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A Theoretical Study to Incorporate Capillary Tubes Action and Evaporation Process as Green Energy Techniques for Water Lifting

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Abstract: The idea proposed in this study can be used in remote areas to lift the water spontaneously instead of using electrical pumps. This research aims to lift the underground water to a high altitude by designing a passive system that simulates the rising water in tall plants due to capillary action and evaporation. The study assumed a set of micro-tubes to lift the underground water to a tank. The flow rate due to capillary rise and evaporation were analytically determined by mathematical models based on energy equations in fluid mechanics calculated using MATLAB software. The study results have shown that a system consisting of 2-10 billion micro-tubes can supply between 16-65 kg of water daily to a tank, depending on the environmental conditions. It was found that a set of tubes with a 20 μm diameter was a suitable choice to raise the water to 7.5 m, where 0.8 m rising was due to the capillary action, whereas the rest was due to the evaporation process suction head.

دراسة نظرية لدمج عمل الانابيب الشعيرية وعملية التبخر كتقنيات للطاقة الخضراء لرفع المياه

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الخلاصة

يمكن استخدام الفكرة المقترحة في هذه الدراسة في المناطق النائية لرفع المياه بشكل تلقائي بدلاً من استخدام المضخات الكهربائية. ان الهدف من هذا البحث هو رفع المياه الجوفية إلى ارتفاعات عالية من خلال تصميم نظام يحاكي رفع الماء في الاشجار العالية بسبب ظاهرتي الحركة الشعيرية والتبخر معا. افترضت الدراسة مجموعة من الأنابيب الشعيرية الدقيقة لرفع المياه الجوفية إلى خزان في الاعلى. تم ايجاد معدل التدفق الناتج عن ارتفاع الماء بسبب عمل الانابيب الشعيرية والتبخر بشكل تحليلي بواسطة نماذج رياضية اعتمدت معادلات حفظ الطاقة في الموائع وتم حسابها باستخدام برنامج ماتلاب. أظهرت نتائج الدراسة أن نظامًا يتكون من 2-10 مليار أنبوب دقيق قادر على إمداد ما بين 16-65 كجم من الماء يوميًا إلى الخزان وفقًا للظروف البيئية. حيث اظهرت الدراسة ان مجموعة الانابيب بقطر 20 مايكرون مناسبة لرفع الماء لغاية 7.5 متر فمنها 0.8متر صعود بسبب الخاصية الشعيرية والباقي بسبب طاقة السحب المتولدة نتيجة للتبخر.

الكلمات الدالة: الانابيب الشعيرية، التبخر، رفع المياه، الحفاظ على الطاقة، التقنيات الخضراء.

