrophilic if the contact angle is less than 90 degrees [32].

The term super-hydrophobicity refers to a solid surface that is extremely hydrophobic, as well as the static water contact angle values between 150 and 180 degrees. The surface is said to be super-hydrophilic when the contact angle is less than 10 degrees [34].

Figure 9, shows the static contact angle of PVC -PVP nanofiber, this fibre is considered as hydrophobic since the contact angle [average contact angle] is 130.25° > 90°. Hydrophobic surface with high contact angle have low surface energy and high surface roughness lead to higher harvesting capacity [25, 28].

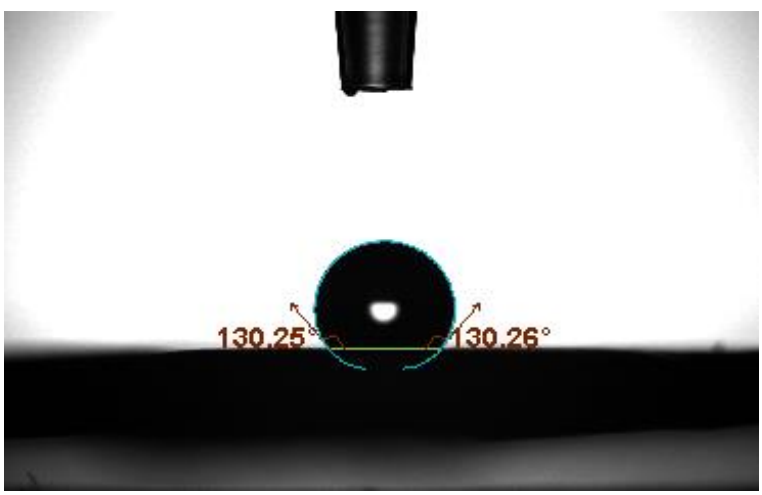

Figure 9: The contact angle of PVC-PVP nanofiber.

Water harvesting by Nanofiber

Tables 1 shows water amount collected [mg/ h.cm2] by nanofiber at different conditions the ambient temperature 28°C and 29°C, relative humidity between 47% and 95%.Figure 10 shows the water drops on the nanofiber surface.

Figure 11,shows the relation between water amount collected by nanofiber and the relative humidity is directly proportional to the relative humidity. The condensation rate increases by increasing the relative humidity, due to the increasing of vapor mass fraction [20, 35].

Figure 10: water drops on PVC-PVP Nanofiber.

Table 1: water collected by nanofiber:

Conditions		**Water Harvested (mg/cm².h)**			
T (°C)	RH (%)	Trial 1	Trial 2	Trial 3	Mean ± SD
28	47	26.06	34.31	32.06	30.81±3.48
28	59	51.19	46.31	53.25	50.25±2.91
29	68	69.19	66.56	60.56	65.44±3.62
29	75	64.13	69.94	69.38	67.81±2.62
29	85	72.38	84.94	84.19	80.50±5.75
29	95	109.31	95.63	109.88	104.94±6.59

