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Investigation of silica gel performance on potable water harvesting from ambient air using a rotatable apparatus with a solar tracking system

Mohammed Oral Alhurmuzi[a,*], Merdin Danışmaz[a], Omer Adil Zainal[b]

[a]*Mechanical Engineering Department, College of Engineering Architecture, University of Kırşehir Ahi Evran, Kırşehir, Turkey, Tel.: +90 5352329764; email: al-hurmuzi.mohammedoral@ogr.ahievran.edu.tr (M. Oral Alhurmuzi) (ORCID: 0000-0002-7045-4628), Tel.: +90 5355632498; email: m.danismaz@ahievran.edu.tr (M. Danışmaz) (ORCID: 0000-0003-2077-9237)*
[b]*Mechanical Engineering Department, College of Engineering, University of Kirkuk, Kirkuk, Iraq, Tel.: +964 7731620244; email: omer.zainal@uokirkuk.edu.iq (ORCID: 0000-0003-0821-6693)*

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ABSTRACT

Over the last century, the scarcity of clean water has emerged as a critical global issue. The changing climate and many other factors have severely strained the world's water resources. As a result, much research has been conducted to find various methods to supply clean water, like water generation from atmospheric air. Many studies have been done in this field, but there is still a need for further developments to enhance the water generation process. So, in the current study, a single-slope apparatus was designed and constructed to study potable water collection from the atmospheric air. The experiments were done in Kirkuk, Iraq (35.4666°N and 44.3799°E). Blue silica gel beads were used as a desiccant material, and solar intensity as a heating source. The process consists of adsorbing moisture at nighttime, regenerating the moisture and condensing the vapour to generate water droplets in the daytime. The apparatus consists of two identical sections isolated from each, having dimensions of 56 cm^3 × 68 cm^3 × 82.5 cm^3 for each. Both sections were used simultaneously to test the silica gel performance in water generation. An acrylic sheet was used as a condensing surface, and solar tracking equipment tracked the sunlight throughout the day using a DC motor to rotate the device with the sun's movement. An internal reflector made of aluminium was installed on all apparatus walls to increase the desiccant temperature. Testing the apparatus with and without the internal reflectors simultaneously revealed that using them can raise the desiccant temperature by nearly 30°C. The findings of several test days in September revealed that the maximum accumulated productivity equals 107 $g/m^2 \cdot d$, the system's maximum thermal efficiency was 22%, and the yearly cost of producing water was 2.54 $/L. Although the relative humidity is low in Kirkuk, 107 $g/m^2 \cdot d$ has been collected. It is possible to reach higher water production levels if this process is used in another location with high relative humidity. Also, this device is a prototype constructed for tests only, so in case of enlarging the dimensions of the apparatus, a larger quantity of desiccant can be used, and a much higher amount of water can be produced. In both cases, the cost of producing water will be much reduced.

Keywords: Solar energy; Water from the air; Silica gel; Adsorption/regeneration; Solar tracking system

1. Introduction

Water has been seen throughout history as the foundation for creating agrarian life and significantly influences the formation of countries. The supply of drinking water has emerged as a global issue. Human development estimates claim that the scarcity of water, or more precisely, the scarcity of clean water, kills over two million children worldwide

* Corresponding author.

each year. Gathering or carrying water over vast distances takes time for women and young girls [1]. The World Health Organization stated in a report that 97.5% of the earth's water is salty, with the rest 2.5% being clean water. The arctic poles have glaciated approximately 70% of this amount, with the remaining 30% somewhat inaccessible. As a result, humans may use less than 1% of freshwater directly [2]. There are two types of water shortages: economic (no water treatment areas) and physical (areas without water treatment). While North Africa's countries have physical water shortages, most Middle African nations experience economic water shortages. This is primarily caused by the relatively inefficient usage and allocation of water. Another significant driving factor is the region's ongoing economic and demographic expansion, which requires more water for new industrial, commercial, and cultural endeavours and more people [3]. Given these worrying findings, we must look for a different way to produce water. Desalination of saline water, water transportation from another site, and moisture extraction from the atmosphere are all methods for supplying water to arid areas. Saline water resources, often rare in several places, are needed for desalination, and transporting drinkable water to such dry areas is typically costly [4].

A significant source of humidity is the atmospheric air. The entire quantity of water in the atmosphere, 13,000 km^3, is far more than the 3,000–4,000 km^3 of clean water needed annually by all of humankind, involving agriculture, industry, and home use. The absolute humidity is significantly greater and exceeds 15 g/m^3 of air in several dry regions. For a long time, these factors have piqued scholarly interest in clean water collection from the air [5]. There have traditionally been two ways to capture moisture from the atmosphere. The first, exceedingly complicated and costly method involves cooling ambient air below the dew point to collect water. In the second method, atmospheric moisture is adsorbed, absorbed, and desorbed using solar intensity as a heating source. The condensation process follows that. The latter method is more straightforward and substantially less expensive [6].

Devices of various forms, such as double-faced conical, accordion, trapezoidal, pyramidal, and box-shaped, have been developed to extract moisture from ambient air. Researchers have made changes like increasing the number of shelves and adding fins to the device to enhance its surface area and the amount of desiccant used inside. They have also used a parabolic concentrator to focus the sun's energy on a fixed point and gravel to raise the temperature at which the desiccant regenerates. All these changes have helped increase the amount of moisture that can be made from air [7].

Potable water has been extracted from the atmosphere in several efforts. For this purpose, a large number of theoretical, simulation, or experimental studies have been conducted by researchers, and various types of desiccant materials have been used to extract water vapour in the nighttime and then vaporise the moisture in the daytime, condensing it on a condenser and collecting the generated clean water.