1.INTRODUCTION

In remote areas with no electrical network, several techniques are used to produce energy for agricultural purposes using renewable sources [1, 2]. The rise of water in a plant due to pressure difference gives a potential idea of investing the natural forces to lift the water in many life applications. Water is absorbed into plant roots by osmosis. Water density in the roots is less than in the soil, so water disperses from the epidermis through the root to the xylem. The water absorption by osmosis produces an action that pushes the water a few inches to the xylem, known as "root pressure." The xylem vessels are continuous pipes from the roots to the leaves. The drops evaporate from the leaves to air interfaces and spread through the stomata [3, 4]. The rise of water in the xylem is due to two phenomena: initially by the capillary action and mainly by evaporation, where there is a potential difference in water pressures that keeps the water in a continuous movement upward through the plant. The pressure difference due to the evaporation in the aerial parts (leaves) produces a process known as "transpiration." This phenomenon causes a potential force that motivates water transport from the stem (xylem) to the tiny bulbs in the branches to compensate for the lost water. The flow of water up through the stem depends on the cohesion-tension mechanism, where the water has a high tension due to the water molecules' tendency to stick together by hydrogen bonding (cohesion), so the water column in the xylem does not break easily under the weight force. Evaporation is driven by the sun, which acts as the potential energy for the entire circulation in the plants [5]. The rising water in tall plants motivates researchers and engineers to utilize capillary action and evaporation process for many livelihood applications, simulating the water transport behavior in plants and the design parameters. It was noticed that water vessels' diameters in a tree are within a range of 10-100 µm, and this range becomes smaller through the branches until the leaves, where the diameter of the porous walls is in the order of nanometer [6]. In tall trees, the force of gravity can only be overcome by decreasing the hydrostatic water pressure in the upper parts of the plant due to water diffusion out of the stomata into the atmosphere. In some trees, water can move up at an 8 m/h rate with a pressure difference between 0.5-1 MPa and reach a height of 100 m [3, 5]. Initially, it is important to analyze the phenomenon of water rise by evaporation in plants (transpiration) to get sufficient experience for industrial applications. The evaporation in a plant depends on a number of parameters, such as temperature and wetness. The quantity of water transported in plant vessels can be determined using a "potometer" device. Typically, most of the water that passes through plants (more than 90%) evaporates through the leaves, while only the remaining water is used by the plant for photosynthesis and turgor [7]. In an interesting study, the evaporation rate was measured by Tanner and Beevers [8] to determine a correlation between the amounts of water a plant took that evaporated. Some sunflower plants were observed under a controlled system to measure the transpiration for 24 hours. The experiment was terminated after 30 work days. The tested plants transported 13.9 L of water. The work included many details and valuable findings. Furthermore, a study by Hodson and Acuff [9] investigated the evaporation rate of a tomato plant. They used a dye to determine how the rising water is transported by a split twig. Some stage photographs were taken by a digital camera. The results figured out the role of leaves in water transport by evaporation using a valuable and stable electronic potometer. The results obtained helped determine the amount of water transport. On average, four leaves may contribute to 7 μL/min of evaporation rate. Recently, several promising studies have been worth highlighting in developing water transport by either capillary action or evaporation to lift and extract water for many applications. Deng et al. [10] argued a scientific perspective to lift water using nanotubes. They referred to an investigation study based on a computer-built-in simulation of water flow through carbon nanotubes (CNTs). The study suggested a trillion CNTs with a constant diameter. The study confirmed that minimizing the tube diameter increased the capillary rise; however, tubes greater than 500 nm may supply a limited flow rate. However, the author admitted the difficulty of applying such transport processes depending on a nanometer scale. Jambhekar et al. [11] suggested a numerical method to illustrate evaporation behavior from a porous medium initially saturated with salt solution, manifesting its influence on dissolved salt distribution, salt precipitation, and porous-media properties. The initial salt concentration influence on the saline water saturation vapor pressure was analyzed. Shen et al. [12] theoretically investigated fluid transport in a microscopic capillary tube under sticky layer effects. The results proved that the capillary radius significantly affected the fluid height. Gruener and Huber [13] presented the capillary rise as a solution for spontaneous imbibition in porous media with wide applications in the petroleum industry. The porous medium is a bundle of capillary tubes and is further simplified as a vertical tube with a small radius. Dangwal and Aggarwal [14] suggested irrigating hilly areas by capillary lift. A capillary tube can be filled with water by capillary action, and then a thin-tube pump will be operated with the power available from a solar-wind microgrid. Many such pumps can be employed at several points depending on the water required for irrigation. Li et al. [15] introduced a method of light-driven water harvesting from soils, where a concentrated solar energy method (Fresnel lens) was used to evaporate the wet soil. Then the steam flew to the condenser through tubes and condensed as freshwater. Considering the dimensions of the samples, the water harvesting rate of a solar flux of 1 kW/m² was estimated to be approximately 360 g/h with a 1 m² solar concentrator area. Furthermore, the water quality testing results indicated that the collected water was high-quality drinking water. The classical Lucas–Washburn equation and its modified forms were implemented by Cai et al. [16] to simulate fluid flow in porous systems driven by capillary pressure. The study included capillary tubes with non-uniform and non-circular cross sections, discrete fractures, capillary tubes that were not straight, and heterogeneous porous media. It can be seen that no literature is available on the use of both capillary action and evaporation process to lift the water for relatively high altitudes. The mentioned previous studies considered the subject from different aspects, such as using a porous medium as a capillary conduit, using a mini-scale tube to determine the rate of evaporation, extracting water from the soil for a limited elevation, or removing salt from it through solar concentration or suggesting a theoretical proposal to use nanotubes that are difficult to assemble in such cases and without mentioning the exact specifications and conditions. The innovative contribution of the current work is presenting a passive system to lift the water to a relatively high altitude. The object of this study is to raise the underground water for a specific elevation by green techniques (capillary action and evaporation) simulating the water transport in plants, where the collected water can be utilized for many applications, especially for irrigation. The system consisted of a bundle of micro-tubes, a solar collector as a source to generate the driving force for evaporation, and a water tank (Fig. 1).