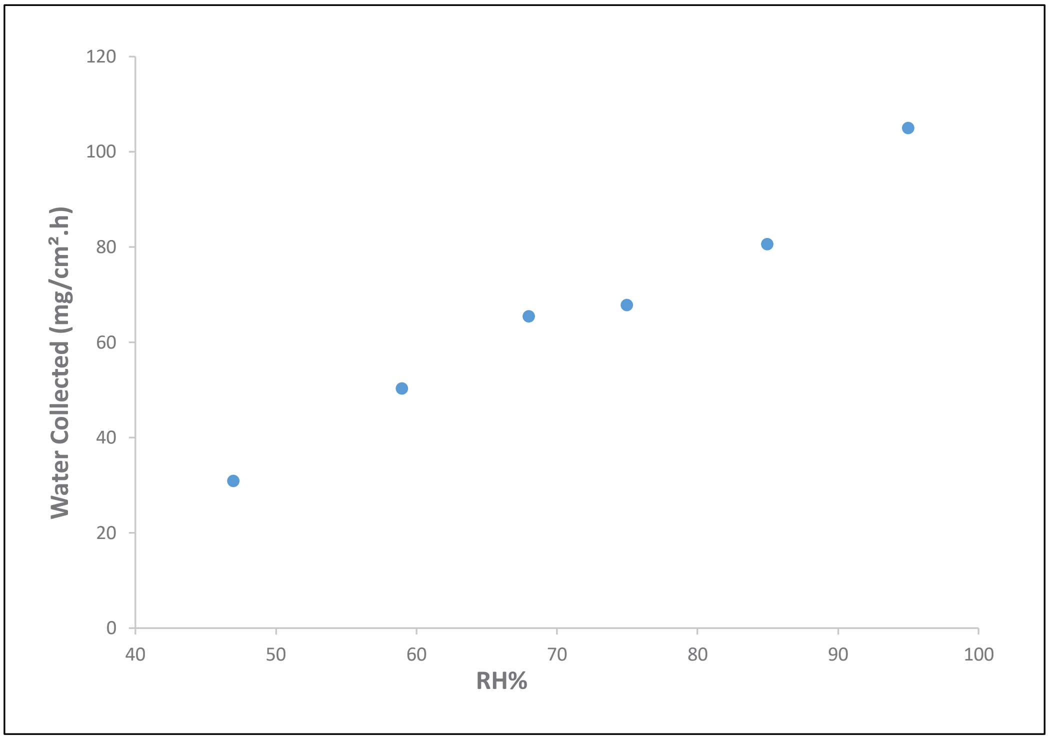

Figure 11: Relative humidity effect on water collected by nanofiber.

Tables 2 shows water amount collected [mg/ h.cm2] by aluminium foil at the same conditions used in nanofiber, ambient temperature 28°C and 29°C, relative humidity between 47% and 95%.

Figure 12 shows the relation between water amount collected by aluminium foil and the relative humidity The condensation rate increases by increasing the relative humidity, due to the increasing of water vapor content in the air [20, 35].

Table 2: water collected by aluminium foil:

Conditions		**Water Harvested (mg/cm².h)**			
T (°C)	RH (%)	Trial 1	Trial 2	Trial 3	Mean ± SD
28	47	23.81	18.94	23.06	21.94±2.14
28	59	29.81	27.38	34.88	30.69±3.12
29	68	56.63	49.5	50.25	52.13±3.4
29	75	51	52.5	57.56	53.69±2.81
29	85	65.06	65.44	65.63	65.38±.024
29	95	88.13	87.75	92.44	89.44±2.13

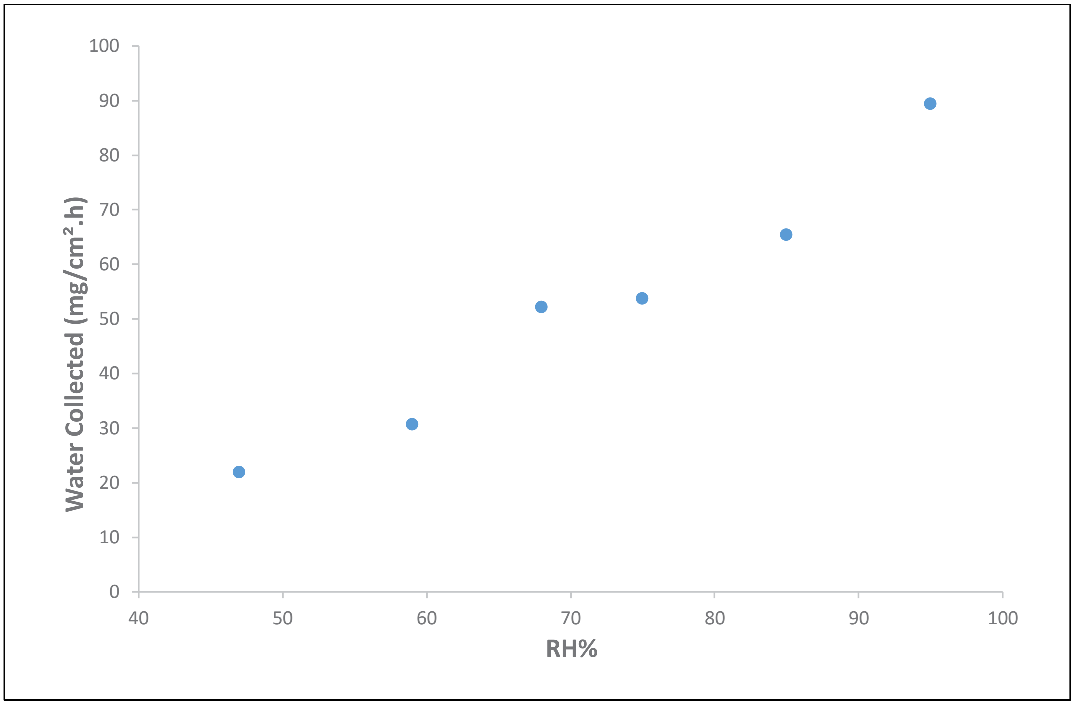

Figure 12: Relative humidity effect on water collected (mg/cm^2.h) by aluminium foil.

The results above show that nanofibers collect water more than aluminium foil due to the increasing of collecting surface area. The maximum amount collected was 109.88 mg/cm2.h by nanofiber and 92.44mg/cm2.h by aluminium foil at temperature 29℃ and relative humidity 95%. And the least amount was collected was 26.06 mg/cm2.h by nanofiber and 18.94 mg/cm2.h by aluminium foil at temperature 28℃ and relative humidity 47%.