Kumar and Yadav [8] investigated and tested a novel composite adsorbent material that collects atmospheric moisture. Hygroscopic salts like calcium chloride ($CaCl_2$) and host materials like vermiculite with saw wood were utilised to prepare the composite material. A "solar glass desiccant box type system (SGDBS)" with an inclination angle of 30° was used, and six patterns of $CaCl_2$ with different concentrations were prepared. The total amount of water collected by utilising 2.5 kg of the adsorbent is 195 mL/kg·d, and the adsorbent concentration has the greatest influence on water production. Wang et al. [9] designed and built an open-type apparatus and an improved semi-open-type device (both solar-powered) to capture moisture from atmospheric air using the sorption technique. A solar radiation reflector can power at temperatures between 70°C and 80°C. The collection of 0.32 kg of pure water was accomplished using a roll-up concept device with 2.25 kg of the composite material (active carbon felt-calcium chloride). The updated semi-open-type apparatus uses a solar reflector with a surface area of 4 m^2 to capture 9 kg of drinkable water. Adsorbents with corrugations and smooth surfaces are designed to hold 40.8 kg of composite material on a bed that is 0.4 m × 0.4 m × 0.6 m. Wang et al. [10] constructed a very effective semi-open apparatus for generating potable water. The material employed was an ACF composite material containing nano silica particles packed in pure active carbon felt fibre that had been gap soaked in lithium chloride. The structure of the composite material is corrugated, allowing it to be moulded into mass transmission channels. CFX is used to examine the sorbent unit. It has been found that as relative humidity, the amount of absorbed water, and desorption temperature rise, the amount of released water also rises. 14.7 kg of water were produced using 40.8 kg of composite material. Kim et al. [11] designed and implemented a box-shaped prototype for atmospheric water collection. Permeable metal–organic framework (MOF)-801 was used as an absorbing material, and the heat source utilised in the desorption phase was solar radiation of 1 kW/m^2. At a relative humidity of 20%, the prototype could gather 2.8 L/kg·d with no further energy input. The research by Mohamed et al. [3] aims to determine how various operating circumstances may impact the system's effectiveness. As a desiccant, calcium chloride has been employed at various initial concentrations. A mathematical model of the production employing two types of beds (sand and black cloth) has been developed to study how the system will operate throughout the desorption phase. The total amount of water produced per square meter per d was 3.02 L. Using $CaCl_2$ as an absorbing material, the aim of this theoretically and experimentally conducted investigation was to identify the variables that influence the performance of a finned transportable device used to capture moisture from the atmosphere. Talaat et al. [12] constructed a "finned double-faced conical" device to remove humidity from the air at night. A "transparent double-faced conical cover" has been used as a condensing surface in daytime operation. The findings revealed that the system could generate between 0.3295 and 0.6310 $kg/m^2 \cdot d$, costing 0.062 $/kg. Srivastava and Yadav [6] conducted an experimental test to extract moisture from the atmosphere using three different composites: lithium chloride/sand (CM_1), calcium chloride/sand (CM_2), and lithium bromide/sand (CM_3). The desiccant's concentration was 37%, and the bed used was sand. The moisture harvesting from the atmosphere was done using absorption and desorption processes. The surface temperature of the composite was raised throughout the daylight procedure using a newly built Scheffler reflector with a surface area of 1.54 m^2. It was found that 90, 115, and 73 mL of the collected water each day were the optimum amounts utilising CM_1, CM_2, and CM_3. The yearly cost of the generated water is $0.71, $0.53, and $0.86, respectively. Kim et al. [13] presented a water-collecting device that used a "metal–organic framework (MOF)-801" as an absorber in an extremely arid environment (10%–40% RH). They used black paint on the backside of the MOF to act as a solar absorber. They predicted that 0.25 L/kg/d could be produced. They used MOF-801 to look at the water made and found that the MOF structure is stable in water and does not let any metal ions or organic linkers into the water. Li et al. [14] prepared a supple water absorber consisting of salt ($CaCl_2$) and hydrogel (PAM-CNT). Under field conditions, they used a simple-to-assemble prototype apparatus containing 35 g of dry hydrogel (PAM-CNT-$CaCl_2$). Under sunlight, the quantity of generated water was found to be 20 g in 2.5 h. The materials required to manufacture such apparatus, which would provide a person with their required daily water intake of 3 kg, are expected to cost only $3.2. Kallenberger and Fröba [15] used sodium alginic acid as the host material in a composite desiccant for moisture collection that also included significant levels of $CaCl_2$ as a hygroscopic salt. A simple ionotropic gelation process produced the composite material as spherical beads with a 2 mm diameter since the spherical form encourages high gas penetration of packed beds. At a water vapour pressure of 10 mbar, the composite desiccant can absorb all the moisture it weighs from the atmosphere. The results showed that at 100°C, most adsorbed moisture (>90%) could evaporate at 150°C, and regeneration could be completed completely. Based on the material's bulk density and how much water it can hold. It is thought that 660 kg of water per m^3 of desiccant could be collected. Using anhydrous and hydrated salt couples, Li et al. [16] showed in this study that it is possible to extract water vapour from dry atmospheric air and then supply potable water using solar radiation as the only energy source. This study fabricates all-to-gather and bi-layered composite disc apparatuses for integrated moisture collection and photo-thermal-assisted humidity release while screening 14 typical anhydrous and hydrated salts. The ability to absorb and regenerate water and be stable chemically and physically make copper chloride, copper sulfate, and magnesium sulfite distinguishable among the salt couples investigated. It has been found that copper chloride performs better under conditions of strong solar radiation and low relative humidity, like deserts. In contrast, copper and magnesium sulfite are better suited for locations with higher relative humidity and limited insolation, like islands or mountainous regions. Fathieh et al. [17] conducted a laboratory-to-desert experiment to determine the viability of collecting water from dry air. Metal–organic frameworks (MOF-801) and (MOF-303) were used as absorbers. Two key parts comprise the prototype utilised in this test: the moisture sorption unit, which retains the MOF, and the case that houses it. A reflector is fastened to the cover to ensure the MOF is only exposed to solar radiation on its surface. The findings showed that a kilogram of MOF-801 generated 100 g of H_2O, whereas 1 kg of MOF-303 produced twice as much water in a single day's work. Kumar et al. [2] investigated the efficacy of three composite materials (vermiculite with saw wood, jute, and burnt clay). $CaCl_2$ with a 37% concentration, has been used as a desiccant in a box-shaped apparatus with a collecting area of 0.36 m^2. On the test day, they found that the system with vermiculite, saw wood and Calcium chloride produced the most water at 130 mL/kg/d. Zhao et al. [18] produced water with great efficiency using atmospheric water collection across a range of relative humidity using a "super moisture absorbent" gel. This design is a unique way to improve AWH because it is a good way to control the movement of water molecules. A simultaneous adsorption/regeneration procedure was used by Qi et al. [19] in an experimental study to gather drinkable water from the atmosphere using a floating glass box-shaped device. They used "interfacial solar-driven atmospheric water generator (ISAWG)" as an absorbing material. It consists of a hydrophilic carbon membrane as an interfacial solar absorber and 1-ethyl-3-methyl-imidazolium acetate as an absorbent. They discovered that the amount of water generated is 0.5 and 2.8 $L/m^2{\cdot}d$. Nandakumar et al. [20] investigated water harvesting from the atmosphere above sea level. A very hygroscopic nano porous hydrogel was used as a desiccant. In extremely humid environments, the hydrogel can absorb more than 420% of its weight in moisture. The experiment was done using a floating prototype with a Styrofoam base. Natural sunlight is the heat source that initiated the hydrogel's regeneration process, which started at 55°C. Even after 1,000 cycles of absorption and regeneration, the hydrogel still displays exceptional stability. The results showed that it is possible to get more than 10 L of drinkable water per 1 kg of hydrogel daily by absorbing and releasing it several times. The extraction of moisture from atmospheric air with an adsorption process in dry locations utilising sunlight is the subject of the study conducted by Gordeeva et al. [5]. Metal–organic frameworks (MOFs) have been used as the desiccant material. The values of ΔFad and ΔFre express the quantitative needs for the optimal adsorbent for three dry climate areas (the deserts of the Sahara, KSA, and Central Australia). MIL-101(Cr), Co_2Cl_2(BTDD), and MIL-101(Cr)-SO_3H appear to be the best viable MOFs for Australia. For KSA and Sahara, MIL-160 and CAU-10 (pydc) are suitable. They exchange 0.34 to 1.6 g of water per gram of desiccant with a regeneration temperature of 75°C–100°C, allowing moisture removal (δ_{ex} = 0.78–0.93) and freshwater collection (δ_{col} = 0.75–0.90) to be obtained. Freshwater collections from the atmosphere through tubular solar still were performed experimentally by Elashmawy [21] in Hail City, KSA, with poor humidity conditions (12%). Calcium chloride is positioned in a rectangular basin with a bed of black cotton cloth. A small air blower has been added to the apparatus for circulating the atmospheric air during the nocturnal process. The absorption process has been studied under five distinct air velocity circumstances (natural, 0.5, 1, 3, and 4 m/s). In the daytime, the air fan had been turned off. The sides of the tube closed, leading the water in the desiccant solution to evaporate and then condense on the tube's internal surface in a regeneration operation. The water droplets were removed outside the apparatus. Natural air circulation produced the least amount of water, 230 $mL/m^2/d$, with a thermal efficiency of 12.2%. The cost of producing fresh water was $0.4/L for natural air circulation and $0.2/L at 4 m/s air speed. Fathy et al. [1] conducted a theoretical and experimental investigation on harvesting potable water from atmospheric air using foldable accordion-shaped apparatus. $CaCl_2$ has been used as a desiccant material and a black cotton cloth as a bed. A cost study was conducted to determine the economic cost of water generation, and a mathematical model was developed for the process simulation. Based on the findings, it is possible to generate roughly 750 g of water each day for a cost of $0.086/kg. An experiment has been done by Essa et al. [22] to evaluate the effectiveness of a "double-slope half cylindrical basin solar still" (DS-SHCBSS) that uses SiO_2 for water harvesting from the atmosphere. Two improvements were considered: adding longitudinal fins within the trough and using gravel in the trough. A parabolic solar collector has been utilised to increase the heat within the apparatus during the desorption process. Productivity under various input factors has been predicted using a mathematical model. According to the findings, utilising longitudinal fins alone or in combination with gravel increases production by around 72% and 166%, respectively, and increases the system's effectiveness by up to 15% and 35%. It has been found that the greatest production is 400 mL/m^2. The research conducted by Mulchandani et al. [23] provides a heat source to enhance the absorber's surface temperature, improve regeneration, and enable more daily water harvesting cycles. This is accomplished using nanomaterials like carbon black (CB) and gold rods and cubes (Au NC, AuNR). The adsorption processes of the desiccants were tested under various relative humidity levels (40%, 60%, and 80%), and a 1-sun simulated solar irradiation was used for the desorption process. The results showed that silica gel coated with carbon black could go through adsorption and desorption cycles more than 10 times and make 0.47 g of drinkable water per gram of desiccant in 12 h. The method proposed by Elashmawy and Alshammari [24] yielded 0.51 L/kg of $CaCl_2$. The system's thermal efficiency was 24.61%, with a cost of producing water of $0.15. TSS productivity and efficiency increased by 292.4% and 82.3%, respectively, while water generation costs were reduced by 25%. The suggested device could be used in deserts, faraway places, and rural areas without access to water because it is small, lightweight, and portable. Kumar et al. [25] used a solar restoration system that used orange silica gel as a desiccant material to investigate the water generation from the atmosphere. So that the system could absorb more, they painted the back of the absorber surface black. The results revealed that 0.98 L/d can be produced. Das et al. [4] tested the usability of a short-cylinder type receiver for water harvesting from the atmosphere. They used a blue silica gel as a desiccant material. A Scheffler-type solar reflector with a 16 m^2 surface area was used to increase the temperature required for the regeneration process. The system's capability to gather water is examined in several radiation-related scenarios. The experiment revealed that the desiccant's highest adsorption capacity was 0.25 g/g of desiccant when relative humidity and temperature were equal to 80% and 25°C, respectively. When the receiver reaches its highest temperature of 132°C and receives average direct radiation of 624 W/m^2, 105 mL of water are produced for every kg of silicon dioxide, and the system operates at a 10.9% efficiency. When the maximum temperature of the receiver is 109°C with average direct radiation of 370 W/m^2, the amount of harvested water equals 64 mL/kg of SiO_2. The total system efficiency is 10.9%. This method could be used at temperatures ranging from 30°C to 340°C, particularly in remote locations. There are two novelties of the current study. The first is examining the performance of the apparatus with the current design in moisture harvesting from atmospheric air and the performance of the ArmaFlex rubber sheet that has been used as insulating material instead of traditional insulating materials like glass wool and foam. At the same time, the second is using a solar tracking system to track the sun's movement during the day by employing a DC motor to rotate the device with the sun's movement to receive the most significant amount of solar radiation during the daytime.