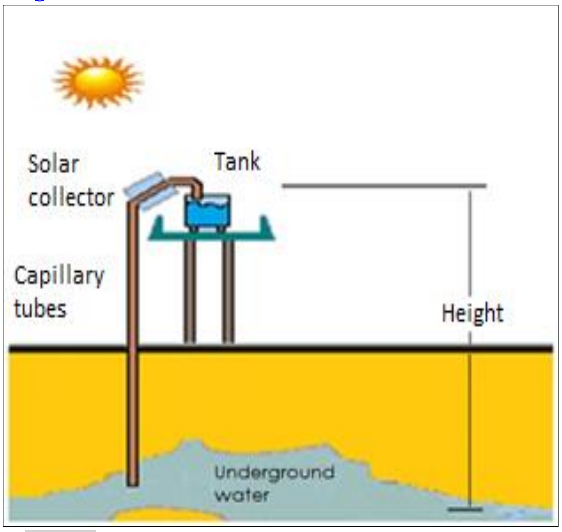

Fig. 1 The System Proposed in the Current Work.

2.MATERIALS AND METHODS

This part of the study aims to select and design the tubes, their quantity, diameters and lengths, and materials. The theoretical analysis included two mathematical models (steps) that were extracted from energy equations in fluid mechanics. The study assumes that the rise of water is due to capillary action and the evaporation process, as shown in the schematic diagram (Fig. 2). The first step focuses on calculating capillary rise, while the second step focuses on calculating the driving force, which is necessary for determining the evaporation rate.

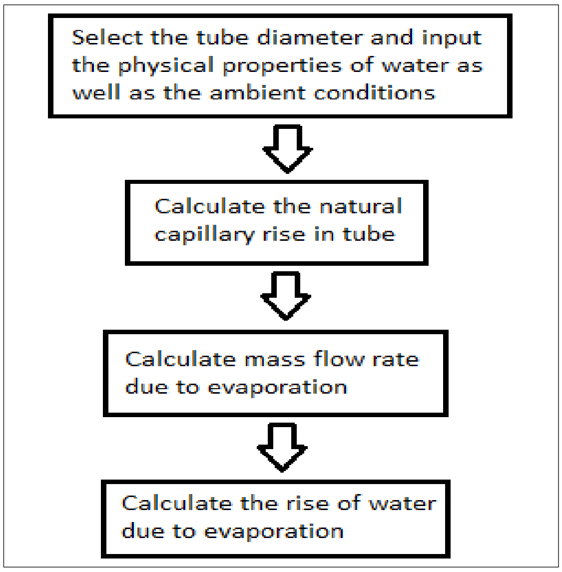

Fig. 2 Schematic Diagram of the Mathematical Models' Sequence.

Initially, the water rises in the tubes due to capillary action. The suggested model for capillary rise assumed that the capillary pressure (P) remains constant and the tube surface is smooth (for example, made of glass). So, the pressure could be formulated depending on the fully-developed profile in a cylindrical tube [5, 17], as shown in Fig. 3, where there are two acting forces: the upward pull force due to surface tension and the downward force due to the suction head of the water.

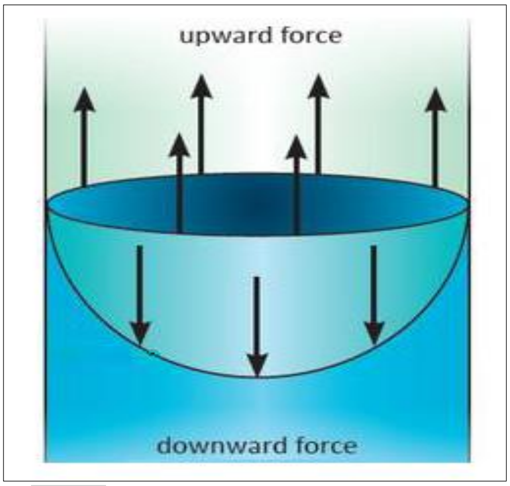

Fig. 3 Assumption of Drop Shape and Equilibrium Forces in the Capillary Tube [18].