Water Characterisation

Table 3, shows the characteristics of water collected by PVC-PVP nanofiber and water collected by aluminium foil. The results show that pH for both samples is similar and slightly alkaline. However, water collected by nanofiber has higher values than water collected by aluminium foil with respect to Electrical conductivity, TDS, and Microbiological test. The ICP test below shows that water collected by the nanofiber had higher value of some elements [maybe due to impurities during nanofibers fabrication, drying or during water collecting] than water collected by aluminium sheet. These chemicals raised the conductivity and TDS of water.

Table 3: Characteristics of water collected by nanofiber and aluminum foil

Parameter	Nanofiber	Aluminum foil	Jordanian standards	WHO standards
pH	6.7	6.8	6.50 – 8.5	6.5 - 8.5
Conductivity (µS/cm)	75.6	59.1	-	400
TDS (ppm)	36	27	1000-1500	500-1000
Microbial test	3 CFU/mL	1 CFU/mL	-	-

Table 4 shows the mineral analysis of the water samples using Inductive Coupled Plasma [ICP] of water collected by PVC-PVP nanofiber and water collected by aluminium foil. The results show that water collected by nanofiber has higher values of [Mg, Al, K, Ca, Mn, Fe, Zn and Cu] than water collected by aluminium foil.

Table 4: ICP of water collected by nanofiber and aluminum foil

Test	STD	Aluminium foil (ppb)	Nanofiber (ppb)
Mg	24Mg (STD)	165	319
Al	27Al (STD)	18	0
K	39K (STD)	4674	7747
Ca	44Ca (STD)	3248	3719
Mn	55Mn (STD)	3	4
Fe	54Fe (STD)	0	0
Fe	57Fe (STD)	26	30
Fe	58Fe (STD)	3	5
Zn	66Zn (STD)	82	137
Cu	65Cu (STD)	13	18

In general most results comply with Jordanian Drinking Water Standards and World Health Organization's drinking water standards. They also are consistent with previous studies. Gandhidasan et. al [2010], found the pH of water collected from descant AWG varies from 6.5 to 7.47, conductivity [103-390] µS/cm , Mn [18-62] ppb ,Fe[10-200]ppb ,Cu [25] ppb, Mg[570-3020]ppb, Ca [1420-5080] and reported that the water collected from AWG met most of the World Health Organization's drinking water standards [8].

Anbarasu and Pavithra (2011), reported that the water from AWG generator was comparable to tap water quality and met the Philippine National Standards for Drinking Water [PNSDW] with regard to the absence of coli form bacteria [6].

Investigated the water quality from AWG, they found that pH of the collected water was [6.6-6.9]. Conductivity [37-45] µS/cm and TDS [30-35] ppm [36].

Found that the water from AWG have the following analysis : pH [6.5], TDS [27]ppm, Mn[7]ppb , Mg[933]ppb , Ca [5080]ppb, Cu[19]ppb. They reported that water collected from AWG met the World Health Organization's drinking water standards and can be used for drinking after the required microbial processes [37].

Reported that the pH of water collected from AWG varies from 6.9 to 7.1, Conductivity [25-83] µS/cm and the number of colonies was zero /100 ml [38].

Reported that the pH of water collected from such system is [7.38] which is close to the result obtained in this study [6.8], and also met the [WHO] drinking water standard [6.5–8.0] [21].

The quality of water extracted from air is effected by the air quality, in some cases post water treatment as disinfection [UV, Ozone], chlorination maybe required to make the harvested water suitable for human consumes [39]. Another explanation for the difference could be due to differences in the testing instruments or AWG components especially collecting surface.

5. Conclusions

A prototype of TEC-AWG was designed and used to produce fresh water from the air under different conditions, relative humidity [RH] levels ranging from 45% to 95%, and different temperatures 28 °C and 29 °C. Two collecting surfaces were used enhanced to the TEC cold side: aluminium foil, and PVC-PVP nanofiber.

PVC-PVP nanofiber was fabricated using electrospinning and attached to the TEC as a collecting surface to increase surface area of harvesting. Using PVC-PVP nanofiber increased the amount of harvested water. At temperature of 29°C and RH 95%, the prototype produced [104.94 mg/cm2.h] using nanofiber, and [89.44 mg/cm2.h] using aluminium foil alone. The electrospun nanofiber is found to be a hydrophobic surface with average contact angle of 130.25 degrees.

The results show that this prototype is not efficient to produce good amount of drinking water and it is still in needs for some improvements. The quality of water produced from AWG comply with most of Jordanian Drinking Water Standards and World Health Organization's drinking water standards. However additional tests should be performed on the water collected by Nanofiber to be sure it doesn't contain DMF and safe for drinking.

The amount of harvested water from the TEC air water generator depends on many factors:

- AWG design: number of TEC units, condensation surface [area and design material].
- Operating conditions such as relative humidity and ambient temperature.
- Using PVC-PVP nanofiber on the collecting surface [aluminium sheet] increased the amount of harvested water.
- The quality of water extracted from AWG is effected by the air quality, and the type of collecting surface.

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