2. Experimental section

2.1. Experimental set-up

As demonstrated in Fig. 1, a single-slope apparatus consisting of two identical sections isolated from each other by a wall and insulating material within the wall, and each section can be used as a small integrated apparatus. In this study, both sections with dimensions of 56 cm^3 × 68 cm^3 × 82.5 cm^3 for each one was used simultaneously to test moisture collection from the atmosphere using the same amount of the desiccant and under the same conditions. The device's frame was built from Aluminium columns of 4 cm thickness. The base, middle, and side walls were built of two sheets with a gap between them. An Aluminium sheet of 0.7 mm thickness was used as an internal sheet, while an Alucobond sheet of 2.5 mm thickness was used as an external sheet. In order to lessen the loss of heat from the device to the surroundings, an ArmaFlex rubber sheet with a 2.5 cm thickness is used for insulation and placed in the gap inside the base and the walls. The top inclined surface and the front surfaces are made of an acrylic sheet of 2.4 mm thickness. On the backside, doors were used that were constructed from polyvinyl chloride (PVC). Fig. 2 depicts the setup's schematic. In order to increase the temperature inside the device, aluminium sheets are used on the internal surfaces of the base, the sides, and the middle walls to act as internal reflectors. Trays made of aluminium sheet with 0.7 mm thickness and 36 cm × 57 cm × 2 cm dimensions were used to hold the desiccant inside the device.

To collect the condensed water droplets, channels made of Aluminium sheets were placed on the side and the middle walls, as well as on the front glass surface. The droplets are transported from the channels to bottles placed outside the device via a water hose. A solar tracking system followed the sunlight throughout the day, and a DC motor was used to rotate the device with the sun's movement.

2.2. Instrumentation devices

The total solar intensity has been measured for the regeneration process using a solar power meter of type TES-132. Wind speed was measured using a wind speed sensor of type RS-FSJT-V05. The accuracy and measuring range of these instruments and sensors are listed in Table 1. Temperatures at various points were measured using eight thermocouples. Two were placed on the internal surface of the translucent cover, four on the desiccant surface at four different points, one thermocouple to measure air gap temperature,