Since the contact angle between the glass and the water is zero, the equilibrium yields [18].

$$F_{upward} = F_{downward} \quad \textbf{(1)}$$

The upward force is equal to the perimeter of contact between the water and the tube multiplied by the surface tension of the water (σ). The downward force provides the suction force, multiplying the pressure drop (ΔP) by the tube area. As a result of substitutions, it yields [18]:

$$2\,\pi\,r\,\sigma = \pi\,r^2\,\Delta P \quad \textbf{(2)}$$

Hence

$$\Delta P = \frac{2\,\sigma}{r} \quad \textbf{(3)}$$

On the other hand, the pressure drop is represented by [19]

$$\Delta P = \rho\,g\,H_c \quad \textbf{(4)}$$

By equalizing Eq. (3) and (4) and substituting the value of water surface tension as 0.075 N/m and the density of the water as 1000 kg/m³ at 25 °C [19], the capillary rise (H_c) will be:

$$H_c = \frac{15\ x\ 10^{-6}}{r} \quad \textbf{(5)}$$

The high magnitude of capillary rise in the tube can be satisfied using a very small radius (in the order of micro- or nano-scale). However, many parameters, such as tube surface roughness and fluid properties, could also change the height magnitude due to the energy levels of the molecules in the fluid and the attraction between them [20]. Since the capillary rise is relatively low and does not achieve the desired total head, it is required to involve the evaporation phenomenon, which offers extra suction head and keeps the water in a continuous flow along the tube. In this step, water is moving up passively due to the driving force generated by the evaporation, i.e., by pressure potential gradients. The water can rise due to the compression-tension mechanism, where water molecules remain in continuous contact due to their strong bonds [3, 5, 6]. In the present study, the evaporation started at the upper end of the tube exposed to the sun (heat). The tubes' ends were opened inside a solar collector, which was covered by a glass cover, where the collector simulated the work of the common water distillation unit based on evaporation-condensation processes, as shown in Fig. 4.

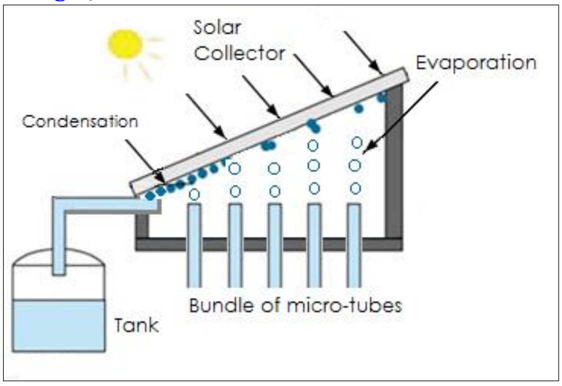

Fig. 4 The Role of Solar Collector in Evaporation.

The evaporation rate can be estimated depending on Reynolds flux as a diffusion process. In this case, water diffuses from the high-concentrated region to the low-concentrated region. In the air-water interface, water leaks into the air when solar energy breaks hydrogen bonds between water molecules, so evaporation happens [21]. Surface tension draws water molecules upwards to replace droplets lost through evaporation. This potential mechanism can be extended through the tube down to the bottom. An analytical model to predict the evaporation rate can be suggested depending on interfacial thermal properties and compared to many experimental parameters. Where the evaporation rate (m) from the interface (air-water surface) can be calculated in (kg/s.m²) using [22].

$$m = \frac{0.00001477\, T_v\, T_l \ln\left[\frac{P_v}{P_S\,.\,T_l}\right] - 0.0213\,(T_v - T_l)}{T_v - 670\,(T_v - T_l) + 0.649\, T_v\, T_l \ln\left[\frac{P_v}{P_S\,.\,T_l}\right]} \quad \textbf{(6)}$$

Where T_l is the liquid temperature, P_s is the saturated liquid pressure, T_v is the vapor temperature in the air-water interface, and P_v is the vapor pressure. Note that the water surface at the upper end of the tube is in direct contact with the air, which has a specific humidity. The water concentration in the air depends on the ambient conditions, such as relative humidity, temperature, and solar intensity. Another important issue is the head falling because the water tension at the upper end of the tube should be able to hold the heavy continuous column of water for the desired length; otherwise, it will lose evaporation advantage. Applying the Bernoulli equation between the lower and upper ends of the tube yields [19]:

$$H_e = \frac{(P_v - P_S) + ½\,\rho\, V^2}{\rho\, g} \quad \textbf{(7)}$$

Where H_e is the available rise of water due to evaporation. Note that the delivered flow velocity (V) can be calculated as follows [21]:

$$V = Sh\, D_w / d \quad \textbf{(8)}$$

where D_w is the diffusion coefficient of water extracted empirically according to McCabe et al. [23] and simplified to:

$$Dw = 3 \times 10^{-9}\, T_w^{\,1.8} \quad \textbf{(9)}$$

where T_w is the water temperature in (K). Sherwood number (Sh) is given empirically by [24].

$$Sh = 0.145\, Re^{0.69}\, Sc^{0.87} \quad \textbf{(10)}$$

Note that Reynolds number (Re) and Schmidt number (Sc) are denoted as [24].

$$Re = V\, d / \nu \quad \textbf{(11)}$$

$$Sc = \nu / D_w \quad \textbf{(12)}$$

The present study assumed that the number of tubes may reach several billion to supply enough water, similar to the plant leaves' stomata density (pores). The pores have a range of diameters within 10-100 µm, and the average density is about (1000 stomata/mm²); therefore, each leaf may contain millions of pores [25]. However, the range of dimensions, quantities, and conditions are shown in Table 1.

Table 1 Dimensions and Operational Conditions.

Item	Value
Number of tubes	2 x 10⁹-10 x 10⁹
Diameter of tube	10 – 100 µm
Length of tube	4-8 m
Liquid temperature (T_l)	25 °C
Vapor temperature (T_v)	30-90 °C

3.RESULTS AND DISCUSSION

A MATLAB program was served to determine capillary rise, evaporation rate, and available head by evaporation for different values of tube diameters and number of tubes. The results are listed and discussed accordingly.

3.1.Capillary Rise

The water rise values for specific capillary tubes are shown in Fig. 5. The values range between 1.5 m for 10 µm diameter to 0.15 m for 100 µm mm diameter. The results showed that the smallest diameter was preferable to raise the water higher because the lowest diameter tube had a higher relative surface area than other diameters, making the capillary action stronger to pull more water up than larger diameter tubes [18]. However, to get a valuable head, the diameter of the tube should not be greater than 20 µm because a greater diameter resulted in a head less than 0.5 m, which is insignificant to initializing a high head.

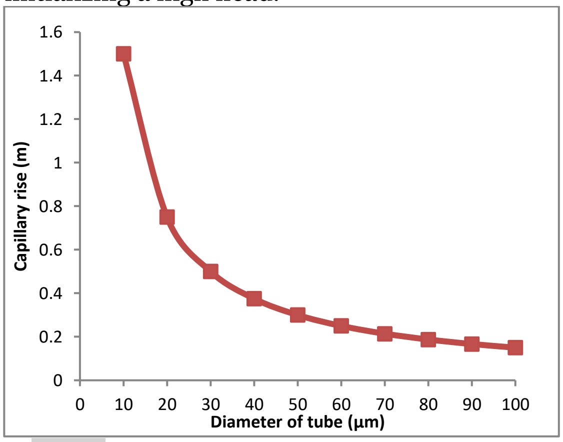

Fig. 5 Capillary Rise for a Range of Tubes.

3.2.Evaporation Rate

The evaporation flow rate results are shown in Fig. 6 with respect to the vapor temperature in the air-water interface, which ranges between 30-90 °C. It can be noticed that increasing vapor temperature led to a high evaporation rate, which was 5.8x10⁻⁴ kg/s.m² at 90 °C because, at higher temperatures, more molecules release from their chains and have enough energy to break away from the liquid to become vapor [26].