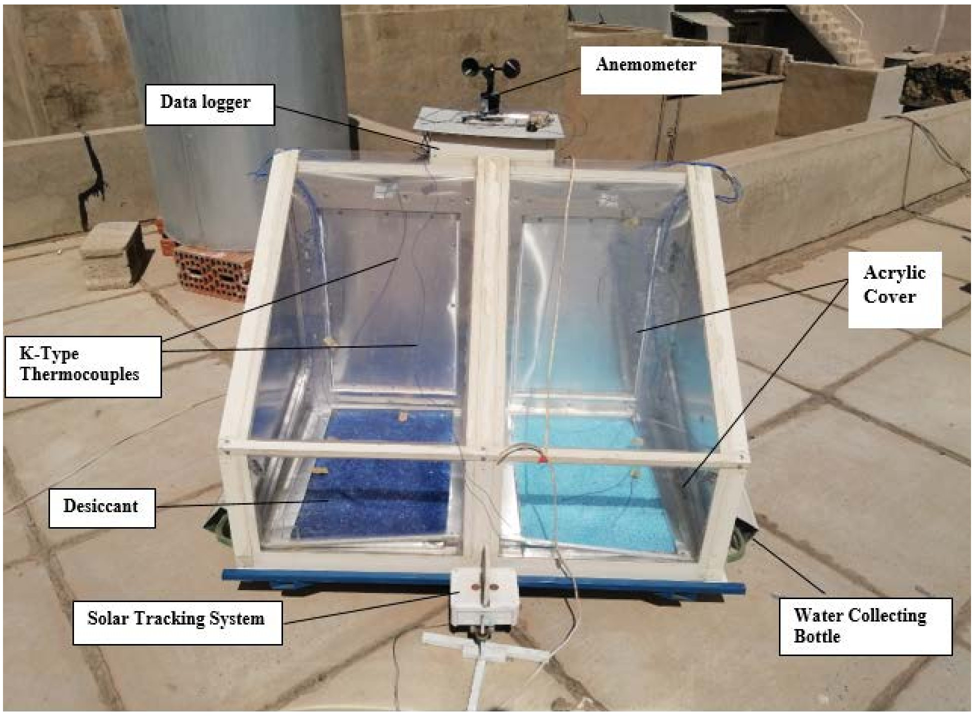

Fig. 1. Apparatus photograph.

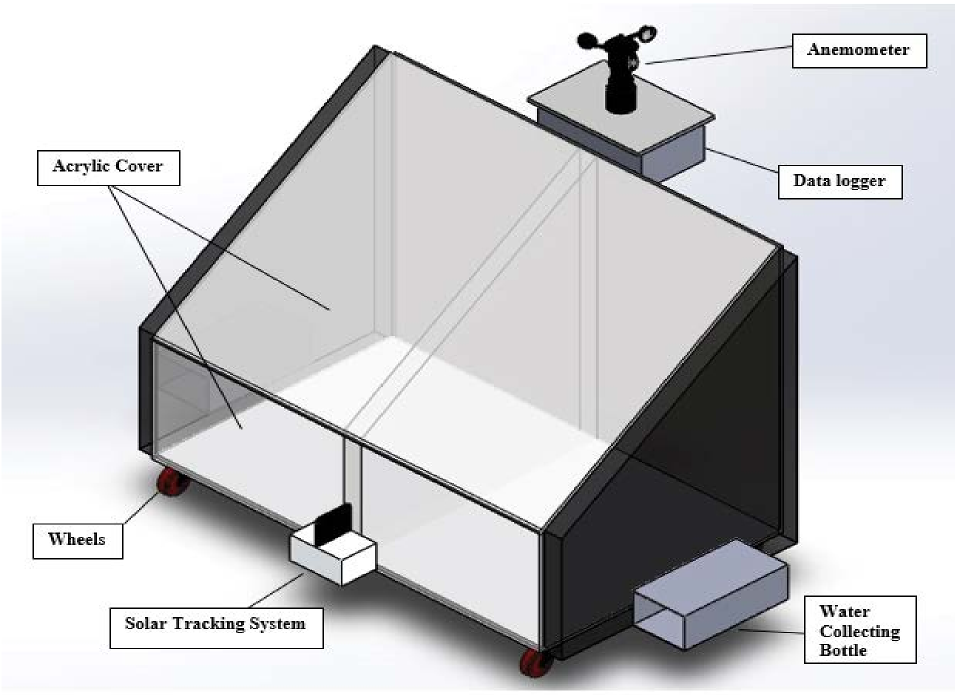

Fig. 2. Schematic diagram of the apparatus.

and one to measure the ambient temperature. The relative humidity was measured using an AM2302 sensor (wired DHT22). A weighing machine with high sensitivity has been used to measure the mass of the desiccant bed before and after both absorption and regeneration processes. It has a capacity of 40 kg with a division of 1 g.

2.3. Desiccant

Chemicals known as desiccants are highly attracted to humidity or water vapour. Creating a vapour pressure differential that causes water molecules to migrate toward the desiccant surface allows desiccants to capture water vapour

Table 1
Measuring instruments' accuracy and ranges

Sensor/Device	Type	Range	Accuracy	Resolution
Solar power meter	TES-132	0–2,000 W/m²	±10 W/m²	0.1
Thermocouples	K	–270°C to 1,260°C	±0.25°C	0.5
Relative humidity sensor	AM2302 (wired DHT22)	0%–100%	±2%–5%	0.1
Wind speed sensor	RS-FSJT-V05	0–60 m/s	±(0.2 + 0.03 V) m/s	0.1

Table 2
Characteristics of the silica gel utilised in the experiment[a]

Item		Blue gel indicator	Discolouring silica gel	Blue silica gel	Typical value
Adsorption capacity %	RH = 20%	8.0	–	–	8.5
	RH = 35%	13.0	–	–	13.6
	RH = 50%	20.0	20.0	18.0	22.5
	RH = 90%	–	–	28.0	31.4
Rattler loss %		10.0	10.0	10.0	0.5
Qualified size ratio		96	9.0	9.0	97
Loss on heating		5.0	5.0	5.0	0.9
Colour	RH = 20%	Blue or light blue	–	–	–
	RH = 35%	Purple or purplish red	–	–	–
	RH = 50%	Light red	Lightered light	Purple or light red	–

[a]Qingdao Double Dragon Industry Co., Ltd., (China) provides these characteristics.

from humid air [26]. Silica gel is an artificially produced solid and a stirring organic substance composed of sodium silicate. Silica gel has the best capacity to absorb moisture due to its development as a beaded and granular substance with a vast surface area [4]. It is available in a range of colours and forms. By changing its colour, the coloured SiO_2 has been utilised to track how much moisture it absorbs. Blue and orange are the most popular silica gel colours [25]. A list of the features of the silica gel used in this investigation is provided in Table 2. The blue silica gel turns pink as it adsorbs moisture and returns to blue when it loses the adsorbed moisture. Fig. 3a depicts silica gel without moisture, whereas Fig. 3b depicts silica gel with moisture absorbed.

2.4. Experimental procedure

The experiments were done in Kirkuk, Iraq, at 35.4666° N and 44.3799° E regarding latitude and longitude. The experiments were done in three steps: adsorption, regeneration, and condensation. When the sun goes down at night, silica gel is exposed to the air, which starts the adsorption process. The differential in vapour pressure between the surface of the silica gel and the surrounding air caused moisture to begin to move from the air to the silica gel. This procedure continued until there was no longer any difference in vapour pressure. When moisture was adsorbed, the desiccant's colour changed from dark blue to light pink. The regeneration process began with the sun rising during the day after the desiccant was placed inside the device and the doors were closed. The desiccant material began to receive energy from the insolation, which caused the temperature and the vapour pressure of silica gel to rise. Moisture evaporated and migrated toward the interior surface of the acrylic sheet as a consequence of the vapour pressure differential. Condensation of the evaporated moisture occurred on the inside surface of the acrylic sheet. The evaporation and condensation processes ended when there was no pressure differential. The silica gel changed from light pink to dark blue again, showing that it had lost all of its water during the regeneration process. On a weight basis, the adsorption and regeneration rates have been computed. The following relationships have been used to compute the adsorption rate (G_a) and regeneration rate (G_r), Srivastava and Yadav [6]:

A-adsorption rate (kg/h):

$$G_a = m_{\mathrm{ws}} \frac{dw}{dt} \tag{1}$$

B-regeneration rate (kg/h):

$$G_r = m_{\mathrm{ds}} \frac{dw}{dt} \tag{2}$$

where m_{ws} and m_{ds} are the weight of silica gel on a dry basis (kg) and wet basis (kg), respectively. While dw/dt: is the moisture content rate in silica gel.