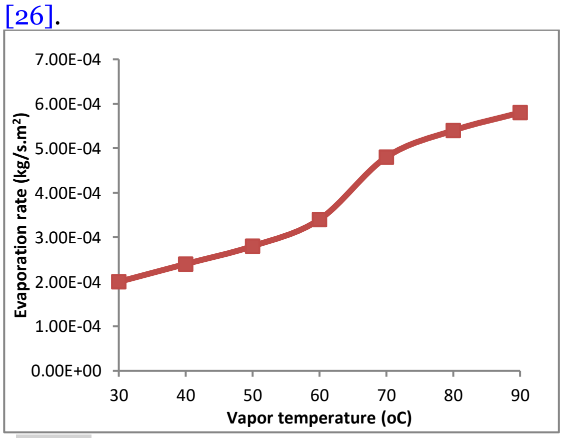

Fig. 6 Flow Rate Due to Evaporation (T_l = 25 °C).

Fig. 7 represents the evaporation flow rate in (kg) according to tube diameter and quantity, assuming a constant vapor temperature of 90 °C, 10 hours of daytime, and ideal collector efficiency for distillation. According to the results, the maximum evaporation rate for the bundle of capillary tubes per day was 16.4 kg for a 10 μm tube and 65.4 kg for a 20 μm tube. Therefore, the lower tubes' diameters may be insufficient because of the low discharge rate. Noting that the large diameter scale had a problem of less capillary rise, as mentioned earlier.

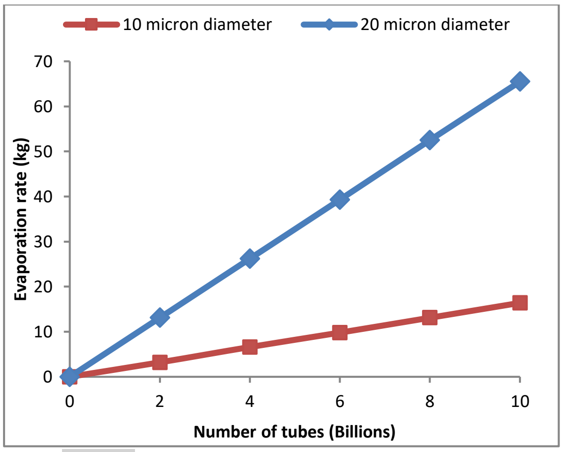

Fig. 7 Evaporation Rate for Different Diameters and Quantity of Tubes (T_l = 25 °C and T_v = 90 °C).

3.3.Available Head by Evaporation

The energy of evaporation to pull the water up is affected by the weight of the water and the gravity, where unconstrained water runs down. This effect is important, and extra pressure force is required to achieve the rise of water for additional height. Usually, this effect increases the pressure by approximately 10 kPa for each meter, increasing in height more than the capillary rise [5]. Thus, it is convenient to introduce the notion of head available by evaporation. A head compensation can be achieved by evaporation, where water moves up passively due to the generated driving force. According to the Bernoulli equation, the head mainly depends on the pressure difference (P_v-P_s) since the velocity was too small and did not affect the overall result. Fig. 8 shows the available head by evaporation phenomenon for various vapor temperatures. The results show that the maximum rise by the evaporation can be achieved at 90 °C, which was 6.7 m (According to Eq. (7)), which depends on specifications and conditions of the water, tube, and surrounding ambient). The results fit for small tube diameters (10-20 μm). Large tube diameters suffered from water falling since the tension was unsuitable to withstand the heavy water along the tube, therefore losing the evaporation advantage.

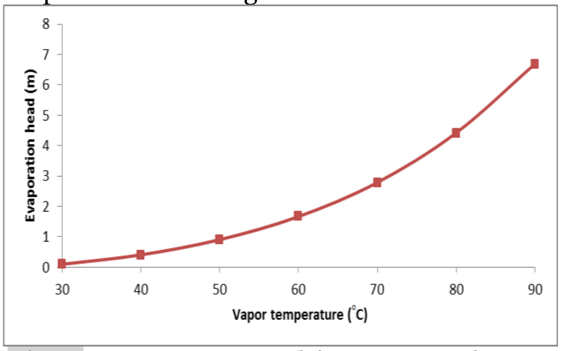

Fig. 8 Evaporation Head for a Range of Vapor Temperatures.