The following relationship has been used to determine the system efficiency: Srivastava and Yadav [6]:

$$\eta = \frac{m_w L}{IAT} \times 100 \tag{3}$$

where m_w is the mass of the collected water (kg/h). L: latent heat of evaporation (kJ/kg). I: solar intensity (kW/m²). A: is

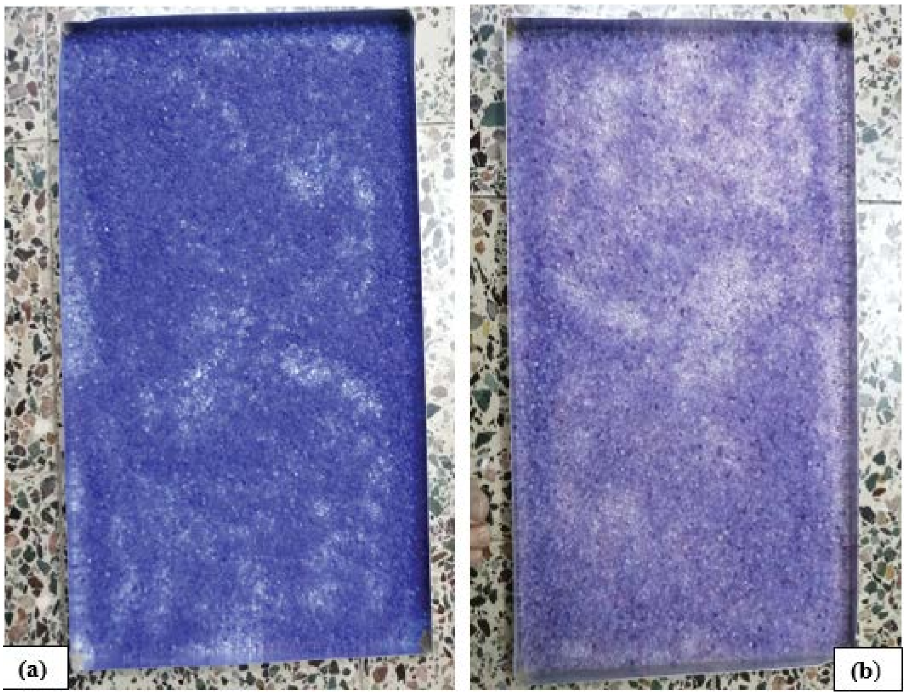

Fig. 3. Silica gel: (a) before moisture adsorption and (b) after moisture adsorption.

the surface area of the absorber (m²). *T*: is the conversion factor (3,600/1,000).

2.5. Uncertainty analysis

The experiment's measured values are inaccurate. These are impacted by the variations brought on by different errors. Systematic error and random error are the two categories of errors. Random errors are brought about by arbitrary and unexpected changes in the experimental settings, while systematic errors are caused by instrument and environmental flaws. Personal mistakes might happen while the observer collects the data [2]. The parameters experimentally measured in this study are solar intensity, relative humidity, wind speed, acrylic cover temperature, desiccant surface temperature, and ambient temperature. An experimental error analysis was carried out based on the content provided by Tahseen [27], and the resultant uncertainty of different parameters is illustrated in Tab. 3. The root sum square (RSS) method was used to calculate the percentage of uncertainty:

2.5.1. Uncertainty of independent parameters

- The uncertainty in solar intensity, wind speed, and relative humidity measurements can be calculated from the following equations:

The absolute uncertainty at 95% confidence can be calculated from the following:

$$U_X = \pm\left[B^2 + \mathrm{Ps}^2\right]^{0.5} \tag{4}$$

The relative uncertainty can be found from:

$$\frac{U_X}{X}\% = \left(\frac{U_X}{X}\right) \times 100 \tag{5}$$

where the bias error (B) and the precision (P) can be expressed as:

$$B = \pm\left[\left(\frac{1}{2}\text{Resolution}\right)^2 + \left(\text{accuracy}\right)^2\right]^{0.5} \tag{6}$$

$$\mathrm{Ps}_X = t_{(n-1),95\%} \times \sigma_{\bar{X}} \tag{7}$$

where $t_{(n-1),95\%}$ is the student-t distribution at a 95% confidence interval with the (N–1) degrees of freedom.

The mean standard deviation ($\sigma_{\bar{X}}$), the standard deviation (σ_x), and the average value of the readings ($\bar{X}$) can be expressed as:

$$\sigma_{\bar{X}} = \frac{\sigma_X}{\sqrt{N}} \tag{8}$$

$$\sigma_x = \left[\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2\right]^{0.5} \tag{9}$$

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{10}$$

- The uncertainty in transparent cover temperature, desiccant surface temperature, and ambient temperature measurements can be expressed as:

$$U_{\text{Temp}} = \pm\left[\left(U_{\text{Std}}\right)^2 + \left(U_{\text{Fitting-curve}}\right)^2\right]^{0.5} \tag{11}$$

where U_{std} is the absolute uncertainty and can be calculated from the same equations used in the absolute uncertainty calculations of the solar intensity, wind speed, and relative humidity measurements.

The uncertainty of the fitting curve can be explained as follows:

$$U_{\text{Fitting-curve}} = \sigma_{\bar{X}} \times t_{(N-1),95\%} \tag{12}$$

where $B_{\text{fitting-curve}} = 0$.

The relative uncertainty can be calculated from the following equation:

$$\frac{U_T}{T}\% = \left(\frac{U_T}{T}\right) \times 100 \tag{13}$$

2.5.2. Uncertainty of dependent parameters

- Uncertainty of the water productivity P:

$$\frac{U_P}{P} = \left[\left(\frac{U_{q_e}}{q_e}\right)^2 + \left(\frac{U_{h_{fg}}}{h_{fg}}\right)^2\right]^{0.5} \times 100 \tag{14}$$

- Uncertainty of the system efficiency η:

$$\frac{U_\eta}{\eta} = \left[\left(\frac{U_{q_e}}{q_e}\right)^2 + \left(\frac{U_H}{H}\right)^2\right]^{0.5} \times 100 \tag{15}$$

where the uncertainty of water pressure at desiccant temperature (P_d), the uncertainty of water pressure at cover temperature (P_{cov}), the uncertainty of latent heat transfer (h_{fg}), and the uncertainty of heat transfer by evaporation (q_e) can be calculated from:

$$\frac{U_{P_d}}{P_d} = \left[\left(\frac{U_{T_d}}{T_d}\right)^2\right]^{0.5} \times 100 \tag{16}$$

$$\frac{U_{P_{\text{cov}}}}{P_{\text{cov}}} = \left[\left(\frac{U_{T_{\text{cov}}}}{T_{\text{cov}}}\right)^2\right]^{0.5} \times 100 \tag{17}$$

$$\frac{U_{h_{fg}}}{h_{fg}} = \left[\left(\frac{U_{T_d}}{T_d}\right)^2\right]^{0.5} \times 100 \tag{18}$$

$$\frac{U_{q_e}}{q_e} = \left[\left(\frac{U_{h_{fg}}}{h_{fg}}\right)^2 + \left(\frac{U_{T_d}}{T_d}\right)^2 + \left(\frac{U_{T_{\text{cov}}}}{T_{\text{cov}}}\right)^2 + \left(\frac{U_{P_d}}{P_d}\right)^2 + \left(\frac{U_{P_{\text{cov}}}}{P_{\text{cov}}}\right)^2\right]^{0.5} \times 100 \tag{19}$$

3. Results and discussion

The experiments were performed over several days in September 2022 to assess the impact of various atmospheric conditions on the water production process. A comparison is made between the results of this work and those of another study. The comparison is made for solar intensity, bed surface temperature, absorption rate, accumulated water productivity, and system efficiency. The findings of the comparison, as well as the findings of several test days of the current study, have all been plotted.

Fig. 4 compares the present work with Srivastava and Yadav [6] for bed temperature and solar intensity. In both works, the bed temperature exceeds boiling temperature, and this is because of the use of reflectors. Before noon, the bed temperature in Srivastava and Yadav's [6] work experienced a sharp, sudden rise, whereas the rise was gradual in the present work. This is because the apparatus used in the present work is much larger than that used in Srivastava and Yadav's [6] work. In both works, the solar intensity reached its maximum value at 11:00 am and decreased gradually until sunset.

In Fig. 5, the change of absorptive rate with time for both works has been plotted. The highest adsorption rates were initially 0.016 kg/h in the current study and 0.024 kg/h in Srivastava and Yadav's [6] work. This is because the pores were empty, but as time passed, they began filling up, and the absorption rate slowed. For absorption operations, the absorption rate of Srivastava and Yadav's [6] work is higher than that of the present study. This is because the absorption rate depends proportionally on the relative humidity, which is higher in Srivastava and Yadav's [6] work.

The accumulated water productivity of both works has been plotted and illustrated in Fig. 6. The productivity in Srivastava and Yadav's [6] work is much higher than in the present work. This is because productivity depends on the amount of absorbed moisture, which is much higher in Srivastava and Yadav's [6] work. Fig. 7 shows the efficiency of both systems. For Srivastava and Yadav's [6] work, the efficiency is higher than the present work since efficiency depends on the amount of collected water. Fig. 8 shows

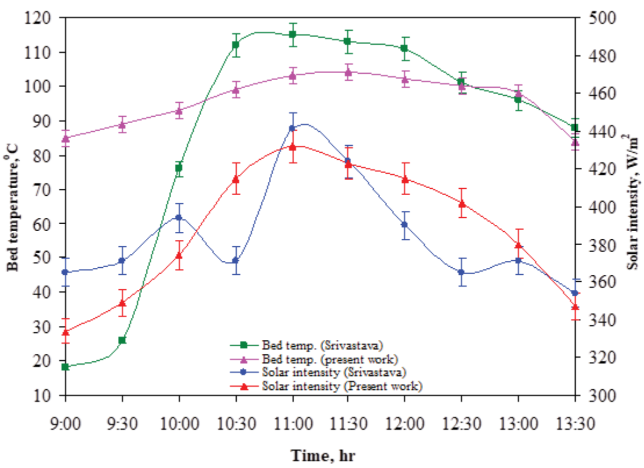

Fig. 4. Comparison of solar radiation and bed temperature of the present work with Srivastava and Yadav [6] work.

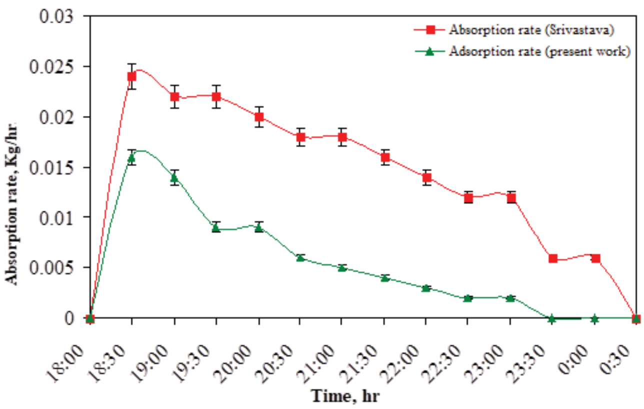

Fig. 5. Comparison of the adsorption rate of the present work with Srivastava and Yadav [6] work.

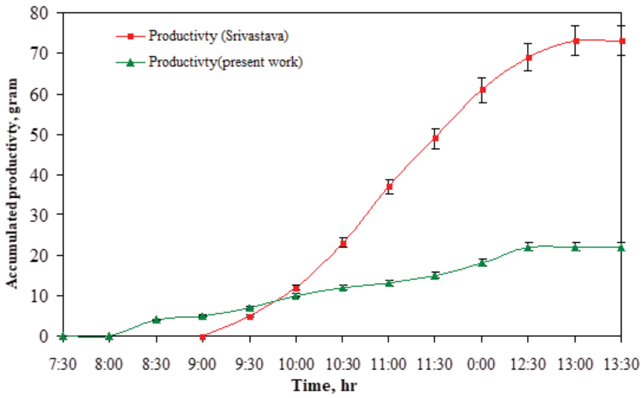

Fig. 6. Comparison of the accumulated water productivity of the current study with Srivastava and Yadav [6] work.

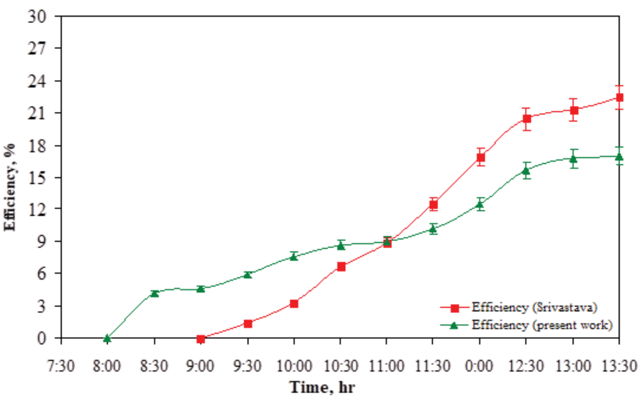

Fig. 7. Comparison of the system efficiency of the current study with Srivastava and Yadav [6] work.