3.4.Comparison Between the Present Study and Previous Studies

For validation purposes, Fig. 9 shows the main parameters for some studies under comparison, while Table 2 compares the results of the present work and the previous ones by computing the overall performance of the system. In general, the performance can be calculated by

$$\eta = \frac{P_{out}}{P_{in}} \quad \textbf{(13)}$$

where the input power is the solar energy, which is a function of solar radiation (I) and collector area (A), as follows

$$P_{in} = I\ A \quad \textbf{(14)}$$

While the output power is the water head energy similar to the pump power, which is a function of total head (H) and flow rate (Q), as follows

$$P_{out} = \rho\ g\ H\ Q \quad \textbf{(15)}$$

Since the flow rate is extremely low for any natural upward flow, including the present and previous studies, the output power was relatively small compared to the input power (solar energy). Therefore, the value of the performance was too low for all cases. However, the present study satisfied a higher performance than other studies. This progression is due to the incorporation of capillary action and evaporation process within the present study and corresponding design parameters.

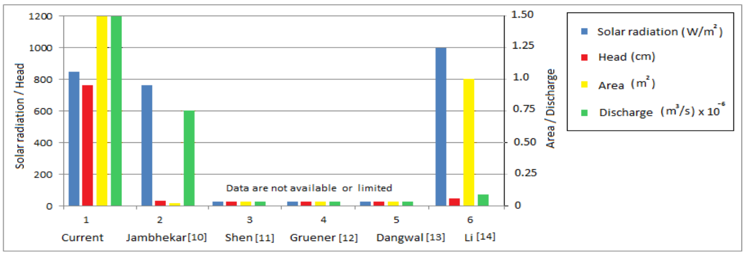

Fig. 9 Main Parameters for Some Studies under Comparison.

Table 2 Comparison between the Performance of the Present and Previous Works.

Study	Characteristics	Description	Performance
Present	I=850 W/m², A=1.5 m², H=7.5 m, Q=1.8x10⁻⁶ m³/s	Capillary action and evaporation High head	1.04×10^{-4}
Jambhekar et al. [10]	I=750 W/m², A=0.02 m², H=0.15 m, Q=0.75x10⁻⁶ m³/s	Capillary action and evaporation Low head	0.74×10^{-4}
Shen et al. [11]	A model to calculate the capillary rise only without calculations	Capillary action only High head	-
Gruener and Huber [12]	The discharge and head are too small and incomparable	Capillary action only Low head	-
Dangwal and Aggarwal [13]	Hypothetical search without data	Capillary action only High head	-
Li et al. [14]	I=1000 W/m², A=1 m², H=0.2 m, Q=0.1x10⁻⁶ m³/s	Capillary action and evaporation Low head	2.0×10^{-7}

4.CONCLUSION

This research investigated the capability of lifting the underground water to a tank with a target of 8 m altitude by simulating the water transport in plants depending on two phenomena, i.e., capillary action and evaporation. The study was based on theoretical analysis. It was found that a set of 10 billion tubes with 20 μm diameter was a suitable choice to raise the water to 7.5 m, where 0.8 m rising was due to the capillary action while 6.7 m was due to the evaporation. The set could supply continuous water with a maximum flow rate of 65 kg/day and a minimum of 16 kg/day, depending on the ambient conditions. The tubes of lower diameters may be insufficient because of the low discharge rate. Large diameter tubes had the problem of low capillary rise and head falling due to weak tension to hold the heavy continuous column of water.

NOMENCLATURE

A	Area of collector.
CNTs	Carbon nanotubes.
D_w	Diffusion coefficient of water.
d	Tube diameter .
g	Gravity.
H_c	Capillary rise.
H_e	Head of water due to evaporation.
I	Intensity of solar radiation .
m	Evaporation rate.
P_{in}	Input power as the solar energy.
P_{out}	Output power as the water head.
P_s	Saturated liquid pressure.
P_v	Vapor pressure.
Q	Discharge of water.
r	Radius of the tube.
T_l	Liquid temperature.
T_v	Vapor temperature in the air-water interface.
Tw	Water temperature.
V	Flow velocity due to evaporation.
η	Efficiency of the system .
ν	Kinematic viscosity of water .
ρ	Water density.
σ	Surface tension of the water .

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