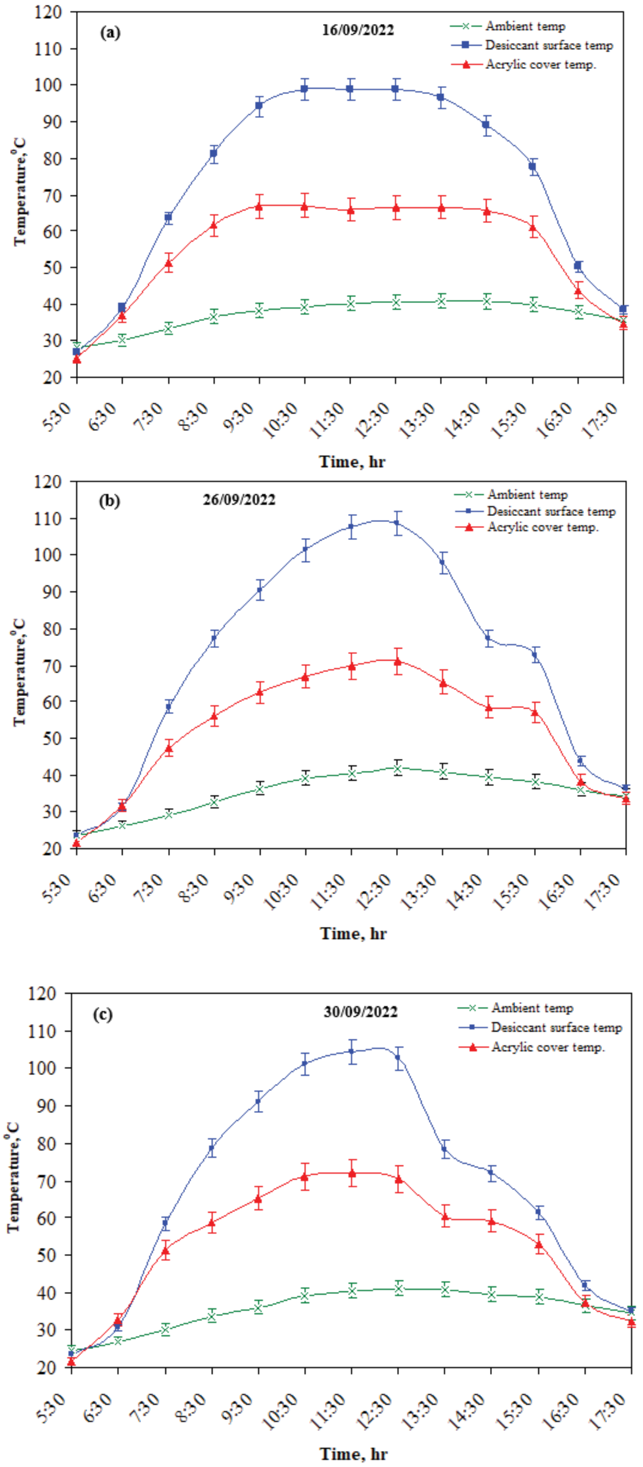

Fig. 8. Change of ambient, desiccant surface, and acrylic cover temperatures with time in (a) September 16, (b) September 26, and (c) September 30.

the change of temperatures (ambient, acrylic cover, and desiccant surface) with time on three chosen days during September.

Both desiccant surface and acrylic cover temperatures increase sharply at 6:30 am, and all temperatures reach their maximum value in the late afternoon. They then start to decrease until they are almost equal at sunset. The desiccant surface temperature is higher than that of the acrylic cover. This is caused by using internal reflectors that strongly increase the desiccant's surface temperature and also because of the low absorbency of the acrylic cover, which is about 0.4. In Fig. 9, the relative humidity for the three test days has been plotted concerning time. It has been observed that the relative humidity increased gradually on both September 16 and 26 from the beginning of the adsorption process and reached its maximum value at 5:30 am, while its value was almost stable on September 30 for the whole process.

Fig. 10 presents the mass of adsorbed and evaporated moisture on test days. The amount of adsorbed moisture on September 25 was noticeably higher than on other test days. This is due to the higher relative humidity on this day than the others since the moisture adsorption rate changes proportionally with the relative humidity percentage. September 25 also has the highest evaporation of moisture, and this is because the amount of evaporated moisture increases as the amount of adsorbed moisture increases. As shown in Fig. 11, the change in solar intensity across time for the three test days has been plotted. It has been observed that solar radiation progressively rises during the day, reaching its peak around midday before gradually decreasing till sunset.

The collected water quantity for the three test days is shown in Fig. 12. The highest amount of accumulated water was 107 g/m^2, collected on September 26. The operation of the water collection took more time than the other 2 d. This is because the adsorbed moisture quantity on September 26 was much higher than on other days. Fig. 13 shows the changes in system efficiency and heat output concerning the test days. The two main elements influencing the system's efficiency are the solar intensity and the quantity of water mass-generated. The system's efficiency is first seen to be zero, but over time, as the amount of water collected grows, the efficiency is shown to improve. Even though the amount of heat output barely changed after 13:30 on September 16 and 30, the system efficiency increased. This is due to a decrease in solar intensity.

4. Cost analysis

To be able to determine the system's water generation costs, a cost analysis is presented. Cost of the items used during the experiment are listed in Table 4. The following are the primary calculation criteria utilised in the cost analysis:

Fixed annual cost, FAC: It can be estimated from the equation [1]:

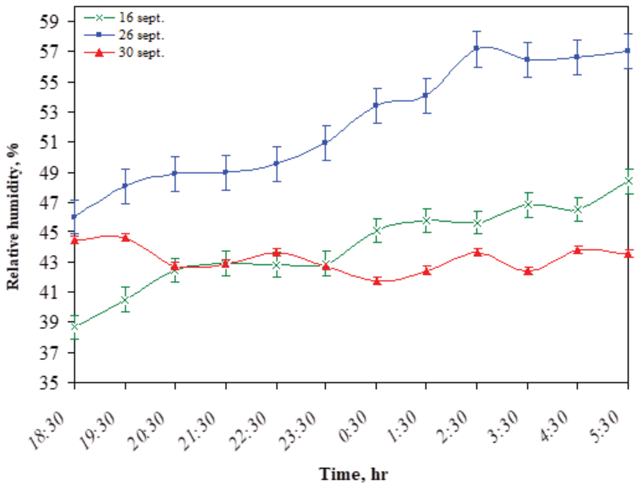

Fig. 9. Change of relative humidity on various days with time.

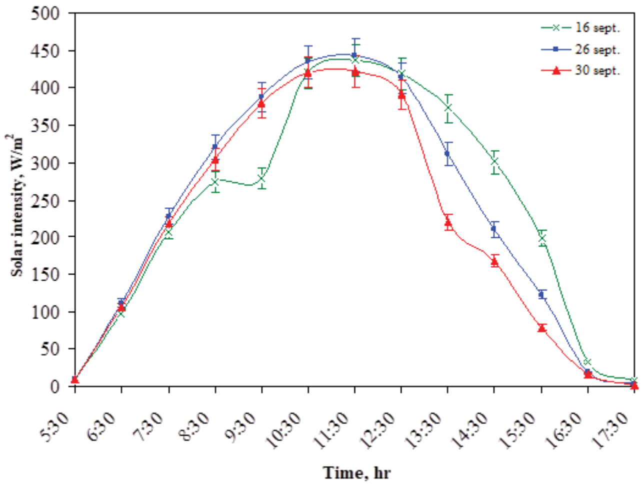

Fig. 11. Solar radiation changes with time on test days.

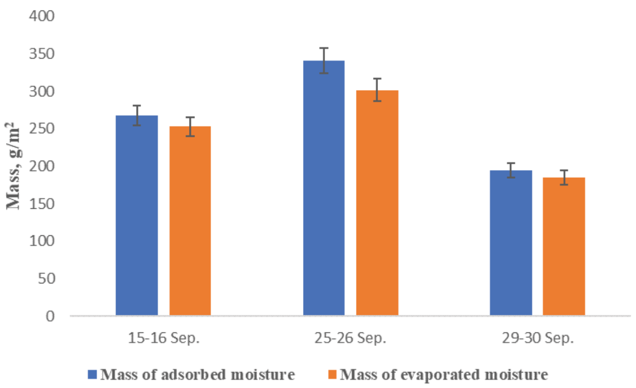

Fig. 10. Mass of adsorbed and evaporated moisture in various test days.

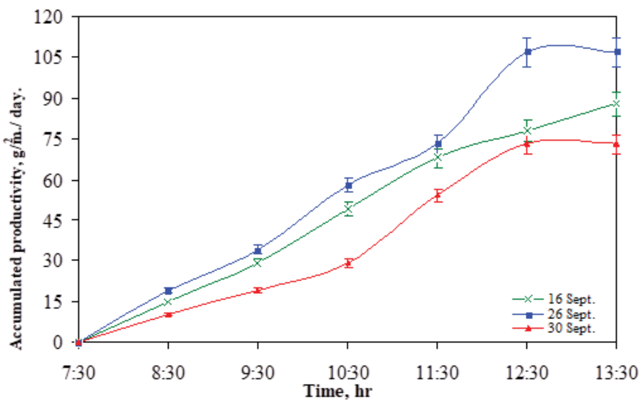

Fig. 12. Accumulated water productivity in test days.

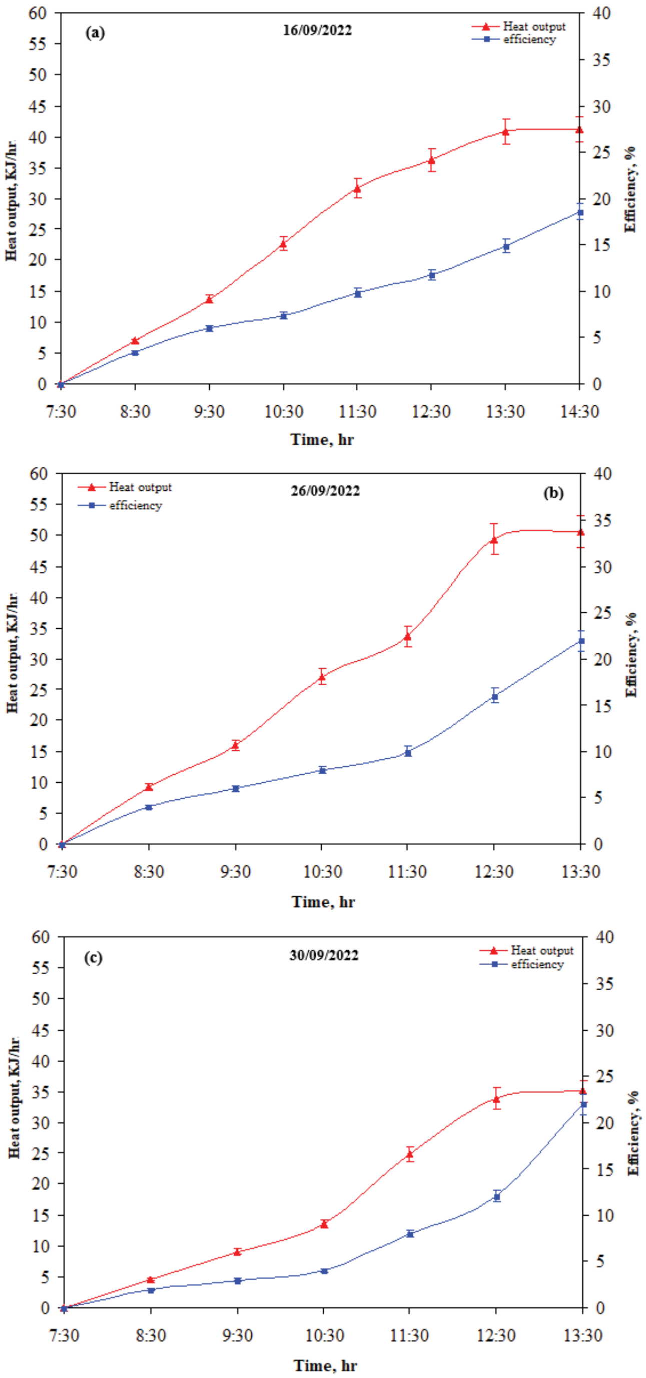

Fig. 13. Change of heat output and system efficiency with time in (a) September 16, (b) September 26, and (c) September 30.

$$\text{FAC} = \text{PC} \times \text{CRF} \tag{20}$$

where PC: present capital cost, CRF: capital cost recovery, that can be expressed as [12]:

$$\text{CRF} = \frac{i(i+1)^N}{(i+1)^N - 1} \tag{21}$$

Table 3
Resultant uncertainty of different parameters

Parameter	Uncertainty (%)
Solar intensity	±1.17
Wind speed	±3.3
Relative humidity	±5.23
Ambient temperature	±1.77
Desiccant temperature	±1.46
Cover temperature	±1.61
Water productivity	±3.7
System efficiency	±3.6

Table 4
Cost estimation for apparatus parameters

Items	Cost in ID/$
Apparatus structure	150,000/103.05
PVC door	50,000/34.27
Acrylic sheet	14,000/9.59
Insulating material	20,000/13.71
Solar tracking system	25,000/17.14
DC motor	25,000/17.14
Silica gel	15,000/10.28
Total	299,000/205.18

Annual maintenance cost, AMC: It assumed as 15% of the fixed annual cost:

$$\text{AMC} = -0.15 \times \text{PAC} \tag{22}$$

Annual salvage value, ASV: It can be calculated from the equation [28]:

$$\text{ASV} = \text{SFF} \times S \tag{23}$$

SFF: Sinking fund factor, which is calculated from [4]:

$$\text{SFF} = \frac{i}{(i+1)^N - 1} \tag{24}$$

S salvage value, which is expressed as [1]:

$$S = 0.2 \times \text{PC} \tag{25}$$

The annual cost, AC: we can calculate the annual cost from [12]:

$$\text{AC} = \text{FAC} + \text{AMC} - \text{ASV} \tag{26}$$

The total amount of produced water over the year, M. It can be expressed as [4]:

$$M = \text{amount of collected water} \times 365 \tag{27}$$

Cost of a produced kilogram of water, CPK:

$$\text{CPK} = \frac{\text{AC}}{M} \quad (28)$$

where PC = \$205.18, S = \$41.04, N = 5 y, and i = 10%.

The total amount of adsorbed moisture in one night is nearly 341 g/m^2; a large portion of this is evaporated, a portion of the vapour is lost, and the rest condenses and is collected as potable water. According to the preceding formulae, producing 1 kg of water costs \$2.54/kg. It is not cost-feasible when comparing this to moisture harvesting in humid air situations. Nevertheless, it can be considered acceptable in dry, distant, and isolated places with deficient humidity levels, and this apparatus would work better in typical humid environments.

5. Conclusion

An experimental study of moisture harvesting from atmospheric air and a comparison of the results with the findings carried out by another researcher has been done. The investigation was performed under the climatic conditions of Kirkuk, Iraq. Two identical integrated apparatuses were used simultaneously to test the performance of silica gel. It has been discovered that the climate and the partial pressure differential between the silica gel surface and the transparent cover impact water production. With a system efficiency of 22%, the maximum accumulated water was 107 g/m^2·d, and the annual cost of water production was nearly \$2.54. More significant water generation levels may be achieved if this procedure is applied in a different environment with high relative humidity. A Peltier is recommended to be used as a condensing surface to increase the amount of condensed vapour.

Conflict of interests

There are no conflicting interests, according to the authors.

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